Eurasian J Soil Sci 2018, 7 (3) 195 - 202

Eurasian Journal of Soil Science

Journal homepage : http://ejss.fesss.org

Imaging soil pore characteristics using computed tomography as influenced by agroecosystems

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Article Info

Received : 01.11.2017
Accepted : 12.02.2018

Abstract

Soil pore parameters are important for water infiltration into the soil and transport within the soil. The aim of this study was to compare influences of agroecosystems on soil pore characteristics (number of pores, macropores, coarse mesopores, porosity, macroporosity, coarse mesoporosity, pore circularity) using computed tomography (CT). This experiment was carried out four different agroecosystem field [Tucker Prairie (TP): native prairie, Prairie Fork (PF): restored prairie, Conservation Reserve Program (CRP), and row crop (RC): corn/soybean rotation] in Missouri state of United States during the year of 2017. Undisturbed soil samples were collected at four soil depths (0-10, 10-20, 20-30, and 30-40 cm) from each treatment with three replications. Five scan images from each sample were acquired using a X-ray CT scanner with 0.19 by 0.19 mm pixel resolution with 0.5 mm slice thickness and analyzed with *Image-J*. TP, PF, CRP, and RC treatments had 195, 88, 112, and 49 pores on a 2500 mm^2 area, respectively across all the depths. Soil under TP and CRP treatment had significantly higher porosity (0.046 m^3 m^{-3}, 0.046 m^3 m^{-3}), and macroporosity (0.036 m^3 m^{-3}, 0.041 m^3 m^{-3}) values than other treatments. The CT-measured number of macropores (>1000 µm diam.) were 5 times higher for TP when compared with RC treatment. The CT-measured pore circularity values were lower for CRP and RC treatments. CT-measured number of coarse mesopores, and mesoporosity were significantly greater under TP treatment. Results show that native prairie can improve soil pore parameters.

Keywords: Agroecosystems, computed tomograpy, *Image-J*, soil pore.

Introduction

Soil porosity is very important for transport and storage of water and nutrients in the soil. Hence, it is essential to understand soil pore characteristics. Water transmission and storage depend on the geometry and size distribution of soil pores (Eynard et al., 2004). Moreover, better water retention is also important to improve plant growth. Pasture, grass buffers, and agroforestry buffers as perennial vegetation increases soil porosity compared to row crop area (Seobi et al., 2005). Macropores (diam. >1000 µm; Zaibon et al., 2016) are pores with diameters larger than 0.3 to 0.5 mm and form from earthworm burrows decaying plant roots, swelling-shrinkage cracks, or interaggregate voids (Jarvis, 2007). The impact of macropores on soil transfer properties is directly related to their geometrical and topological characteristics, among which continuity and pore size distribution are of prime importance. Many investigators have shown that macropore characteristics such as shape, size, orientation, and size distribution affect the rate, flow, and retention of water (Scott et al., 1998; Udawatta et al., 2006).

Porosity determined by traditional methods often lacks detailed information on pore characteristics and sometimes porosity is estimated by indirect procedures (Udawatta et al., 2006). These procedures do not provide information on the spatial distribution of pores (Gantzer and Anderson, 2002).

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e-ISSN: 2147-4249
DOI: 10.18393/ejss.396237

X-ray computed tomography (CT) provides a direct procedure to quantify the geometrical attributes of soil pore space in three dimensions (Wildenschild and Sheppard, 2013). It has been used effectively for measuring pore size, shape, distribution and arrangement of soil pores, surface area and pore connectivity (Udawatta and Anderson, 2008; Kumar et al., 2010; Rab et al., 2014). The connected and unconnected pores could easily be visualised and quantified using the X-ray CT method (Munkholm et al., 2012; Tracy et al., 2012) while this is not possible using the soil-water retention method.

Objectives of the study were to compare differences in CT-measured soil pore characteristics (number of pores, macropores, coarse mesopores, porosity, macroporosity, coarse mesoporosity, pore circularity) as influenced by Tucker Prairie, Prairie Fork, Conservation Reserve Program, and row crop (corn/soybean rotation).

Material and Methods

Study site

This study was conducted in four different agroecosystem fields: Tucker Prairie (TP: native prairie), Prairie Fork (PF: restored prairie), Conservation Reserve Program (CRP), and row crop (RC; corn/soybean rotation) in central Missouri during the year of 2017. The undisturbed TP area has been under native prairie vegetation and includes big blue stem (*Andropogon gerardi* Vitman.), little blue stem (*Schizachyrium scoparium* Nash.), prairie dropseed (*Sporobolus heterolepis* [A. Gray] A. Gray), and Indian grass (*Sorghastrum nutans* [L.J. Nash]) (Buyanovsky et al., 1987). The PF area was under row crop management for approximately 100 years and was restored in 1993 with native grasses and legumes. The study site vegetation consisted of little blue stem, side-oats gamma (*Bouteloua curtipendula var. curtipendula*), and Indian grass. CRP and RC sampling plots are located within the USDA-ARS Agricultural Systems for Environmental Quality site near Centralia, MO which had originally been under cultivation for approximately 100 years. The CRP sampling sites had been in CRP since 1991 with present vegetation consisting of 95% tall fescue, some orchardgrass, and red clover. The RC sampling areas were managed with mulch tillage since 1991 with 0.19 t ha^{-1} N during corn years and lime, P and K applied based on soil analysis for a grain yield of 1 t ha^{-1} for corn and 2.5 t ha^{-1} for soybean. These areas were in corn in 2005. Soils at these sites (TP, PF, CRP and RC) are Mexico silt loam (Fine, smectitic, mesic Vertic Epiaqualfs). The Mexico series are composed of very deep and poorly drained soils with an argillic horizon at varying depths on 0 to 4% slopes. The potential for runoff is high to very high and permeability is very slow. The native vegetation consists of warm-season grasses and forbs. Most areas are used to grow corn, soybeans, hay, pasture, and small grains.

Soil sampling and preparation

Undisturbed soil samples were removed from four soil depths (0-10 cm, 10-20 cm, 20-30 cm and 30-40 cm) with three replications using a Uhland sampler with Plexiglas cylinders (76.2 mm x 76.2 mm) during spring 2017. Two plastic caps and masking tape were used on each end of the sample to secure soil inside the cylinders. The soil samples were trimmed, labeled, and sealed in plastic bags and then transported to the laboratory. Samples were stored in a refrigerator at 4°C until measurements were taken. Selected soil properties for the sites are given in Table 1.

Table 1. Some physical and chemical properties of the treatments.

Treatments	Sand (%)	Clay (%)	Silt (%)	pH	Total Org. C (g kg^{-1})	CEC (c mol kg^{-1})
TP	6.28	27.26	66.46	4.98	15.40	19.54
PF	5.67	36.43	57.90	5.86	11.66	25.66
CRP	4.11	39.47	56.42	5.47	10.75	28.35
RC	4.03	38.90	57.07	5.77	9.25	28.67

TP: Tucker Prairie, PF: Prairie Fork, CRP: Conservation Reserve Program, RC: Row Crop (corn/soybean rotation), CEC: Cation Exchange Capacity, Org.C: Organic Carbon.

The bottom end of the cores was covered with two layers of fine nylon mesh to secure soil within the cylinder. The soil cores were slowly saturated from the bottom with distilled water using a Mariotte system. After 24 hours saturation, wet weights were recorded and samples were placed on a -3.5 kPa glass-bead tension table for 24 hours for draining. This procedure removed water from macropores and coarse mesopores to enhance the image contrast. Samples were re-weighed and two plastic end caps were secured with masking tape, and refrigirated until the scanning process.

Soil samples were taken out from refrigerator and re-weighed and prepared (put into the wooden boxes container) for transport to the University of Missouri Veterinary Medicine Hospital for computed tomography (CT) measurement. Two phantoms; a 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 of values through scans.

Scanning and imaging procedure

The X-ray CT scanner used in this study was a Toshiba Aquilion 64 set at a peak voltage of 120 keV and a current of 100 mA to acquire CT scan images. Soil samples were placed horizontally on the scanner bench so that the X-ray beam was perpendicular to the longitudinal axis. The scanning produced images with a slice thickness of 0.5 mm with a pixel size of 0.19 by 0.19 mm. Five scan slices per sample were taken. The scanned images were analyzed using the *Image-J* version 1.50i software (Rasband, 2013) to determine macropore (>1000µm diam.) and coarse mesopore (200-1000µm diam.) characteristics of the soils. The Threshold tool was used to characterize pores from solids after converting the image into an 8-bit grayscale image. A value of 40 was chosen as the threshold value to analyze all images. The values lower than the threshold value (40) were identified as the air-filled pores and values greater than the threshold value (40) were identified as non-pore (Figure 1). Statistics of individiual pores were estimated under the Analyze Particles Tool. The following CT-measured pore parameters were used in the analysis: CT-measured number of total pore area, macropore area, and coarse mesapore area of an image. These values were divided by the 2500 mm^2 scan area to calculate total porosity (macroporosity+coarse mesoporosity), macroporosity and coarse mesoporosity, respectively. Additionally, the circularity of pores was determined by dividing the pore area by 4 π multiplied by the pore perimeter squared (Tracy et al., 2015).

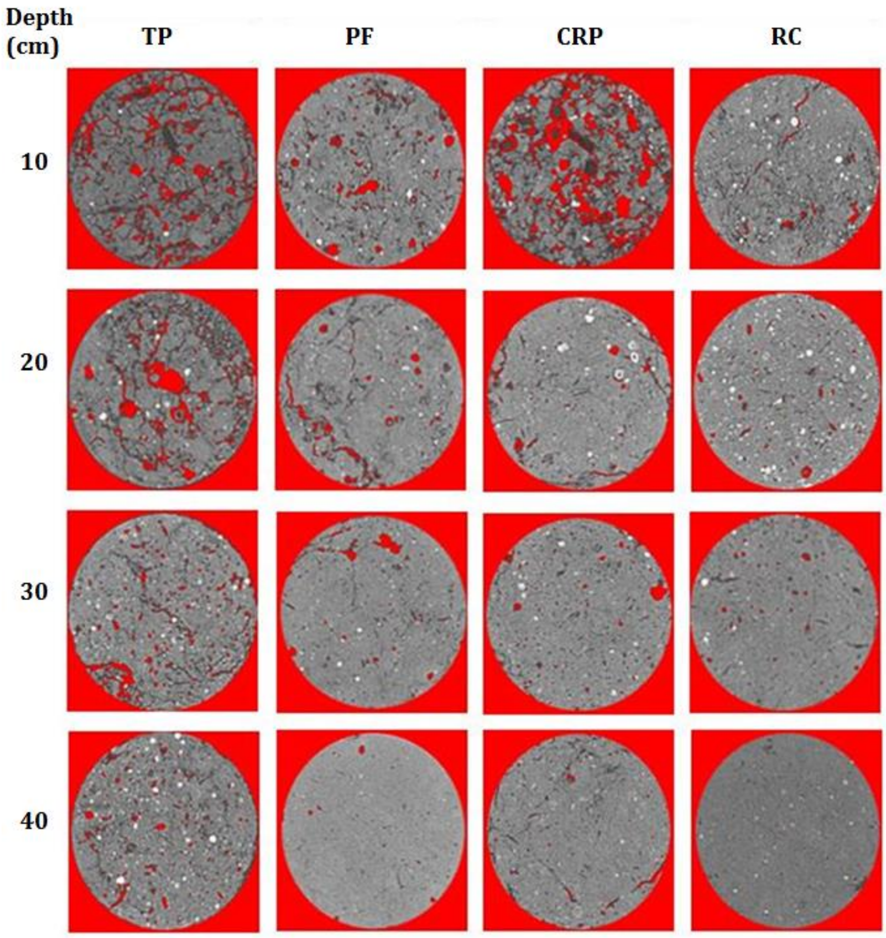

Figure 1. Selected some scan images of TP (Tucker Prairie), PF (Prairie Fork), CRP (Conservation Reserve Program), RC (Row Crop: corn/soybean rotation) treatments at four scan depths. Air-filled pores are in red, solid areas in gray and manganase in white colour.

Statistical analysis

Analysis of variance (ANOVA) was performed with SAS 9.4 using the GLM procedure. Means and differences among means for the measured parameters were determined with PROC MEANS. Statistical differences were declared significant at the α=0.05 level. Contrasts among treatments were analyzed to find significant differences among management practices.

Results

Computed tomography-measured number of pores, macropores and coarse mesopores

Two terms (depth zone and scan depth) were used to distinguish between the four depth zones or soil core depths (0–10, 10–20, 20–30, and 30–40 cm) and the 20 scan depths (five scans per depth zone), respectively, to examine CT-measured pore parameters. Number of pores refers to CT-measured pores, which indicate the lower limit of resolution on detecting pores and is directly related to the scanner resolution. The distribution of CT-measured pore sizes varied among the treatments and depth zones and significant (P<0.05) differences were observed between the treatments and depth zones and some interactions (Table 2). The average CT-measured number of pores were greater (195) in TP (Tucker Prairie) treatment as compared to the PF (Prairie Fork), CRP (Conservation Reserve Program), and RC (row crop) treatment (Table 2, P<0.05). The number of pores were higher in TP treatment in first soil depth zone compared to RC; values decreased from 310 at the 10 cm soil depth zone to 120 at the 40 cm soil depth zone for the TP treatment (Figure 2A) Also, this parameter was significantly higher in first soil depth zone compared to the other soil depth zones, values decreased from 221 at the 10 cm depth zone to 45 at the 40 cm depth zone (Table 2, P<0.05).

Averaged across the four depth zones, TP, PF, CRP, and RC treatments had 42, 22, 27, and 8 macropores on a 2500 mm^2 scan area, respectively (Table 2). No significant differences (P<0.05) were observed between the PF and CRP treatments. Soil under TP treatment had significantly more macropores than the other treatments (P<0.05). CRP treatment showed higher number of macropores (86) at the 10 cm soil depth zone when compared with the other treatments (Figure 2B).

TP, PF, CRP, and RC treatments had an average of 84, 38, 44, and 21 coarse mesopores across all scan depths on a 2500 mm^2 scan area, respectively (Table 2). The number of coarse mesopores was significantly different among the treatments and depths. The TP treatment area had the highest number of coarse mesopores when compared with the other treatments (P<0.05). TP treatment was also higher (120) in first depth zone than other treatments (Figure 2C).

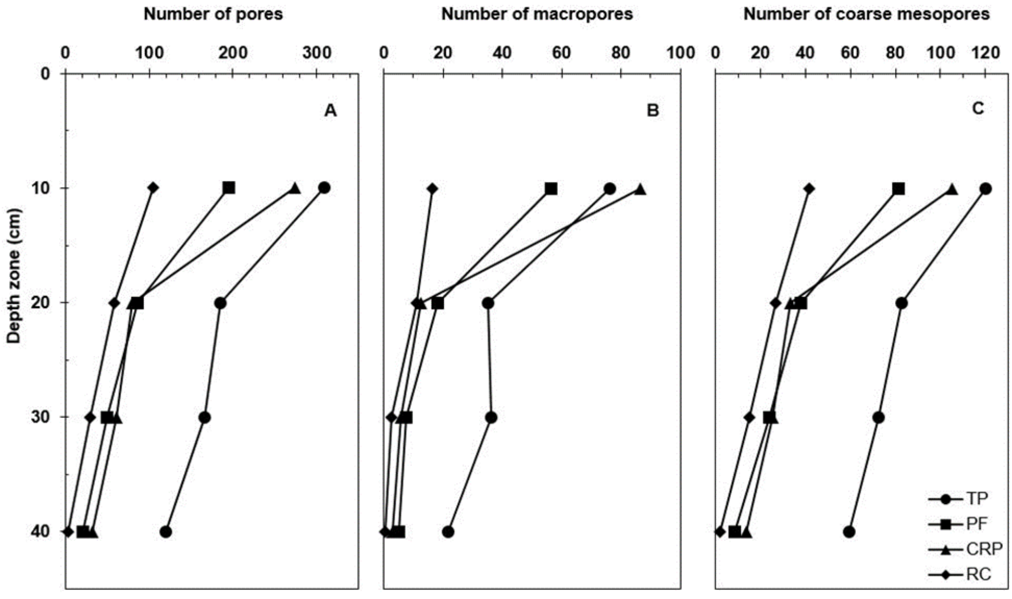

Figure 2. Computed tomography-measured (A) number of pores, (B) number of macropores, (C) number of coarse mesopores for tucker prairie (TP), prairie fork (PF), conservation reserve program (CRP), and row crop (RC) treatments by depth.

Computed tomography-measured porosity, macroporosity and coarse mesoporosity

The CT-measured porosity, macroporosity (diam.>1000 μm) and coarse mesoporosity (diam.200-1000 μm) were significantly affected by all the treatments, depth zones and some interactions (Table 2, P<0.05). TP and CRP treatments had greater porosity (0.046 m^3 m^{-3}) than PF (0.027 m^3 m^{-3}) and RC (0.011 m^3 m^{-3}) treatments. The CT-measured porosity, on average, significantly decreased with depth zone for all the treatments (Table 2). The higher CT-measured porosity was determined by CRP treatment as 0.158 m^3 m^{-3} at the first soil depth zone (Figure 3A). Similar to CT-measured porosity results, CT-measured macroporosity and coarse mesoporosity values decreased with increasing depth zones for all the treatments.

Table 2. Computed tomography-measured number of pores-macropores-coarse mesopores, porosity, macroporosity, coarse mesoporosity, and pore circularity as affected by depth and treatment and the ANOVA.

	Number			Porosity (m^3 m^{-3})			Pore circularity
	Pores	Macropores	Coarse mesopores	Porosity	Macroporosity	Coarse mesoporosity	
Treatment means							
TP	195 a	42 a	84 a	0.046 a	0.036 a	0.009 a	0.432 a
PF	88 b	22 ab	38 b	0.027 ab	0.022 ab	0.004 b	0.434 a
CRP	112 b	27 ab	44 b	0.046 a	0.041 a	0.005 b	0.348 b
RC	49 b	8 b	21 b	0.011 b	0.008 b	0.003 b	0.350 b
Depth zone means							
0-10 cm	221 a	59 a	87 a	0.084 a	0.073 a	0.009 a	0.437 a
10-20 cm	102 b	19 b	45 b	0.023 b	0.017 b	0.005 b	0.408 ab
20-30 cm	77 bc	13 b	34 bc	0.017 b	0.012 b	0.004 bc	0.367 bc
30-40 cm	45 c	8 b	21 c	0.007 b	0.004 b	0.002 c	0.352 c
Analysis of variance *p*>F							
Treatment	0.007	0.025	0.006	0.014	0.014	0.007	0.002
RC vs. Others	0.009	0.013	0.011	0.005	0.006	0.011	0.008
TP vs. PF&CRP	0.006	0.044	0.004	0.280	0.534	0.005	0.038
PF vs. CRP	0.451	0.583	0.623	0.065	0.046	0.741	0.002
Scan depth	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	0.001
Treatment x scan depth	0.266	0.043	0.321	<0.001	<0.001	0.124	<0.001

The ANOVA table presents significance levels among treatments and by depth for the measured parameters. (TP: Tucker Prairie; PF: Prairie Fork; CRP: Conservation Reserve Program; RC: Row Crop). (Treatment x scan depth= Treatment by scan depth interaction.) Mean comparisons were only made when *P* values for the main effects were ≤0.05. Means with different letters for a pore parameter are significantly different at the 0.05 probability level.

Macroporosity values averaged across all scan depths were 0.036, 0.022, 0.041, and 0.008 m^3 m^{-3} for TP, PF, CRP and RC treatments, respectively (Table 2). TP and CRP treatments had same significant level and also higher than the other two treatments (P<0.05, Table 2). CRP treatment had greater macroporosity values (0.143 m^3 m^{-3}) than the other treatments in first depth zone (Figure 3B). The greater CT-measured averaged coarse mesoporosity (diam. 200-1000 μm) values were found within the TP (0.009 m^3 m^{-3}) treatment (P<0.05, Table 2). TP treatment had about 3 times higher coarse mesoporosity than the RC treatment (0.003 m^3 m^{-3}). There were not observed any significant differences (P<0.05) between the PF, CRP and RC treatments. In addition, there were not found any coarse mesoporosity values in RC treatment at the fourth depth zone (Figure 3C).

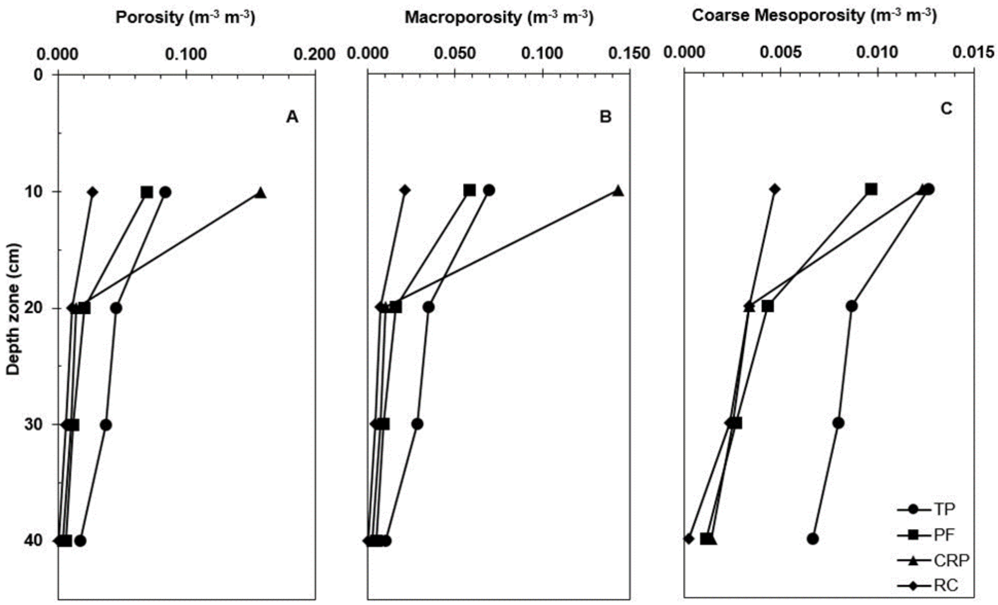

Figure 3. Computed tomography-measured (A) porosity, (B) macroporosity, (C) coarse mesoporosity for tucker prairie (TP), prairie fork (PF), conservation reserve program (CRP), and row crop (RC) treatments by depth.

Computed tomography-measured pore circularity

The CT-measured averaged circularity values were sifnificantly larger (about 25%) for the TP (0.432) and PF (0.434) treatments compared to CRP (0.349) and RC (0.350) treatments (P<0.05, Table 2). However, CRP treatment showed greater pore circularity value (0.493) than the other treatments at the first depth zone (Figure 4). Moreover, all the treatments showed significant differences averaged over scan depth.

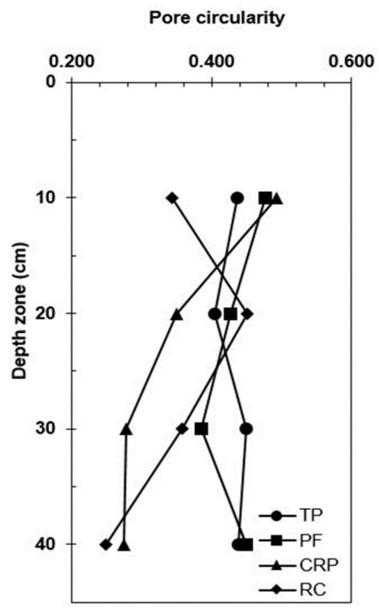

Figure 4. Computed tomography-measured pore circularity for tucker prairie (TP), prairie fork (PF), conservation reserve program (CRP), and row crop (RC) treatments by depth.

Discussion

This project evaluated the differences in CT-measured soil pore parameters under TP, PF, CRP, and RC managements at four depth zones. Differences were significantly higher for all pore parameters at the first depth zone (0-10 cm) compared with deeper depth zones. CT-measured number of pores, macropores, coarse mesopores, total porosity, macroporosity, coarse mesoporosity, and pore circularity were found to be significantly different among the treatments, depth zones and some interactions. Results showed that soil pore parameters were improved by tucker prairie and conservation reserve program treatments. The tucker prairie treatment had significantly greater pore parameters than the other treatments. Similar to tucker prairie, the conservation reserve program managements were also showed greater porosity, and macroporosity values with same significance level. Distribution of pores and macropores affect the ability to transport water and thereby influence nutrients in runoff (Pachepsky et al., 2000; Cadisch et al., 2004). Pachepsky et al. (1996) reported that management practices mostly effect the number and area of large elongated pores. Similarly, Rachman et al. (2005), observed significantly larger number of pores in soils under grass as compared with crop areas.

Some researchers found that permanent vegetation improves soil porosity compared with row crop land under till or no-till management (Bharati et al., 2002; Seobi et al., 2005). Rachman et al. (2005) and Udawatta et al. (2006) reported some differences in computed tomography measured macroporosity and mesoporosity under grass and trees compared with row crop areas. They found these differences due to roots, organic matter, agricultural activities, and duration of the vegetation period.

Pore circularity is one of the parameters that are often adopted to characterize pore shape. If the circularity approaches 1.0, the pore approaches a round shape. If the area of the pore is fixed, the more irregular its circumference is, the smaller its circularity will be (Zhao et al., 2010). CT-measured pore circularity was the highest in soil under the prairies and the smallest under row crop management. Prairie fork and tucker prairie treatments showed the highest CT-measured pore circularity with same significance level. Native and restored praires had increased more elongated larger pores in soils when compared with conservation reserve program and row crop treatments. Udawatta and Anderson (2008) demonstrated that prairie restoration improves CT-measured pore parameters, morphological characteristics and porosity. Results of this current study indicate that pore shape or form was highly related to vegetation treatment.

These findings show that native prairie (also known tucker prairie) and conservation reserve program soils improved pore parameters when compared to other treatments. Increased macroporosity in tucker prairie and conservation reserve areas will probably increase soil water infiltration, increase gas exchange and reduce runoff and nonpoint-source pollution. In addition, these management practices might help prevent surface runoff and serve as a sediment trap and they may enhance the groundwater recharge. This study also show that the usefulness of CT-scanning techniques combined with image analysis for quantifying pore parameters. These nondestructive techniques will prove useful for similar experiments in the future and will further expand the knowledge of soil pore systems.

Acknowledgements

This work is part of the international postdoctoral research financially supported by The Scientific and Technological Research Council of Turkey (TUBITAK-2219). I express our sincerest gratitude to them for their support.

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