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Effects of cover crop and biofuel crop management on computed tomography-measured pore parameters

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ABSTRACT

Understanding the effects of cropping practices on soil pore characteristics is important for determining soil productivity and ecosystem services. Objectives of the study were to compare differences in computed tomography (CT) measured soil pore parameters (number of macropores, macroporosity, area of the largest pore, circularity and fractal dimension) among cover crops (CC), no-cover crops (NCC), and biofuel crops [Miscanthus (M): *Miscanthus x giganteus* and switchgrass (SG): *Panicum virgatum*] and examine relationships between CT-measured pore parameters and soil hydraulic and thermal properties. Cover crops were Cereal rye (*Secale cereale* L.), Hairy vetch (*Vicia villosa*) and Austrian winter pea (*Pisum sativum* subsp. *arvense*). Three replicates each of undisturbed soil cores were collected at two soil depths (0–10 and 10–20 cm) from each treatment using plexiglass cores measuring 76.2 mm diameter by 76.2 mm long. Ten scan images from each core were acquired using an X-ray CT scanner with 0.19 by 0.19 mm pixel resolution with 0.5 mm slice thickness and analyzed with *Image-J*. Soil under CC, NCC, M, and SG on average had 21, 14, 17, and 12 macropores on a 2500 mm^2 area across all the depths. Soil under miscanthus had significantly greater macroporosity (0.049 $m^2\,m^{-2}$) and area for the largest pore (89.70 mm^2) than other treatments. The cover crop treatment had approximately 50%, 28%, and 75% greater number of macropores than NCC, M, and SG treatments. Bulk density (D_b) of soil was 13% lower in M than the NCC. Saturated hydraulic conductivity (K_{sat}) values were positively correlated with most CT-measured pore parameters. In contrast, D_b was negatively correlated with most CT-measured pore parameters (circularity and fractal dimension were positively correlated). While the circularity values were correlated positively with D_b and thermal conductivity (λ), the fractal dimension was correlated positively with volumetric heat capacity (C_v). The study illustrates that M and CC treatments can improve soil pore parameters.

1. Introduction

Fluid and gas transmission and storage depend on the geometry and size distribution of soil pores (Eynard et al., 2004). The soil pore network, especially the pore size distribution and connectivity of the pores, is believed to control soil hydraulic properties (Perret et al., 2000; Pierret et al., 2002; Vogel, 2000). Macropores allow rapid preferential (i.e. non-equilibrium) flow of water, dissolved solutes and particulate matter to subsurface and deeper soil horizons. However, excessive flow with contaminants potentially causes serious water quality issues (Jarvis, 2007).

Various soil and crop management practices can influence soil pore parameters. Examples of such management practices include cover crop usage and biofuel cultivation. Cover crops are defined as “crops grown primarily for the purpose of protecting and improving soil between periods of regular crop production” (Schnepf and Cox, 2006). Cover crops have long been valued for their soil conservation benefits, including reducing erosion, increasing infiltration, and improving soil health (Chatterjee, 2013; Kaspar et al., 2001; Kaspar and Singer, 2011; Schnepf and Cox, 2006). The introduction of cover crops within the crop rotation cycle is a widely used measure to improve soil quality and fertility. Most cover crops are grown in periods when the field is left bare to help prime the soil for the corresponding cash crops (Yunusa and Newton, 2003) by influencing soil physical and hydraulic properties.

Because of the necessity for alternative energy production,

Abbreviations: CC, cover crop; CT, computed tomography; M, miscanthus; NCC, no-cover crop; PB, perennial biofuel crops; SG, switchgrass

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perennial biofuel crops like miscanthus (*Miscanthus x giganteus*) and switchgrass (*Panicum virgatum*) are being grown for conversion to biofuel (Gressel, 2008). Due to their year-round surface cover, these perennial crops may protect soil from erosion, improve soil properties, water retention, soil productivity, and wildlife habitat and diversity (Blanco-Canqui et al., 2011). Roots and earthworm burrows under perennial biofuel crops can penetrate compacted soil layers and alter the pore structure, increasing water infiltration and storage at lower depths (Katsvairo et al., 2007). Thus, management practices greatly influence soil hydraulic properties and soil pore parameters and these parameters can be analyzed in the laboratory.

In order to examine the hydraulic properties of soil, non-invasive measurements of soil structure are required. Various properties of soil macropores and macropore networks have been estimated by X-ray CT imagery: porosity (Rachman et al., 2005; Udawatta et al., 2006, 2008a, 2008b; Udawatta and Anderson, 2008), solute movement (Anderson et al., 2003), pore continuity (Pierret et al., 2002), fractal dimension of porosity (Gantzer and Anderson, 2002), and plant root development (Tracy et al., 2010). In recent studies, Rachman et al. (2005), Udawatta et al. (2006, 2008a, 2008b) and Udawatta and Anderson (2008) used X-ray CT to delineate soils under row crop, no-till, and perennial buffers using macropore parameters. They observed strong correlations between macropores estimated using water retention and CT procedures. Macropore characteristics such as shape, size, orientation, and size distribution affect the rate, flow, and retention of water (Anderson, 2014; Udawatta et al., 2013).

There has been significant growth in the use of X-ray CT-measured pore parameters to quantify water flow in soil non-destructively (Mooney, 2002; Mooney et al., 2012). Mathematical modelling combined with CT has also been widely used to obtain properties of porous materials based on pore scale geometries (Blunt et al., 2013). Recently, Tracy et al. (2015) combined CT imaging and image based quantification with numerical modelling (Daly and Roose, 2014; Pavliotis and Stuart, 2008) to calculate the hydraulic conductivity of soil using direct measurements of soil pore structure under a range of different saturation conditions.

Despite the increased growth in the use of X-ray CT in quantifying soil pore parameters resulting from management practices such as tillage, such studies are limited on pore parameters generated by cover and perennial biofuel crops. The objective of the study was to compare differences in CT-measured pore properties (number of macropores, macroporosity, area of the largest pore, circularity and fractal dimension) as affected by cover crop and perennial biofuel crops and correlate these CT-measured pore parameters with soil hydraulic and thermal properties. This study will provide improved understanding of the influence of cover crops and perennial biofuel crops on fluid and gas transmission and storage within the soil.

2. Materials and methods

2.1. Experimental site

This study was carried out at the University of Missouri Bradford Research Center, which is located about 18 km east of Columbia. The soil was classified by the United States Department of Agriculture (USDA) as Mexico silt-loam (fine, smectitic, mesic Vertic Epiaqualfs) (Table 1). The study site was in a 50 yr corn (*Zea mays* L.)-soybean (*Glycine* max L.) rotation with moldboard plow prior to the establishment of this research. The experiment was laid out in a completely randomized design with three replications each of cover crops, at two levels (cover crop, CC; no-cover crop, NCC), and two levels of perennial biofuel crops (PB). The cover crop mixture consisted of Cereal rye (*Secale cereale* L.), Hairy vetch (*Vicia villosa*) and Austrian winter pea (*Pisum sativum* subsp. *arvense*). The main crop grown on the field was corn (*Zea mays* L.), planted in May and harvested in September of each growing season and the soil was under no tillage management. The perennial biofuel crops were miscanthus (M) (*Miscanthus x giganteus*) and switchgrass (SG) (*Panicum virgatum*), both referred to as perennial biofuel crops.

Table 1
Soil physical and chemical properties for the University of Missouri Bradford Research Center study site (Mexico silt loam).

Soil depth	Soil horizon	Sand	Silt	Clay	SOC
(cm)		(%)			(g kg^{-1})
0–10	Ap	5.4	75.9	18.7	17.2
10–20	Ap	4.8	77.2	18.0	12.2

SOC: soil organic carbon.

The cover crop plots were established in 2010 and they were seeded each year in September and October, allowed to grow throughout the winter months, and then terminated in late spring of the following year. The cover crop for this research study was over-seeded on September 8, 2014 and then drilled in on October 1, 2014 at the following rates; Cereal rye (50 kg ha^{-1}), Hairy vetch (17 kg ha^{-1}) and Austrian winter pea (34 kg ha^{-1}) using a Kinze® 38 cm row planter with special blades that allowed small seeded cover crop to be planted. The cover crop was allowed to grow during the winter months and terminated in June using glyphosate (*n*-[*phosphonomethyl*]*glycine*). The perennial biofuel crops were established in 2007. Miscanthus seedlings were hand planted (plugs) in a 0.9 × 0.9 m grid (1984 plants ha^{-1}). Switchgrass was planted using a Tye Drill in 19 cm spacing at 7 kg seeds ha^{-1}. The perennial biofuel crops were harvested with a silage chopper every year and the biomass was removed and used for biofuel production. All plots were rain-fed during this study.

2.2. Sampling and preparation

Soil samples were removed vertically from nontrafficked row areas using a sampler (Uhland, 1950) with Plexiglas cylinders measuring 76.2 mm diameter by 76.2 mm long in early June 2015. These samples were collected one week before the cover crop termination from each of the aforementioned treatments and replicates from two depths, 0–10 and 10–20 cm (4 treatments × 2 depths × 3 replicates = 24 cores). 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 in the field, labeled, and sealed in plastic bags and then transported to the laboratory. All soil samples were stored in a cold storage room at 4 °C until analysis was performed.

After the soil cores were removed from the cold storage, the plastic cap on the bottom was removed. The bottom end of the cores was covered with two layers of fine nylon mesh to secure soil within the cylinder and the top plastic cap was removed. The soil cores were slowly saturated from the bottom with distilled water using a Mariotte system. After 24 h saturation period, wet weights were recorded and samples were placed on a 3.5 kPa glass-bead tension table and left to drain for 24 h. This procedure removed water from macropores to enhance the image contrast between air-filled pores and soil solids. Samples were re-weighed and secured with two plastic end caps using masking tape, and then refrigerated prior to scanning. The samples were then taken out from refrigerator and weighed again and prepared (put into the wooden box container) for transport to the University of Missouri Veterinary Medicine Hospital for computed tomography (CT) measurement. A distilled water phantom (in an aluminum tube, outside and inside diam. 2.32 and 1.60 mm) and a solid copper wire phantom (outside diam. 0.55 mm) were attached to the long axis of the Plexiglas cylinder for a standard comparison of values through scans.

2.3. Scanning and image analysis

A Toshiba Aquilion 64 X-ray CT scanner set at a peak voltage of