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Biomass and buffer management practice effects on soil hydraulic properties compared to grain crops for claypan landscapes

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Abstract Biomass production systems as well as agroforestry and grass buffers have been found to improve soil hydraulic properties and water quality relative to row crop management for temperate regions. Objectives of this study were to assess the effects of biomass crops, agroforestry buffers, and grass buffers grown on claypan soils relative to a traditional corn (*Zea mays L.*)–soybean (*Glycine max L.*) rotation for hydraulic properties which included saturated hydraulic conductivity (*Ksat*), soil water retention, bulk density, and pore size distributions. Experiment was conducted in northeastern Missouri, USA. Buffers and biomass crops were established in 1997 and 2012, respectively. Grain crop production watersheds were established in 1991. Agroforestry buffers consisted of grasses and forbs with pin oak (*Quercus palustris Muenchh.*) trees. Redtop (*Agrostis gigantea* Roth), brome grass (*Bromus* spp.), and birdsfoot trefoil (*Lotus Corniculatus* L.) were planted in grass buffer areas. Biomass crops included switchgrass (*Panicum Virgatum* L.) and native grasses. Undistributed soil cores (7.6 cm diam. by 7.6 cm long) were taken by 10 cm depth increments with six replications from the surface to the 40 cm depth. Samples were measured and evaluated for bulk density, *Ksat*, water retention, and pore size distributions. Results illustrated that bulk density values were significantly lower ($P < 0.01$) for the buffer treatments and biomass crops compared to the row crop treatment averaged across depths. Significantly greater *Ksat* occurred for biomass crops and agroforestry buffers than row crops affected by soil depth, particularly at the soil surface 0–10 and 10–20 cm depths. Macropores (> 1000 μm effective diam.) and coarse mesopores (60–1000 μm effective diam.) were significantly higher for the biomass treatment than the other treatments for the first depth 0–10 cm. Although the claypan soil horizon dominates hydrology in northeastern Missouri, this study showed that biomass crops as well as agroforestry and grass buffer practices improve soil hydraulic properties relative to row crop management; they also have valuable economic and environmental benefits.

Keywords Pore size distributions · Saturated hydraulic conductivity · Water retention

Introduction

Soil and water losses are considered as major challenges in management of claypan soils which

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have a very low subsoil hydraulic conductivity; these properties subsequently affect agricultural productivity (Yost et al. 2016; Conway et al. 2017). Maintaining productivity at high levels to meet the increasing demand of food, fiber and fuel is a significant challenge in modern agriculture (Godfray et al. 2010; McLaughlin and Kinzelbach 2015). Therefore, using appropriate erosion management approaches are helpful for these production systems to protect soil from erosion (Akdemir et al. 2016). Appropriate cultural practices such as selection of conservation buffer practices are considered the best strategy to reduce surface runoff (Evans and Sadler 2008).

Conservation buffer systems represent a significant practice for conserving soil and water resources and deserve wider application; these approaches are utilized to improve agricultural production and protection of soil and water quality (Lowrance et al. 2002). These conservation buffers can be beneficial in soils which are susceptible to water runoff and soil erosion. Conservation buffers are any species of trees or grass grown in an area or are narrow strips of permanent vegetation widely prescribed to decrease nutrient losses and soil erosion as well as improve water quality, water infiltration, and landscape diversity (Jiang et al. 2007; Kumar et al. 2010a; Schmitt et al. 1999). Perennial vegetation management which includes biomass crops as well as agroforestry buffer and grass buffer practices provides diversified productivity and ecosystem services (Udawatta et al. 2002).

Agroforestry is a land management system which utilizes trees in the landscape as well as traditional plants simultaneously in the same area for environmental and economic benefits (Nair 1993). Agroforestry buffers have been shown to improve soil quality by enhancement of organic matter accumulation and soil microbial activity (Weerasekara et al. 2016). Agroforestry practices are often used to improve water quality and control erosion (Branca et al. 2013). Agroforestry systems can provide many positive environmental benefits such as climate change mitigation, production improvement, and sustainable use of soil and water resources (Mbow et al. 2014). Agroforestry and grass buffers are adopted as an alternative approach to enhance water movement within the soil profile and reduce surface runoff during rainfall events due to their deep root systems which can improve soil structure as compared to regular row crop management (Udawatta et al. 2005a). Agroforestry and grass buffer areas establish deep root systems which increase the proportion of macropores and enhance the soil hydraulic properties as compared to row crop systems which have lower root density among treatments (Rasse et al. 2000; Udawatta et al. 2006).

A different conversation practice, production of biomass crops, has been utilized to improve soil conservation. Biofuel production is a new technology which will be economically viable for converting plant fiber to ethanol. Switchgrass (*Panicum virgatum* L.) and native grasses are new crops that can be grown specifically for biofuel production (Tvedten et al. 2001). Switchgrass, a warm-season perennial grass native to North America, has potential as a biomass energy crop (Sanderson et al. 1999). Switchgrass is suited economically and ecologically for energy crop production, and it is an excellent biofuel because of its high fiber content, high biomass yield, drought resistance, easy establishment, and perennial growth habits (Roth et al. 2005; Sanderson et al. 1999; Turhollow 1994). The establishment of switchgrass creates more permanent soil pores which contribute to enhanced soil hydraulic properties and subsequently reduced surface runoff particularly in claypan landscapes (Zaibon et al. 2016).

The knowledge of soil–water movement in the field depends on the soil hydraulic properties (Ali et al. 2014). Soil hydraulic properties are excellent indicators of the environmental effects of soil and plant management practices as well as evaluating the effects of agroforestry buffers and biomass crops (Anderson et al. 1990; Seobi et al. 2005). Measurement of infiltration rates and surface runoff have been utilized to understand relationships between conservation buffers (agroforestry and grass practices) and production areas (Kumar et al. 2012).

A study conducted by Seobi et al. (2005) found that agroforestry and grass buffers enhance the capability of soil to store more water by 1.1 cm and 0.90 cm, respectively in the upper 30 cm as compared to row crops in claypan soils. Additionally, they stated that the value of Ksat in agroforestry buffers was higher than under grass buffers or row crops. Agroforestry and grass buffers were found to reduce bulk density 2.3% as compared to row crop treatments. Many researchers have studied the effects of buffers on soil pore parameters (Udawatta et al. 2006, 2008;

Udawatta and Anderson 2008). They have found that agroforestry and grass buffers enhance soil pore characteristics (macroporosity and mesoporosity) which enhance water infiltration and reduce surface runoff.

A better understanding of how soil hydraulic properties are affected by management practices may improve agricultural sustainability. Few studies have been performed to assess the effects of biofuel crops and vegetative buffers on soil hydraulic properties and surface runoff; however, biofuel vegetation and conservation buffers can contribute to solving many challenges such as food and energy security, climate change, and environmental degradation caused by current agricultural practices. The objective of this study was to evaluate the effects of biomass crops as well as agroforestry and grass buffers on soil hydraulic properties relative to a traditional corn/soybean rotation for claypan soils.

Materials and methods

Experimental site

The experimental site for this study was located at the University of Missouri Greenley Memorial Research Center in Knox County near Novelty, Missouri, USA (40°01′N, 9211′W). Three adjacent north-facing watersheds were developed in 1991 (Fig. 1). Details on the soils, management practice, and climate have been described by Udawatta et al. (2002) and (2004). Agroforestry buffers, grass buffers, and grain crop treatments were randomly assigned to the watersheds in 1997. The 3.16 ha grass buffer area (contour strip, West watershed) and 4.44 ha agroforestry buffer area (Central watershed) consisted of 4.5 m wide buffer strips at 36.5 m spacing (22.8 m at lower slope positions). The control area (corn-soybean rotation, East watershed) was 1.65 ha. The areas between buffers on the grass buffer and agroforestry buffer watersheds were planted to a corn-soybean rotation with no-till practice beginning in 1991; these areas were transferred to biomass crops in 2012 in two of the watersheds (West and Central watersheds).

The production of corn and soybeans ranged between 5.20–10.70 and 1.68–3.70 Mg ha^{-1}, respectively from 1992 to 2000 (Seobi et al. 2005). In the grass and agroforestry buffer watersheds, birdsfoot trefoil (*Lotus corniculatus* L.), brome grass (*Bromus* spp.), and redtop (*Agrostis gigantea* Roth) were planted with Pin oak trees (*Quercus palustris* Muenchh), swamp white oak trees (*Quercus bicolar* Willd.) and bur oak trees (*Quercus macrocarpa* Michx.) planted 3 m apart down the center of the grass–legume stripes of the agroforestry watershed in 1997. For biomass crops, a mix of switchgrass (*Panicum virgatum* L.) and winter peas (*Pisum Sativum* Subsp) were planted between buffers in 2012.

The soils in this study area were mapped as Putnam silt loam (fine, smectitic, mesic Vertic Albaqualfs) and Kilwinning silt loam (fine, smectitic, mesic Vertic Epiaqualfs). The parent material for the soils of the watersheds was glacial till and loess materials. Both soils, Putnam and Kilwinning, have a drainage restrictive B horizon with a claypan at a variable depth (4–37 cm) (Udawatta et al. 2002). These researchers also stated that the restrictive claypan produces surface runoff during the spring and early summer. The experimental site (soil sample collection) for this study was conducted only on the Putnam silt loam soil.

The 30-year average annual precipitation of the experimental site is 920 mm, of which more than 66% falls from April through September. In addition, the average annual air temperature is about 11.7 °C with a mean monthly high of 31.4 °C in July and with a mean monthly low of − 6.6 °C in February. The average snowfall is approximately 590 mm per year (Owenby and Ezell 1992). Clay content, silt content, cation exchange capacity, organic C, and water pH data for the upper soil horizons of the agroforestry watershed are shown in Table 1.

Sampling procedures

The study design consisted of four different management practices: agroforestry buffers, grass buffers, biomass crops, and corn/soybean rotation. Soil cores (7.6 cm diam. by 7.6 cm long) were taken from four soil depths 0–10, 10–20, 20–30 and 30–40 cm with six replicates in early summer to measure *Ksat*, soil water retention, dry bulk density, and pore size distribution. Soil samples were sampled from the second and the third contour buffer strips for the agroforestry and grass buffers with three replicates from each buffer (Fig. 1). For biomass crop treatment, six replicate locations were chosen with three between the second

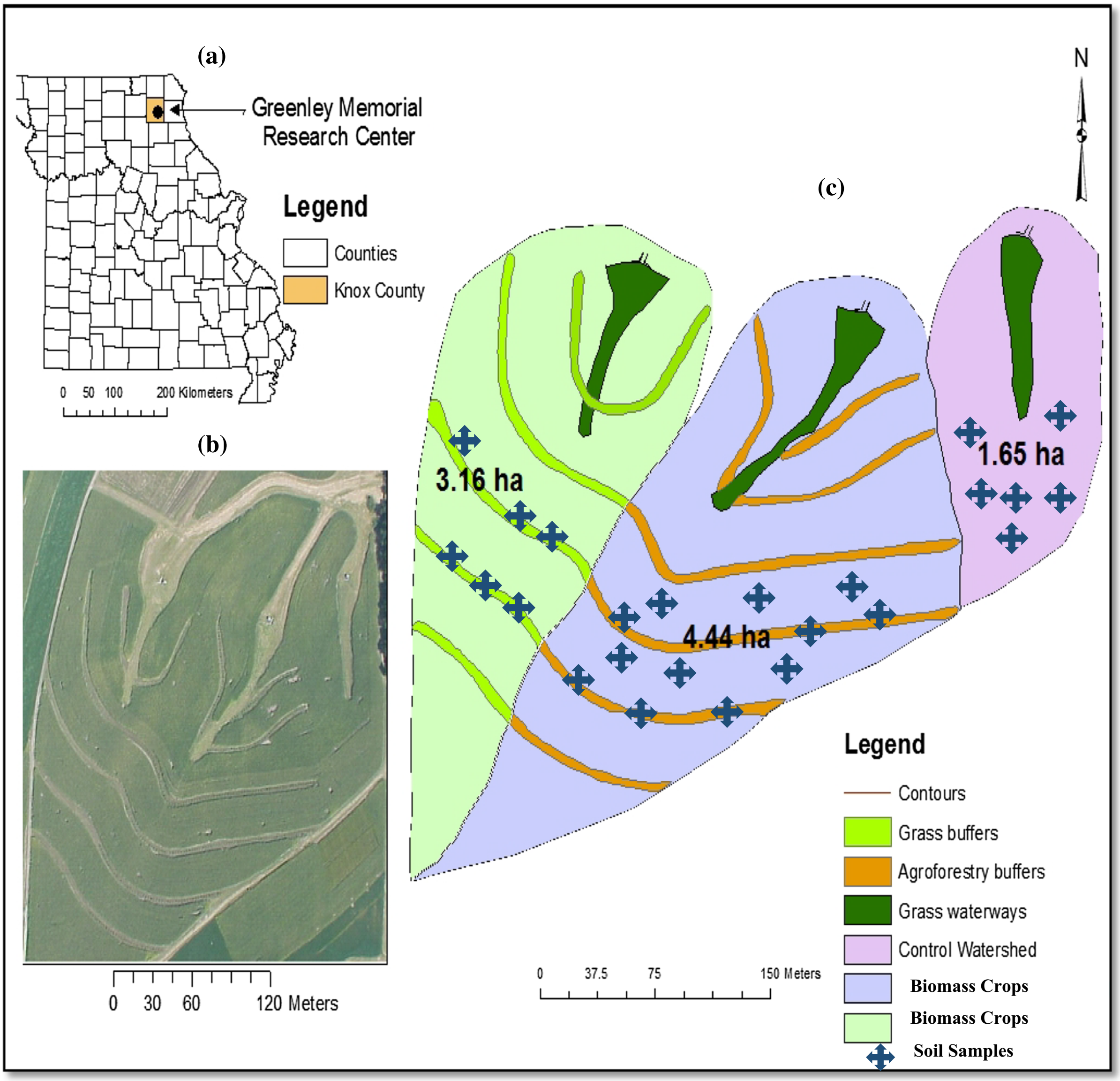

Fig. 1 **a** Location of the study site in Missouri, USA, **b** Aerial view, and **c** land management maps for the grass buffers (West watershed), agroforestry buffers (Central watershed) and control (corn–soybean rotation, East watershed) watersheds. All three watersheds have grass waterways at the downslope end of each watershed. Areas between the grass and agroforestry buffers are managed with biomass crops since 2012. Crosses represent the soil sample locations with samples taken from treatments with four soil depths

and third buffer and three between the third and fourth buffer in the agroforestry buffer area (Fig. 1). The row crop area was selected in the control watershed with six replicates. Soil samples were labeled, trimmed, sealed with two plastic covers on the top and bottom of the soil cores, transported to the laboratory and stored in a refrigerator at 4 °C until measurements were conducted.

Laboratory analyses

The bottom of the cores was covered with cheesecloth, and the samples were put in a plastic tray and gradually saturated by wetting with tap water (electrical conductivity = 0.68 dS m^{-1}, Na absorption ratio = 2.34) from the bottom for at least 24 h. A syringe was used to apply bentonite slurry, mixed at an

Table 1 Soil physical and chemical properties for the study site (Putnam silt loam, 1–2% slope) determined in the agroforestry watershed by horizon (Seobi et al. 2005)

Soil horizon	Soil depth (cm)	Clay (g kg^{-1})	Silt (g kg^{-1})	CEC[b] ($Cmol_C$ kg^{-1})	Organic C (gkg^{-1})	pH_w^c
Ap	0–7 (2.9)[a]	219 (9)	729 (18)	19.4 (2.3)	21 (5)	6.8 (0.2)
AE	7–22 (5.1)	227 (23)	721 (23)	18.9 (1.3)	13 (2)	7.0 (0.2)
E	22–38 (2.8)	287 (31)	643 (31)	20.5 (2.3)	9 (1)	6.1 (0.6)
Bt1	38–57 (5.1)	531 (30)	439 (30)	38.4 (1.7)	9 (1)	5.2 (0.1)

[a] Number in parenthesis is the standard deviation of the mean of 6 observations

[b] *CEC* cation exchange capacity

[c] pH_w pH of water

8:1 ratio of bentonite to water, around the edge of the surface of the soil cores to seal gaps between the soil cores and aluminum rings (Blanco et al. 2002). The purpose of sealing was to remove boundary flow along the core edge. The *Ksat* measurements were conducted using the constant-head method given by Reynolds and Elrick (2002a) if the *Ksat* was > 1 mm h^{-1} or the falling head method which was used if the *Ksat* was < 1 mm h^{-1} as described by Reynold and Elrick (2002b).

After *Ksat* measurements, the soil cores were resaturated before soil water retention measurements were performed. Soil water retention was measured at different pressures, (i) with ceramic plates for higher pressures 0.0, − 0.4, − 1.0, − 2.5, − 5.0, − 10.0, and − 20.0 kPa using the soil cores (subsequently cores were air-dried at 35 °C until constant weight after − 20 kPa with a sub-sample oven-dried at 105 °C to measure gravimetric water content), (ii) with pressure chambers at − 33.0 and − 100 kPa pressures using aggregates from the air-dried cores, and (iii) with pressure chambers at − 1500 kPa using less than 2 mm screened soil material (Dane and Hopmans 2002). The air-dried soil water content value was utilized in determination of soil bulk density for the core method given by Grossman and Reinsch (2002). Mass of oven dry soil and total soil core volume were used to estimate soil bulk density.

Pore size distributions were estimated using the capillary rise equation to determine effective pore size classes from soil water retention measurements (Radcliffe and Šimůnek 2010). Soil pore sizes were divided into four classes: macropores (> 1000 μm effective diam.), coarse mesopores (60 to 1000 μm effective diam.), fine mesopores (10 to 60 μm effective diam.), and micropores (< 10 μm effective diam.) (Luxmoore 1981; Anderson et al. 1990; Rachman et al. 2004). Soil total porosity was calculated by use of the saturated core water content at 0 kPa soil water pressure. The macroporosity, coarse mesoporosity, and fine mesoporosity were calculated by subtracting the water content at −0.4 kPa from the water content at saturation (0 kPa), the water content at −5 kPa from the water content at −0.4 kPa, and the water content at −33 kPa from the water content at −5 kPa respectively, while the microporosity was equal to the water content at −33 kPa.

Statistical analysis

The General Linear Model (GLM) procedure in SAS was conducted to test statistical significances of measured soil hydraulic properties among the treatments, soil depths, and treatment by depth interactions (SAS Institute 2013). Least significant differences (Duncan's LSD) were used to assess significant differences among the treatments at the 95% probability level at each soil depth 0–10, 10–20, 20–30, and 30–40 cm. Contrasts among treatments were determined to find significant differences among management practices. These were divided into 'buffers vs. biomass', 'grass buffers vs. agroforestry buffers', and 'row crop vs. others'.

Results and discussion

Bulk density

Significant differences ($P < 0.05$) were found for vegetative management practices, sampling depth, and the interactions between treatment and soil depth on soil bulk density (Table 2). Our results showed that bulk density was significantly lower for two contrasts ‘row crop vs other treatments’ and ‘buffers vs biomass crop’. Biomass crop treatment had the lowest bulk density (1.28 Mg m^{-3}) compared to other treatments averaged across depths while the row crop treatment had the highest value (1.37 Mg m^{-3}) (Fig. 2). Similar trends for bulk density were found by Zaibon et al. (2016) and Seobi et al. (2005). Bulk density was significantly different for the first and last sampling depths (Fig. 2) with the lowest bulk density (1.22 Mg m^{-3}) at 0–10 cm depth and the highest value (1.40 Mg m^{-3}) at 10–20 cm soil depth. Typically, bulk density for the fourth depth was lower than the second and third depths due to an increase in concentration of smectitic clays as well as their associated swelling in these subsoil horizons (Table 1).

At the first depth (0–10 cm), the lowest value of bulk density was found in the biomass crop treatment (1.04 Mg m^{-3}) compared with the buffer and row crop treatments (Table 2). For the second depth, bulk density values were higher for the row crop and grass buffer treatments than the biomass crops and agroforestry buffers. There were no significant differences between grass buffers and row crop treatments for the third depth, and bulk density for the agroforestry buffers was lower at this depth compared with biomass crops. For the 30–40 cm sampling depth, no significant differences occurred among the agroforestry buffers, biomass crop, and row crop treatments while bulk density was lower for the grass buffers compared with other treatments. Our results demonstrate that there were significant interactions between treatments and soil depth ($P < 0.05$). These differences can be attributed to the greater increase in soil bulk density versus soil depth for the three vegetative management practice treatments relative to the row crop treatment.

Previous literatures have shown that perennial vegetation management helps to decrease soil bulk density compared with row crop management practically at the soil surface (Rachman et al. 2004; Seobi et al. 2005; Kumar et al. 2008; Mudgal et al. 2010; Zaibon et al. 2016). These researchers reported vegetation management practices with perennial root systems (agroforestry and grass buffers as well as biomass crop) had lower bulk density than annual root systems (row crop management). Generally, lower soil bulk density values which have occurred under buffer systems and biomass crops (switchgrass) can possibly be attributed to higher root density and greater root decay in the soil surface (0–10 cm). These roots improve soil structure by creating deep root systems which increase the proportion of macropores and add organic matter and subsequently reduce runoff particularly in claypan landscapes. Also, researchers have reported that after the first depth, the influence of root systems begin to decrease, and bulk density also increases.

Saturated hydraulic conductivity (*Ksat*)

There were significant differences in Ksat as a function of vegetative management practices and soil depths (Table 2). No significant differences occurred for treatment by depth interactions. Statistical results showed that significantly higher Ksat values were for two contrasts: ‘row crop vs others’ and ‘agroforestry and grass buffers vs biomass crops’. The mean Ksat value (averaged across sampling depth) for biomass crops (37.1 mm h^{-1}) was 28, 64, and 70% higher than for the agroforestry buffers, grass buffers, and row crops, respectively (Table 2).

Ksat values were significantly different with higher Ksat values at the first and second depths (33.4 and 33.5 mm h^{-1}) respectively and lower Ksat values in the third and fourth depths. The results of this study have shown that the Ksat values were significantly decreased with increasing soil depths. Similar trends were found by Seobi et al. (2005). They reported that the Ksat value at 0–10 cm was 97.2 mm h^{-1} higher than at the 30–40 cm. These changes were due to the role of management practices in improving soil structure, particularly in the soil surface.

Ksat values showed significant differences between the biomass crop treatment and other treatments (agroforestry buffers, grass buffers, and row crops) for the first and second soil depths (0–10 and 10–20 cm) while no significant differences occurred in the third and fourth soil depths (20–30 and 30–40 cm, Fig. 3). The values of *Ksat* for the biomass

Table 2 Arithmetic means of bulk density and arithmetic means of saturated hydraulic conductivity (*Ksat*) with bentonite around core edges as influenced by agroforestry buffers (AgB), biomass crop (BC), grass buffers (GB), and row crop (RC) treatments and soil depths

	Means[1]	
	Bulk density (Mg m^{-3})	*Ksat* (mm h^{-1})
Vegetative management (M)		
0–10 cm depth		
Agroforestry buffer	1.28fg	40.4ab
Biomass crop	1.04i	65.3a
Grass buffer	1.21h	14.8bc
Row crop	1.36cde	13.3bc
10–20 cm depth		
Agroforestry buffer	1.37bcd	24.1bc
Biomass crop	1.34def	67.7a
Grass buffer	1.43ab	18.3bc
Row crop	1.46a	23.9bc
20–30 cm depth		
Agroforestry buffer	1.37bcde	14.5bc
Biomass crop	1.41abc	9.1bc
Grass buffer	1.38bcd	9.28bc
Row crop	1.38bcd	5.65bc
30–40 cm depth		
Agroforestry buffer	1.29fg	27.1bc
Biomass crop	1.30feg	6.28bc
Grass buffer	1.26gh	11.3bc
Row crop	1.29fg	0.83c
Vegetative management		
Agroforestry buffer	1.33b	26.5ab
Biomass crop	1.28a	37.1a
Grass buffer	1.32b	13.4b
Row crop	1.37c	10.9b
Sampling depth (D), cm		
0–10	1.22a	33.4a
10–20	1.40c	33.5a
20–30	1.39c	9.6b
30–40	1.29b	11.4b
Source of variation		
ANOVA $P > F$		
Vegetative management	< 0.01	0.02
Sampling depth	< 0.01	< 0.01
M × D	< 0.01	0.18
RC versus others	< 0.01	0.09
Buffers versus Biomass	< 0.01	0.06
GB versus AgB	0.61	0.21

[1] Means with different letters for a soil property are significantly different at the 0.05 probability level

crops were 39, 77, and 79% higher than for the agroforestry buffers, grass buffers, and row crops respectively in the first depth. In the second depth, values were 64, 74, and 64% higher than for the agroforestry buffers, grass buffers, and row crops respectively. The greatest *Ksat* value was at the 0–10 cm under the biomass treatment which was consistent with a lower soil bulk density, this could

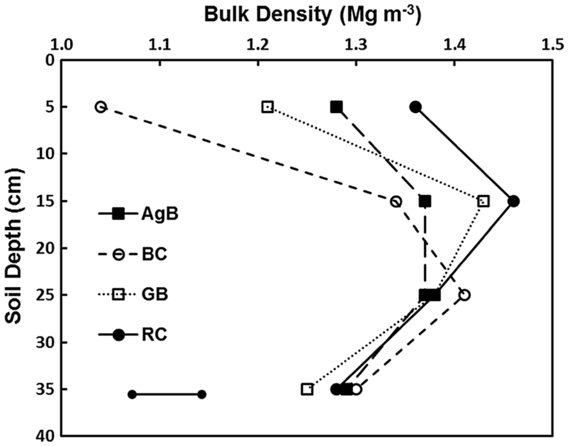

Fig. 2 Effects of treatments and soil depth on soil bulk density. AgB = agroforestry buffers, BC = biomass crops, GB = grass buffers, and RC = row crop. Bar is the least significant difference (0.05) for bulk density

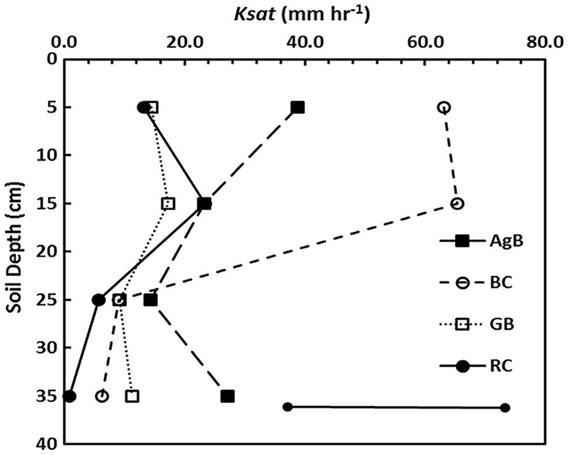

Fig. 3 Effects of treatments and soil depth on saturated hydraulic conductivity (*Ksat*). AgB = agroforestry buffers, BC = biomass crops, GB = grass buffers, and RC = row crop. Bar is the least significant difference (0.05) for *Ksat*

probably be attributed to more perennial roots which have formed many macropores in the soil profile. Generally, the *Ksat* values in the third and fourth depths were lower relative to the first and second depths due to the higher content of smectitic clay in these deeper depths for all treatments except for the agroforestry buffer where the Ksat for fourth depth was slightly higher than the second depth.

Many researchers have studied the effects of different management practices on Ksat (Fuentes et al. 2004; Rachman et al. 2004; Seobi et al. 2005; Kumar et al. 2008; Mudgal et al. 2010; Zaibon et al. 2016). They found that Ksat values were higher in the management practices such as agroforestry and grass buffer as well as biomass crops than row crop management. These differences were probably due to long-term management which may lead to improving the proportion of macropores which help water move easily through the soil. These findings support our observations in the current study.

Generally, Ksat is a key property for controlling water movement in the soil layers and can affect solute transport through soil as well as influence patterns of infiltration and surface runoff (Wang et al. 2013; Becker et al. 2018). Ksat depends on the pore size distribution and continuity of pores especially the role of macropores which are created by roots of perennial plants that are effective in forming channels which subsequently allow water movement. Rachman et al. (2004) reported that greater macroporosity was probably responsible for higher *Ksat* values for their buffer treatment relative to a row crop treatment. A study conducted by Seobi et al. (2005) for claypan soils in northeastern Missouri found 14 times higher *Ksat* for agroforestry buffers when compared to row crop management and also 3 times higher *Ksat* than grass buffer management. They have attributed these changes to lower bulk density values and an increasing proportion of macroporosity and coarse mesoporosity. They also found that in claypan soils, agroforestry and grass buffers have enhanced the capability of soil to store more water by 1.1 and 0.9 cm, respectively in the upper 30 cm as compared to row crops. Therefore, most of the differences among treatments for this study occurred within 6 years of establishment.

A study conducted by Kumar et al. (2008) found that significant differences in *Ksat* values among conservation buffers (agroforestry buffers, grass buffers, rotational grazed areas, and continuously grazed areas). They showed that agroforestry buffers and grass buffers had higher *Ksat* values (61.3 and 57.0 mm h^{-1}) respectively compared to continuously and rotationally grazed pastures (3.1 and 4.0 mm h^{-1}), respectively. Zaibon et al. (2016) compared the hydraulic properties under switchgrass and corn–soybean management for a Mexico silt loam soil (Vertic Epiaqualfs) at the University of Missouri South Farm. They discovered that the *Ksat* value under switchgrass (122.6 mm h^{-1}) was 74% higher than for row-crop management (32.5 mm h^{-1}). However, biomass areas as well as agroforestry and grass buffers establish deep root systems which increase the proportion of macropores and enhance the soil hydraulic properties as compared to row crop systems which have lower root density among treatments (Rasse et al. 2000; Udawatta et al. 2006; Zaibon et al. 2016).

Soil water retention

Soil water retention as a function of soil water pressure was significantly different ($P < 0.05$) among treatments for all pressures averaged across soil depth except for two pressures, − 1 and − 2.5 kPa as shown in Table 3. Analysis of variance for soil water retention as a function of soil water pressure showed that there were significant differences ($P < 0.05$) among sampling depths for all pressures (Table 3). These results also illustrated that there were significant differences occurring for the treatment by depth interactions for all soil water pressures except at − 2.5 kPa (Table 3). The 'grass buffers vs. agroforestry buffers' contrast was significant at the − 5, − 10, − 20, − 33, and − 100 kPa while 'Buffers vs Biomass' was not significant at any pressure except at 0.0 kPa. The 'row crop vs. others' contrast was also significant at three pressures, 0.0, − 0.4, and − 1500 kPa.

Volumetric water content at saturation and − 20 kPa were significant for biomass crops compared to other treatments. At − 5 and − 20 kPa, water content values were greater for biomass crops and grass buffers. No significant differences occurred among treatments at − 1 and − 2.5 kPa. The row crop treatment was significantly higher at permanent wilting point (− 1500 kPa) compared to other management practices. However, buffers and biomass crop treatments had higher soil water content at higher soil water pressures > − 2.5 kPa. These findings were probably due to higher root density of the perennial root system which enhances soil structure.

Soil water content as a function of water pressure was greater for the first sampling depths at 0.0, and − 0.4, and − 1.0 kPa (Fig. 4a) with decreasing water content for the next two depths (10–20 and 20–30 cm, Fig. 4b, c). However, there were no significant differences in water content for the second and third soil depths for all pressures. The volumetric water content was greater for the fourth sampling depth from − 2.5 to − 1500 kPa pressures compared with other soil depths as shown in (Fig. 4d). This was probably because bulk density for the fourth depth was lower than the second and third depths due to an increase in concentration of clay content through these subsoil horizons (Table 1). These soil water retention results are similar to those found by Seobi et al. (2005) and Zaibon et al. (2016).

Differences among treatments for specific sampling depths are shown in Fig. 4a–d. These can be attributed to changes in clay content throughout the soil profile (Table 1). Soil water content values for the first sampling depth were higher in the buffer and biomass treatments than row crop management at 0.0, − 0.4, and − 1 kPa as illustrated in Fig. 4a. Results of soil water content for the grass buffers were higher compared with row crops from − 2.5 to − 100 kPa. For the second soil depth, buffers as well as biomass crop treatments were higher than the row crop treatment for pressures > − 5.0 kPa, and the biomass treatment had the highest water content among other treatments for <− 2.5 kPa at this depth. These results were possibly due to greater root development which occurred under buffers and biomass crops that created greater macroporosity and added higher amounts of organic matter, particularly in the soil surface.

For the 30–40 cm sampling depth, the volumetric water content was greater for row crop management from − 2.5 to − 1500 kPa pressures compared with the buffers and biomass treatments as presented in Fig. 4d. The reason was probably due to the row crop treatment having lower water content at several pressures at the shallow depth due to its greater soil bulk density compared with the agroforestry and grass buffers as well as biomass crops. On the other hand, row crop management had higher volumetric water content at several pressures at the fourth depth due to having higher clay content. Also, the greater clay content in the 30–40 cm soil depth was due to more soil erosion having occurred to a greater extent in the row crop treatment and greater clay content occurring at the deepest sampling depth (closer to the soil surface) with continuous cultivation relative to the buffers and biomass crop treatments.

Studies conducted by Rachman et al. (2004), Seobi et al. (2005), Kumar et al. (2008), Mudgal et al. (2010), Chandrasoma et al. (2016) and Zaibon et al. (2016) stated that soil water retention was affected by management practices at shallow soil depths but

Table 3 Mean water retention values as a function of soil water pressure (0.0 to − 1500 kPa) as affected by agroforestry buffers (AgB), biomass crop (BC), grass buffers (GB), and row crop (RC) treatments and soil depths

	Soil water pressure (kPa)									
	0.0 θ m^3 m^{-3}	− 0.4	− 1.0	− 2.5	− 5.0	− 10.0	− 20.0	− 33.0	− 100	− 1500
Vegetative management mean (M)[a]										
Agroforestry buffer	0.499ab	0.472a	0.439a	0.408a	0.373b	0.358b	0.341b	0.303b	0.249b	0.174b
Biomass crop	0.520a	0.484a	0.452a	0.423a	0.397a	0.383a	0.365a	0.321ab	0.287a	0.192ab
Grass buffer	0.503ab	0.469ab	0.453a	0.417a	0.405a	0.379ab	0.362a	0.340a	0.301a	0.177b
Row crop	0.483b	0.455b	0.433a	0.406a	0.393ab	0.374ab	0.353ab	0.310b	0.278a	0.2158a
Sampling depth mean (D) cm[a]										
0–10	0.538a	0.501a	0.466a	0.429b	0.405b	0.382b	0.355b	0.308b	0.248c	0.158c
10–20	0.471c	0.434c	0.413b	0.388c	0.368c	0.353c	0.339c	0.299b	0.263bc	0.159c
20–30	0.477c	0.457b	0.428b	0.388c	0.368c	0.349c	0.333c	0.307b	0.273b	0.189b
30–40	0.517b	0.487a	0.471a	0.449a	0.425a	0.410a	0.395a	0.361a	0.330a	0.252a
ANOVA P > F										
Source of variation										
Vegetative management	< 0.010	< 0.010	0.025	0.199	< 0.010	0.024	0.013	< 0.010	< 0.010	< 0.010
Sampling depth	< 0.010	< 0.010	< 0.010	< 0.010	< 0.010	< 0.010	< 0.010	< 0.010	< 0.010	< 0.010
M × D	< 0.010	< 0.010	< 0.010	0.098	0.018	0.016	< 0.010	< 0.010	< 0.010	0.032
RC versus others	< 0.010	< 0.010	0.079	0.285	0.898	0.949	0.684	0.244	0.908	0.021
Buffers versus biomass	0.033	0.056	0.434	0.243	0.409	0.119	0.093	0.960	0.277	0.269
GB versus AgB	0.697	0.739	0.165	0.390	< 0.010	0.050	0.025	< 0.010	< 0.010	0.863

[a] Means with different letters for a soil property are significantly different at the 0.05 probability level

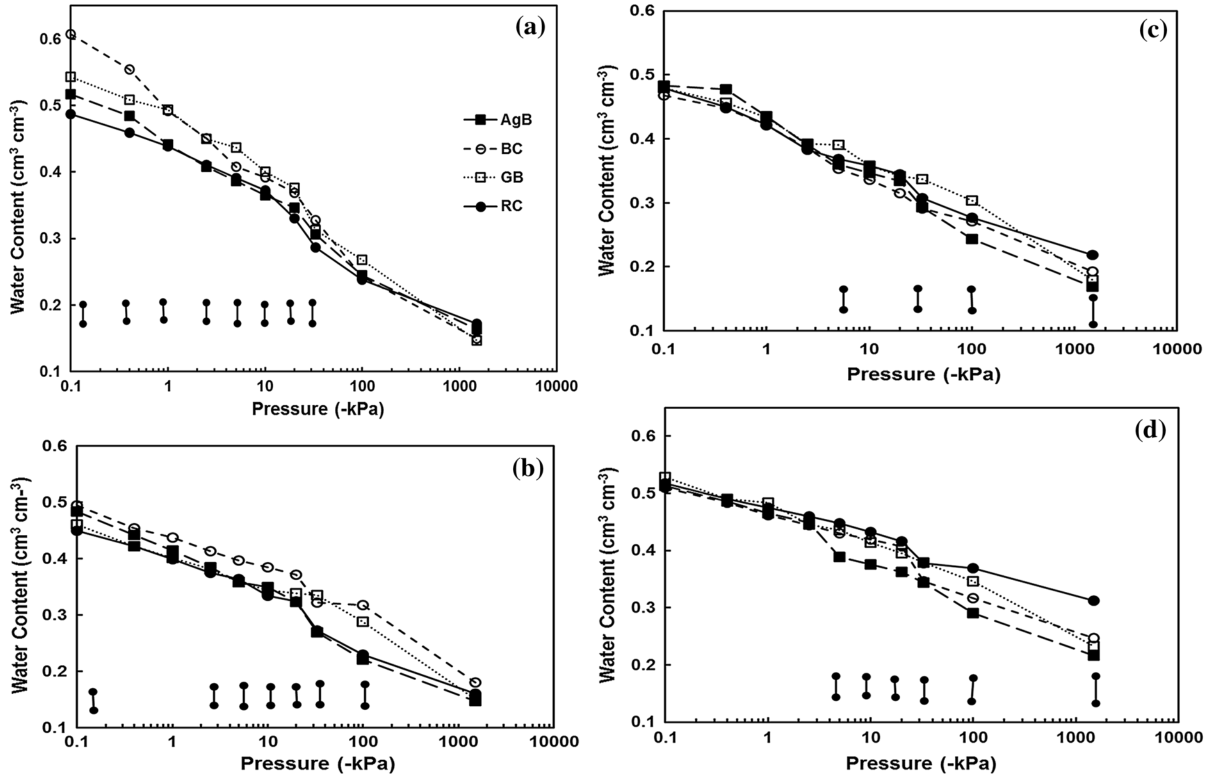

Fig. 4 Effects of buffer treatments on soil water retention at depths of **a** 0–10 cm, **b** 10–20 cm, **c** 20–30 cm, and **d** 30–40 cm. AgB = agroforestry buffers, BC = biomass crops, GB = grass buffers, and RC = row crop. Bars indicate the least significant difference (0.05) for soil water retention

changes also occur in subsoil horizons due to an increase in smectitic clays as well as their associated swelling in these subsoil horizons. Mudgal et al. (2010) reported that the variations in water content were associated with variations in clay content and depth to the argillic horizon. Seobi et al. (2005) and Akdemir et al. (2016) found that soil water content was higher in agroforestry and grass buffers than row crop management. They reported that buffers may have more root development with subsequent greater porosity relative to row crop management. Additionally, a study conducted by Zaibon et al. (2016) found that soil water content for a switchgrass treatment was higher than row crop management at all water pressures except at − 100 and − 1500 kPa; these findings indicate that management practices can improve soil water retention.

Udawatta et al. (2002, 2004, 2015, Zhang et al. (2010), Bonin et al. (2012), Jacobs et al. (2015), Weerasekara et al. (2016), and Zaibon et al. (2016) have stated that conservation buffers such as agroforestry and grass buffers as well as biomass crops can be adopted as an alternative management approach and potentially used to improve soil water retention, increase soil carbon, control soil erosion, decrease surface runoff, and reduce nonpoint source pollution during rainfall events. This is due to their root systems which can improve soil structure as compared to regular row crop management. However, the changes that occur in soil water retention results as affected by vegetative management can reduce surface runoff by increasing water storage in the soil profile.

Pore size distribution

Significant differences ($P < 0.05$) in pore size distribution were found for sampling depth and the interactions between treatment and soil depth (Table 4 and Fig. 5). There were no significant management practice effects on macropores and fine mesopores, but there were significant differences for coarse mesopores and micropores. Pore size distributions were not

Table 4 Arithmetic means of macropores (> 1000 mm), coarse mesopores (60–1000 mm), fine mesopores (10–60 mm), and micropores (< 10 mm) as influenced by agroforestry buffers (AgB), biomass crop (BC), grass buffers (GB), and row crop (RC) treatments and soil depths

Vegetative Management (M)	Macropores (> 1000 µm) θ m^{3} m^{-3}	Coarse mesopores (60–1000 µm)	Fine mesopores (10–60 µm)	Micropores (< 10 µm)
0–10 cm depth				
Agroforestry buffer	0.032bc	0.097bc	0.080bcd	0.306def
Biomass crop	0.053a	0.145a	0.080bcd	0.327cd
Grass buffer	0.034abc	0.072cdef	0.123a	0.313cdef
Row crop	0.027bc	0.067defg	0.104ab	0.286fg
10–20 cm depth				
Agroforestry buffer	0.041ab	0.083cd	0.088bc	0.269g
Biomass crop	0.041ab	0.0566efg	0.074bcde	0.321cde
Grass buffer	0.038abc	0.064defg	0.022f	0.334cd
Row crop	0.027bc	0.058defg	0.091bc	0.271g
20–30 cm depth				
Agroforestry buffer	0.005d	0.117b	0.067cde	0.292efg
Biomass crop	0.020cd	0.094bc	0.061cde	0.290efg
Grass buffer	0.022bcd	0.066defg	0.053def	0.336cd
Row crop	0.028bc	0.080cde	0.061cde	0.307def
30–40 cm depth				
Agroforestry buffer	0.027bc	0.096bc	0.044ef	0.344bc
Biomass crop	0.025bc	0.053fg	0.084bcd	0.345bc
Grass buffer	0.037abc	0.054efg	0.056de	0.378a
Row crop	0.026bc	0.042g	0.070cde	0.377ab
Vegetative management mean[a]				
Agroforestry buffer	0.027a	0.099a	0.070a	0.303b
Biomass crop	0.035a	0.088a	0.075a	0.321ab
Grass buffer	0.033a	0.064b	0.064a	0.341a
Row crop	0.027a	0.063b	0.082a	0.311b
Sampling depth mean (D) cm[a]				
0–10	0.037a	0.096a	0.097a	0.308b
10–20	0.037a	0.066b	0.069a	0.299b
20–30	0.019b	0.089a	0.061a	0.307b
30–40	0.029ab	0.062b	0.064a	0.362a
ANOVA P > F				
Source of variation				
Vegetative management	0.776	< 0.010	0.129	< 0.010
Sampling depth	< 0.010	< 0.010	< 0.010	< 0.010
M × D	0.128	< 0.010	< 0.010	< 0.010
RC versus others	0.233	< 0.010	0.245	0.244
Buffers versus biomass	0.184	0.415	0.454	0.961
GB versus AgB	0.147	< 0.010	0.636	< 0.010

[a] Means with different letters for a soil property are significantly different at the 0.05 probability level

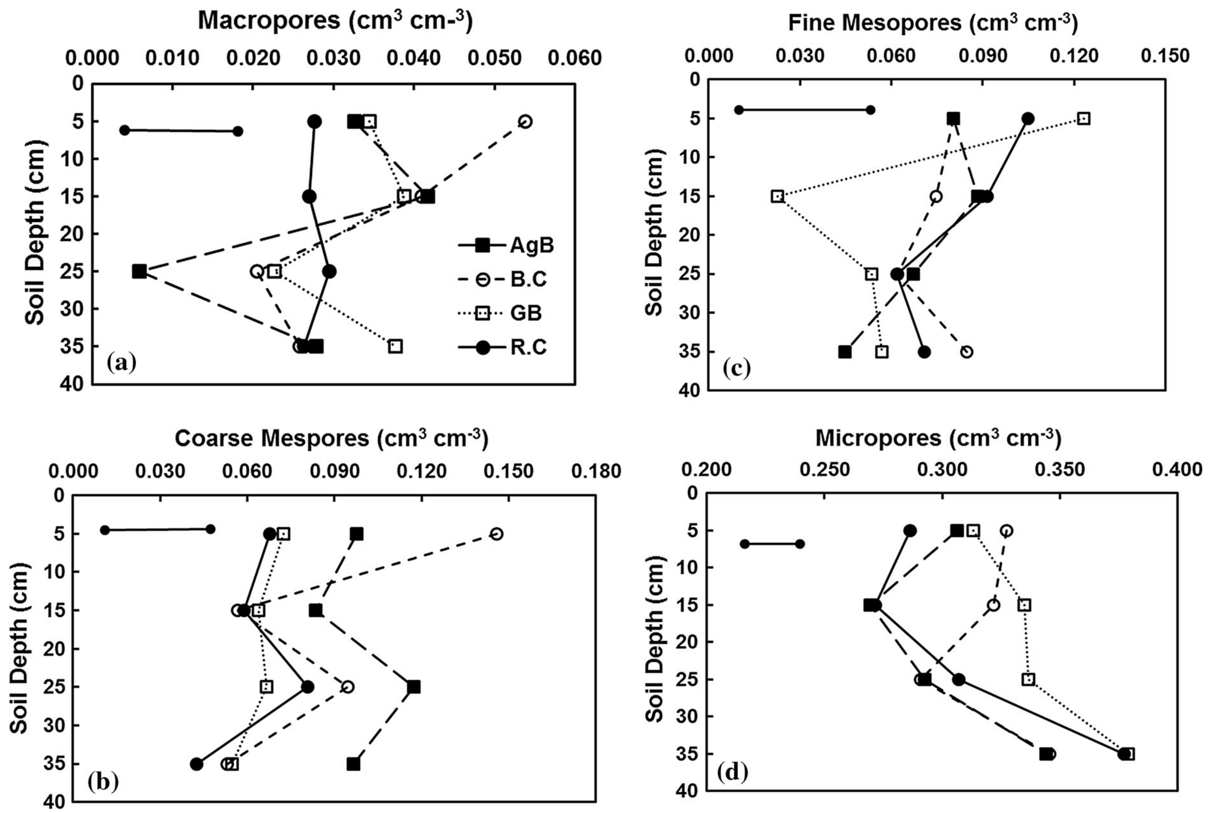

Fig. 5 Effects of buffer treatments and soil depth on pore-size classes of **a** macropores (> 1000 μm diam.), **b** coarse mesopores (60–1000 μm diam.), **c** fine mesopores (10–60 μm diam.), and **d** micropores (< 10 μm diam.). AgB = agroforestry buffers, BC = biomass crops, GB = grass buffers, and RC = row crop. Bars indicate the least significant difference (0.05) for pore size distributions

significantly affected by contrasts: ‘row crop vs others’ and ‘buffers vs biomass’ except for coarse mesopores at ‘row crop vs others’. Coarse mesopores and micropores values were only significant at ‘grass buffers vs agroforestry buffers’. This can be attributed to a higher amount of root development for the agroforestry and grass buffers relative to the row crop management.

Agroforestry buffers and biomass crop treatments had significantly higher coarse mesopore values than other treatments, with the highest values (0.099 and 0.088 $m^3 m^{-3}$) at agroforestry and biomass treatments respectively while the lowest values were (0.064 and 0.063 $m^3 m^{-3}$) for grass buffer and row crop treatments, respectively. Microporosity was significantly higher for grass buffer treatment (0.341 $m^3 m^{-3}$) compared to other treatments (Table 4). Macropores, coarse mesopores, and micropores were significantly affected by sampling depth while numerical differences (not significant) were found for fine mesoporosity (Table 4). The interactions between vegetative management and sampling depth were found to be significant ($P < 0.01$) for coarse mesoporosity, fine mesoporosity, and microporosity.

Macroporosity (Fig. 5a) was significantly ($P < 0.05$) higher for the biomass crop treatment than the other treatments for 0–10 and 10–20 cm depths, with switchgrass having values of 0.053 $m^3 m^{-3}$ and 0.041 $m^3 m^{-3}$ at the 0–10 and 10–20 cm depth respectively, while the lowest macroporosity values were found for agroforestry buffers at 20–30 cm which was 0.005 $m^3 m^{-3}$. Figure 5b shows that the highest coarse mesoporosity was for agroforestry buffer and biomass crop treatments at 0–10 and 20–30 cm as well as for agroforestry buffers at 30–40 cm. Agroforestry and switchgrass treatments have deeper roots, which increases porosity and organic matter, with improved soil structure compared with the row-crop system (Rachman et al. 2004; Mudgal et al. 2010; Zaibon et al. 2016). However, the impacts of management practices reduce with increased sampling depth because a decrease in the amount of roots occurs with increasing depth.

Fine mesoporosity was also affected ($P < 0.05$) by vegetative treatment at 0–10 cm depth for grass buffer and row crop treatments as well as at 10–20 cm for agroforestry buffers and row crop management (Fig. 5c). Microporosity values ranged from 0.27 m^3 m^{-3} for agroforestry treatment at 10–20 cm to 0.38 m^3 m^{-3} for grass treatment at 30–40 cm (Fig. 5d). However, the effect of soil structure decreased among the treatments for the deeper depths (Seobi et al. 2005; Mudgal et al. 2010). Also, macroporosity and coarse mesoporosity decreased from the soil surface (0–10 cm) to the third and fourth depths. This was probably due to there being an increase in concentration of smectitic clays (Table 1). Similar findings were found by Seobi et al. (2005) and Zaibon et al. (2016). They reported that clay content increased with soil depth which increased microporosity and decreased macroporosity.

A study conducted by Zaibon et al. (2016) reported that switchgrass had 53, 27, 7.5, and 5% greater macroporosity, coarse mesoporosity, fine mesoporosity, and microporosity respectively than the row-crop treatment. Also, they indicated switchgrass enhances soil porosity compared with row crop management for claypan landscapes. Seobi et al. (2005) evaluated soil hydraulic properties on the same site as the current study. They concluded that agroforestry and grass buffers had more total porosity and coarse mesoporosity relative to row crop treatment due to greater amounts of root development under buffers and hence more beneficial to improved water infiltration and decreased surface runoff for claypan landscapes. A study conducted by Mudgal et al. (2010) to assess the effects of long-term soil and crop management on soil hydraulic properties for claypan soils showed that coarse mesoporosity and fine mesoporosity for the native Tucker Prairie management (0.080 and 0.089 m^3 m^{-3}) respectively were almost double those values from the long-term row crop management (0.040 and 0.050 m^3 m^{-3}).

Kumar et al. (2008) found that agroforestry and grass buffers had 11, 54, 89, and 62% higher total porosity, macroporosity, coarse mesoporosity, and fine mesoporosity respectively compared with pasture treatments but 5% lower microporosity for all depths (0–10, 10–20, 20–30, and 30–40 cm). They reported that these systems will have a significant impact on water transport in macropores and coarse mesopores and hence increase infiltration rates.

Measurements of root length density or root distribution patterns are important to provide a better understanding of how different management practices impact the creation or development of macroporosity, coarse mesoporosity, etc. in the soil. Udawatta et al. (2005a) and Kumar et al. (2010b) reported that agroforestry and grass buffers have more roots; their measurements included root dry weight, root length, root surface area as well as soil carbon which compared with row crop treatments were higher. These root characteristics may improve soil hydraulic properties. These results can be attributed to perennial plants that have extensive deep root systems in the subsurface compared to annual crops. Also, the researchers stated that the size of the roots is proportional to above ground plant biomass. Perennial plant roots persist longer than row crop roots; these roots may create larger, longer, and more continuous pores spreading into the subsurface soil (Udawatta et al. 2008).

Generally, claypan landscapes have fewer macropores and more micropores and subsequently lower water infiltration and higher surface runoff. Establishment of buffers and biomass crops can help to improve porosity and hence increase infiltration as well as reduce surface runoff and sediment losses.

The current study was performed on the same site as used by the Seobi et al. (2005) study, but this study has included a biomass crop treatment which was not studied and evaluated by Seobi et al. (2005). The biomass crop treatment was established in 2012. *Ksat* values were slightly different 20 years after buffer establishment compared with 6 years after buffer establishment assessed in 2003. Few changes occurred for soil bulk density, soil water retention and pore size distributions with the 2017 sampling compared to the 2003 sampling (14 years difference between the two sampling studies). Most of the changes occurred within the first 6 years, and small changes occurred over the next 14 years.

Root systems could be possible impact causing these changes. The agroforestry buffers consisted of three kinds of trees which are pin oak, swamp white oak, and bur oak. Among these tree species, pin oak had more roots than the swamp white and bur oak trees. During early growth stages of the oak trees, significant energy is put into the root system (Udawatta et al. 2005a, b). Oak trees put more energy in the root system during the first 6 years; while during the next 14 years, more energy is put into the above ground system. During the latter period (current study), less changes may occur in the root system and hence less changes occurred with soil hydraulic properties.

Another reason is that core samples were not taken from the entire root system because the samples were a fixed size. Because these single cores did not sample the entire root system, they will not assess all differences after 20 years (2017 sampling) compared with 6 years (2003) after establishment of agroforestry and grass buffers. The biomass crop treatment, which was established in 2012 on the same site, was not sampled by the Seobi et al. (2005) study. Biomass crops have also confirmed what are discussed above, that more changes occur with soil hydraulic properties 5 years after establishment.

Conclusions

This study was conducted to assess the effects of agroforestry buffers, grass buffers, and biomass crop management practices on soil hydraulic properties (soil bulk density, *Ksat*, soil water retention, and pore size distribution) compared to row crops for a claypan soil. The results of this study showed that the buffer treatments and biomass crops had lower bulk density values ($P < 0.01$) compared to the row crop treatment averaged across depths, particularly in the soil surface (0–10 cm). The mean *Ksat* value (averaged across sampling depth) for biomass crop treatment (36.0 mm h^{-1}) was 28, 64, and 70% higher than for the agroforestry buffers, grass buffers, and row crops, respectively.

Agroforestry and grass buffers as well as biomass crop treatments had higher soil water content at high soil water pressures > -2.5 kPa relative to row crop management. Macropores and coarse mesopores were significantly higher for the biomass treatment than the other treatments (buffers and row crops) for the first depth 0–10 cm. Also, the highest coarse mesopores values were found in agroforestry buffers and biomass crop treatments compared to grass buffer and row crop treatments.

This study has shown that establishment of agroforestry buffers and biomass crops on strategic locations within row crop watersheds is useful for improving soil physical and hydraulic properties compared with row-crop systems, and hence may help reduce non-point source pollution from row crop agriculture. Thus, conservation buffers and biomass crops will be helpful for soil and water conservation as well as for improving soil quality. In addition, planting perennial vegetation systems may enhance soil quality by increasing soil carbon and water storage on degraded soils particularly in claypan landscapes as well as these systems also have valuable economic and environmental benefits. However, sustainable vegetative management practices on vulnerable claypan soils require improved knowledge and a better understanding of the long-term effects of these conservation management systems.

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