Soil Hydraulic Properties Influenced by Stiff-Stemmed Grass Hedge Systems

Achmad Rachman, S. H. Anderson,* C. J. Gantzer, and E. E. Alberts

ABSTRACT

The effectiveness of stiff-stemmed grass hedge systems in controlling runoff and soil erosion is influenced by the water transport properties of the soil under grass hedge management. This study evaluated soil hydraulic properties within a grass hedge system 10 yr after establishment. The study was conducted at the USDA-ARS research station near Treynor, IA in a field managed with switchgrass (*Panicum virgatum*) hedges. The soil was classified as Monona silt loam (fine-silty, mixed, superactive, mesic Typic Hapludolls). Three positions were sampled: within the grass hedges, within the deposition zone 0.5 m upslope from the grass hedges, and within the row crop area 7 m upslope from the hedges. Intact soil samples (76 by 76 mm) were taken from the three positions at four depths (100-mm increments) to determine saturated soil hydraulic conductivity (K_{sat}), bulk density (ρ_b), and soil water retention. The grass hedge position had significantly greater ($P < 0.05$) macroporosity than the row crop and deposition positions in the first two depths and greater than the deposition position in the last two depths. The K_{sat} within the grass hedge (668 mm h^{-1}) was six times greater than in the row crop position (115 mm h^{-1}) and 18 times greater than in the deposition position (37 mm h^{-1}) for the surface 10 cm. Bulk density and macroporosity were found to provide the best two-parameter regression model for predicting the log-transformed K_{sat} ($R^2 = 0.68$). These results indicate that grass hedges significantly affected soil hydraulic properties for this loess soil.

Soil loss by water from land under crop management is a major source of contaminants. Terraces are a principal erosion control practice, which reduce slope steepness and slope length and consequently slow runoff velocity. Terrace systems are costly, semi-permanent changes to cropped fields, and affect crop production during the first few years after installation (Troeh et al., 1980). An alternative to terraces, which has been considered recently, is narrow, stiff-stemmed grass hedges planted on the contour. Some cooperators in India, the West Indies, Fiji (Kemper et al., 1992), and Indonesia (Abujamin et al., 1985) have successfully established grass hedges during the past 30 yr. These systems have several advantages over traditional terraces.

Stiff-stemmed grass hedges have been shown to be an effective management practice to control nonpoint source pollution from sediment, nutrients, and pesticides. Once grass hedges are established, they have been found to increase in-field sedimentation and to promote infiltration, while simultaneously reducing the velocity of runoff (Dillaha et al., 1989; William et al., 1989; Robinson et al., 1996; McGregor et al., 1999). In-field sedimentation occurs upslope from the grass hedges mainly due to sediment trapping through ponding of runoff water (Dabney et al., 1995). This ponding of water is attributed to the slowing of the runoff velocity by the erect, stiff-stems of the grass hedge and subsequent deposition of sediment. These researchers (Dabney et al., 1995) also reported that finer soil particles settled in a deposition zone near the grass hedges.

Active and decaying root systems of the stiff-stemmed grasses may improve the porosity of the soil and result in increased hydraulic conductivity within the grass hedge area. Gilley et al., (2000) reported that grass hedges reduced runoff by about 52% on Monona silt loam (Typic Hapludolls) at Treynor, IA. They noted that the significant reduction of runoff for the grass hedge treatment was due to the ponding of water upslope from the grass hedges. The ponded condition created a positive hydraulic head at the soil surface, which enhanced infiltration. McGregor et al. (1999), however, reported only a 5 to 7% reduction of runoff due to grass hedges on Providence silt loam (Typic Fragiudalfs) in Mississippi. Differences in runoff reduction between these two studies were probably governed by differences in hydraulic conductivity of the soils. Deposition of finer soil particles upslope from the grass hedge due to reductions in runoff velocity and subsequent sedimentation may also affect soil hydraulic properties as finer particles clog soil pores. Few studies have been conducted to evaluate changes in soil physical and hydraulic properties under grass hedge management. This information is critical to better understand runoff and erosion processes for these systems. Quantification of soil hydraulic properties at different positions within the grass hedge system may assist in prediction of runoff and soil erosion from watersheds with grass hedges.

The objectives of this study were to (i) evaluate the effects of position within a stiff-stemmed grass hedge system on soil texture, organic matter, bulk density, soil water retention, and saturated hydraulic conductivity; (ii) use soil water retention data to estimate the effects of grass hedges on pore-size distributions; and (iii) evaluate relationships between saturated hydraulic conductivity, bulk density, and porosity.

MATERIALS AND METHODS

Experimental Site

The study was conducted at the USDA-ARS National Soil Tilth Laboratory Deep Loess Research Station near Treynor, IA. The watershed is a 6-ha area representing the Iowa and Missouri Deep Loess Hills, Major Land Resource Area 107

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Published in Soil Sci. Soc. Am. J. 68:1386–1393 (2004).

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Abbreviations: CV, coefficient of variance; K_{sat}, saturated hydraulic conductivity; LSD, least significant difference.

Table 1. Selected soil physical and chemical properties of the Monona silt loam collected from within a 600-m^2 area located on a 2 to 4% slope within the row crop position on the southwestern portion of Watershed 11, Treynor, IA in 2001.

	Depth			
Soil Properties	0–10 cm	10–20 cm	20–30 cm	30–40 cm
pHw	5.3 (0.2)†	5.6 (0.3)	6.2 (0.3)	6.6 (0.1)
OM, g kg^{-1}	20.0 (0.0)	8.7 (0.6)	7.3 (1.5)	4.3 (1.2)
CEC, $cmol_c$ kg^{-1}	23.1 (1.0)	24.8 (1.5)	24.9 (1.2)	25.1 (1.5)
Sand, g kg^{-1}	108 (14)	108 (14)	117 (14)	125 (0)
Silt, g kg^{-1}	609 (14)	617 (14)	625 (25)	633 (14)
Clay, g kg^{-1}	283 (14)	275 (25)	258 (14)	242 (14)

† Numbers in parentheses are the standard deviation of the mean of three observations.

(USDA-SCS, 1981). The predominant soil is Monona silt loam. The Monona series consists of deep, well-drained soils formed under prairie vegetation in loess on uplands and stream benches. The surface soil is dark brown approximately 37 cm thick (Kramer et al., 1999). Surface soils are silt loam in texture (Table 1) and the soils are classified as highly erodible land (HEL).

The original watershed slope ranged from 2 to 4% within the ridges and valleys to 12 to 16% on side slopes. Soil erosion was a serious problem in the watershed. From 1975 through 1991, the mean annual sediment yield, measured at the watershed outlet, was 17 Mg ha^{-1}, ranging from <1 to 50 Mg ha^{-1} annually. In 1975, the watershed was instrumented to monitor runoff and erosion from continuous row crop corn (*Zea mays* L.) production (Kramer et al., 1999). Beginning in May 1991, the first grass hedges were established using switchgrass from seed. The distance between hedges is 15.4 m to accommodate sixteen rows of corn at a 0.96-m spacing. The hedges' vertical interval, the vertical difference between two hedges, ranged from 0.6 to 2.5 m following the range in slope between hedges of 5 to 16.5%. Hedges at the time of this study were between 0.75 to 1 m wide. Ten hedges were established on the southern portion of the watershed and seven hedges on the northern portion, which accounted for a total length of about 2400 m. Hedges covered about 0.3 ha or 4% of the watershed area. Grasses planted were mainly switchgrass on the southern portion of the watershed and eastern gamagrass [*Tripsacum dactyloides* (L.) L.] on the northern portion; both grasses are warm season grasses. Sampling was conducted on the southwestern portion of the watershed on the second through the fourth hedges counted from the summit. The area selected for study was on the same watershed and near the same general area as the Gilley et al. (2000) study.

Continuous corn was grown from 1975 to 1996 using conventional tillage. Tillage included moldboard plowing or disking and harrowing in mid-April, followed by disking and harrowing before planting about 2 wk later (Kramer et al., 1999). Cultivation for weed control was also conducted one or two times during the early growing season. No-till soybeans (*Glycine max*) were grown from 1997 to 2000, and currently the watershed is in a no-till corn–soybean rotation. During the soil sampling for this study, the watershed was planted to soybeans.

Soil Sampling and Analysis

Three sampling positions within the grass hedge system were selected representing the grass hedge, deposition zone, and row crop positions. The deposition zone position was 0.5 m upslope from the upper edge of the grass hedge and the row crop position was 7 m upslope from the grass hedge (Fig. 1). Intact soil cores were collected on 8 June 2001. Sampling positions in the row crop area were taken in nontrafficked interrows.

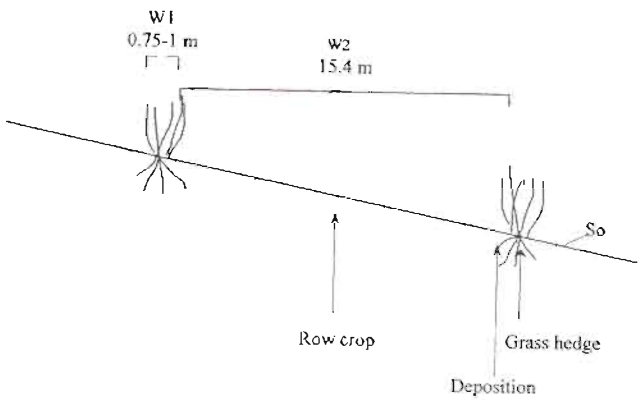

Fig. 1. Schematic sketch of grass hedge system illustrating the width of hedge (W1), width of cropped area (W2), original soil slope (So), and sampling positions (grass hedge; deposition zone, 0.5-m upslope of the hedge; and row crop 7-m upslope of the hedge).

Intact samples were collected using a core sampler (76 by 76 mm; Blake and Hartge, 1986). Four soil depths were sampled at 10-cm depth intervals with six replicates per treatment position. The six replicates were chosen between and within the second through fourth hedges counted from the watershed summit. For the row crop and deposition positions, three replicates were randomly chosen between the second and third hedges and the other three replicates randomly between the third and the fourth hedges. For the grass hedge position, three replicates were randomly selected within the third hedge and three replicates randomly within the fourth hedge. The samples were labeled, sealed in plastic bags, and placed in cases for transport to the laboratory. The samples were stored at 4°C to reduce biological activity until laboratory analyses were conducted.

The soil cores were placed in a plastic tray and slowly (10 mL min^{-1}) saturated by wetting from the bottom to zero water pressure for 24 h with 6.24 g L^{-1} $CaCl_2$ and 1.49 g L^{-1} $MgCl_2$ solution (Palmer, 1979). The constant head method was used to measure saturated hydraulic conductivity (K_{sat}; Klute and Dirksen, 1986).

Immediately after K_{sat} measurements, soil water retention was determined at soil water pressures of −0.4, −1, −2.5, −5, −10, −20, and −40 kPa using compressed air and glass funnels with ceramic plates. Intact cores were used to measure water retention (Klute, 1986). Bulk density was determined from oven-dried samples (Blake and Hartge, 1986).

The capillary rise equation was used to estimate effective pore size from the soil water pressures (Jury et al., 1991, p. 41). Pore-size distributions were then estimated from the water retention data (Hill et al., 1985). Pore-size classes were divided into macropores (>1000 μm effective diam.), coarse mesopores (60–1000 μm effective diam.), fine mesopores (10–60 μm effective diam.), and micropores (<10 μm effective diam; Anderson et al., 1990).

Additional soil samples from the four soil depths were collected at three of the replicate locations. The three subsamples obtained from each position using a stainless steel push probe were mixed, composited, air-dried, ground, and passed through a 2-mm sieve. The air-dried soils were analyzed for sand, silt, and clay content using the hydrometer method (Gee and Bauder, 1986) and organic matter content using the combustion method (Nelson and Sommers, 1982).

A test of homogeneity of variance (*F*-test between the largest and smallest position variances) among positions was conducted to determine whether a further analysis of variance could be conducted due to the systematic arrangement of the positions. If there were no significant differences among position variances, an analysis of variance was done assuming a completely randomized design with soil depth as a split-plot. The GLM procedure in the SAS program (SAS Institute, 1989) was used with significance set at $P = 0.05$. Significant differences between position means were assessed using the LSD (least significant difference) procedure at a 95% probability level (Duncan's LSD). Single degree-of-freedom contrasts for the position effect were divided into 'grass hedge position vs. others' and 'deposition position vs. row crop position'. An estimate for the LSD between positions at the same depth or different depths was obtained using the MIXED procedure in SAS. Step-wise regression analysis was performed to obtain the best two-parameter model for predicting log K_{sat} from bulk density and pore-size distributions. This regression analysis was conducted for each position separately.

RESULTS AND DISCUSSION

Texture, Organic Matter, and Bulk Density

Position within the grass hedge system, soil depth, and their interaction had statistically significant effects ($P < 0.05$) on clay content, organic matter content, and bulk density (Table 2). The contrasts of 'grass hedge vs. others' and 'deposition vs. row crop' were both significant ($P < 0.05$) for clay content, organic matter content, and bulk density (Table 2). The mean silt contents, averaged across depth, in the grass hedge, row crop, and deposition positions, were 644 ± 26, 621 ± 18, and 640 ± 23 g kg^{-1}, respectively. The slightly higher silt content in the grass hedge (10.8%) and deposition (3.9%) positions (significant at the 0- to 10-cm depth; Fig. 2A) can be attributed to the movement of soil by water erosion from the row crop position. When runoff water velocity is lowered above the hedge, silt particles are deposited or trapped by the grass hedge resulting in an increase in silt content in the grass hedge and deposition positions (Meyer et al., 1995; Dabney et al., 1995).

We speculate that clay particles passed through the hedge during erosion events and did not deposit in the grass or upslope from the hedge as the silt particles. The process caused the significantly ($P < 0.05$) greater clay content in the row crop position than in the grass hedge and deposition positions (Table 2). The mean clay content averaged across depth for the row crop position was 14% greater (265 ± 23 g kg^{-1}) than for the grass hedge position (229 ± 28 g kg^{-1}), and 11% greater than for the deposition position (238 ± 23 g kg^{-1}).

Table 2. Depth and position means and probability values ($P > F$) from analysis of variance for silt, clay, organic matter content ($n = 3$), and bulk density ($n = 6$) as affected by position and depth 10 yr after the establishment of a grass hedge system.

Mean	Silt content	Clay content	Organic matter	Bulk density
	Depth mean			
0–10 cm	639	239	21.6	1.18
10–20 cm	628	261	14.8	1.37
20–30 cm	633	242	9.7	1.33
30–40 cm	639	233	5.9	1.33
	Position mean			
Grass hedge (GH)	644	229	15.8	1.22
Row crop (RC)	621	265	10.1	1.28
Deposition (DZ)	640	238	13.0	1.41
	Analysis of variance $P > F$			
Position	0.065	0.012	<0.01	<0.01
GH vs. others	0.104	0.021	<0.01	<0.01
DZ vs. RC	0.061	0.016	0.035	<0.01
Depth	0.622	0.024	<0.01	<0.01
Position by depth	0.073	0.013	0.019	<0.01

Soil organic matter was significantly ($P < 0.01$) greater in the grass hedge than in the row crop and deposition positions; and organic matter was higher in the deposition position ($P < 0.05$) than in the row crop position (Table 2). The mean organic matter contents averaged across depth, for the grass hedge, deposition, and row crop positions were 15.8 ± 7.1, 13.0 ± 7.1, and 10.1 ± 6.3 g kg^{-1}, respectively. The higher organic matter content found in the grass hedge position was attributed to the concentration of grass roots observed during sampling through the 30-cm soil depth.

Bulk density in the grass hedge position was significantly ($P < 0.01$) lower (9.3%) than in the other two positions. Significantly ($P < 0.01$) lower (9.2%) bulk density values were also found for the row crop position as compared with the deposition position. The mean bulk densities, averaged across depth, were 1.22 ± 0.14, 1.28 ± 0.11, and 1.41 ± 0.09 Mg m^{-3} in the grass hedge, row crop, and deposition positions, respectively.

Least significant differences among positions for a specific depth or between depths for the silt, clay and organic matter contents, and bulk density are shown in Fig. 2A-D. Silt and clay contents were found to be significantly different only at the 0- to 10-cm depth with the grass hedge position having the highest silt and the

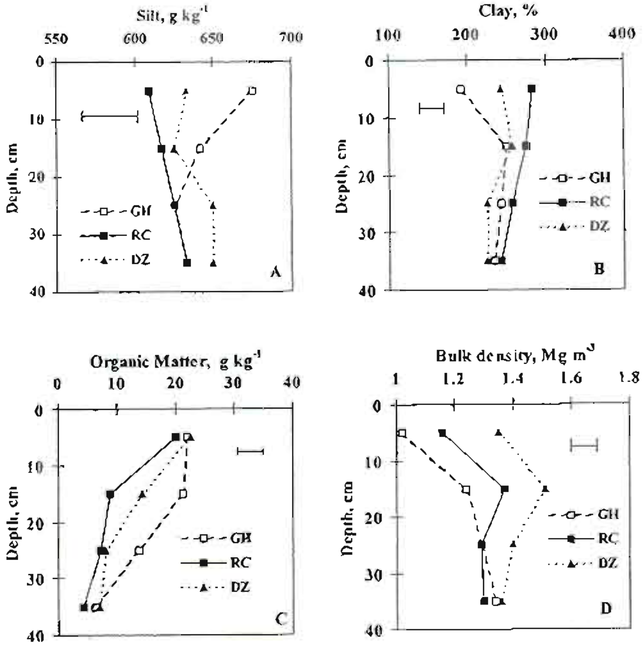

Fig. 2. Effects of position and depth on (A) silt content, (B) clay content, (C) organic matter, and (D) bulk density. GH = Grass hedge; RC = Row crop; DZ = Deposition zone. Bars indicate LSD(0.05) values.

lowest clay content (Fig. 2A-B). Silt content decreased with depth in the grass hedge position, while it increased with depth in the row crop and deposition positions.

Organic matter was significantly affected by position in the 10- to 20- and 20- to 30-cm depths (Fig. 2C) with the grass hedge position being significantly higher compared with the other positions. Organic matter content was found to be similar for the 0- to 10- and 10- to 20-cm depths in the grass hedge position, and then decreased significantly (70%) from the 10- to 20- to the 30- to 40-cm depth (Fig 2C). In the row crop position, the largest decrease (57%) was found from the 0- to 10- to the 10- to 20-cm depth, while in the deposition position the largest decrease (65%) was from the 0- to 10-cm to the 20- to 30-cm depth (Fig. 2C).

Position significantly affected bulk density to a depth of 30 cm with grass hedge having the lowest and the deposition position having the highest bulk density (Fig. 2D). Bulk density increased with depth under grass hedges, while in the row crop and deposition positions, bulk density increased to the highest level in the 10- to 20-cm depth and then decreased. There were no significant differences in bulk density found among positions at the fourth depth (30 to 40 cm). Other researchers have also found no significant differences in bulk density due to tillage at depths >30 cm (Gantzer and Blake, 1978). The increase in bulk density found at the second depth (10–20 cm) in the row crop and deposition positions agrees with Voorhees et al. (1978), who found that traffic compaction will generally be limited to the upper 30 cm of soil for axle loads <4.5 Mg. Possible reasons for the higher bulk density in the deposition position include slightly higher water content at the time of trafficking and also the lack of developed soil structure due to recent deposition. In addition, lack of root growth in the deposition position may be an additional reason for the increased bulk density (no row crops were planted and few weeds grew due to shading from the grass hedges).

Soil Water Retention

Results from the analysis of variance of the soil water retention data indicated that position significantly ($P <$ 0.01) affected soil water retention for 0 and −0.4 water pressures (Table 3). Heterogeneities among position variances were found for the other soil water pressures. For these water pressures, the row crop position had a significantly ($P > 0.05$) greater variance compared with the grass hedge and deposition positions. The variances for the row crop position were not unusually high relative to the mean (coefficient of variation [CV] ranged from 7 to 11%), but the variances for the grass hedge and deposition positions were very low (CV ranged from 1 to 4%).

Table 3. Probability values ($P > F$) from analysis of variance for volumetric water content over a range of soil water pressures as affected by position and depth ($n = 72$).

	Source of variation ($P > F$)		
Soil water pressure	Position	Depth	Position by depth
kPa			
0.0	<0.01	<0.01	<0.01
−0.4	<0.01	<0.01	0.02
−1.0	*	*	*
−2.5	*	*	*
−5.0	*	*	*
−10.0	*	*	*
−20.0	*	*	*
−40.0	*	*	*

* The homogeneity of variance test indicated that the row crop position had a significantly higher ($P > 0.05$) variance compared with the other two positions; thus further analyses were not conducted at these water pressures.

The saturated water content (θ_s) was significantly higher in the grass hedge position than in the row crop and deposition positions (Table 4). The volumetric water content values of the row crop position were similar to those of Hill et al. (1985) who collected cores from Canisteo clay loam (Typic Haplaquolls) near Ames, IA, at the 5.0- to 7.5-cm depth. The higher θ_s in the grass hedge position indicates that since the hedges were established they have created significantly higher porosity than that found for row crop management. This result mirrors the lower bulk density observed in this position. This property allows increased infiltration and reduced surface runoff.

The amount of water retained at any soil water pressure for soil under grass hedge management exceeded that under row crop and deposition positions in (Fig. 3A–D). The pattern of positional effects within the grass hedge system was grass hedge > row crop > deposition positions in the amount of water retained. There were no significant differences in soil water retention found between grass hedge and row crop positions at the 20- to 40-cm depth for the 0 and −0.4 kPa water pressures (Fig. 3C–D). Figure 3A–B also indicated that the slope of the curves for the grass hedge position were higher than for the other two positions. Cameron (1978) related the decrease in water content differences over the range of pressures evaluated and the shape of the curve to bulk density. In general, he found that the water content differences between soil water pressures or the slope of the water retention curve decreased with an increase in bulk density, which was similar to our results. We found the lowest slope for the water retention curve in the deposition position, which had the highest bulk density.

Table 4. Volumetric water content values averaged across depths for position means comparison for a range of soil water pressures.

	Position mean		
Soil water pressure	Grass hedge	Row crop	Deposition
kPa	$m^3\ m^{-3}$		
0.0	0.52a†	0.47b	0.43b
−0.4	0.48a	0.45ab	0.42b
−1.0*	0.47	0.45	0.42
−2.5*	0.45	0.44	0.41
−5.0*	0.43	0.42	0.40
−10.0*	0.42	0.40	0.39
−20.0*	0.40	0.38	0.37
−40.0*	0.37	0.35	0.35

* Comparisons of means were not conducted because of heterogeneity of variance.

† Different letters indicate statistical significance at the 5% level with use of least-significant differences. Statistical comparisons are made by row for a given soil water pressure.

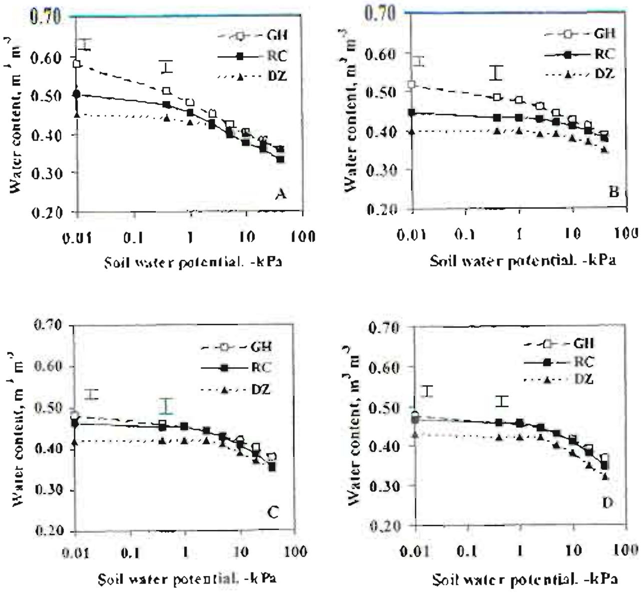

Fig. 3. Effects of position on soil water retention at depths of (A) 0 to 10 cm, (B) 10 to 20 cm, (C) 20 to 30 cm, and (D) 30 to 40 cm. GH = Grass hedge; RC = Row crop; DZ = Deposition zone. Bars indicate LSD(0.05) values that are the same for all four depths at a water potential. LSD values are presented for the first two water potentials; other values were not determined due to heterogeneity of variance among positions.

Pore-Size Distributions

Analysis of variance indicated that position and depth had significant ($P < 0.05$) effects on macropores, coarse mesopores, and fine mesopores; however, position had no significant effect on micropores (Table 5). The grass hedge position was found to have significantly ($P < 0.05$) greater macroporosity and coarse mesoporosity as compared with the row crop and deposition positions (Table 5). After 10 yr, soil under grass hedge management had macroporosity of 0.038 m^3 m^{-3}, which is over two times greater than under the row crop position (0.016 m^3 m^{-3}) and five times higher than under the deposition position (0.007 m^3 m^{-3}). These results agree with Chan and Mead (1989), who found that permanent pasture had nearly four times the volume of macropores than tilled soil. In addition, Voorhees and Lindstrom (1984) reported that 3 to 4 yr are required for conservation tillage to produce a higher porosity than for conventional plowing. The contrasts between the grass hedge and other positions were significant ($P < 0.05$) for macropores and coarse mesopores, while the contrasts between the row crop and the deposition positions were all significant ($P < 0.05$) except for micropores.

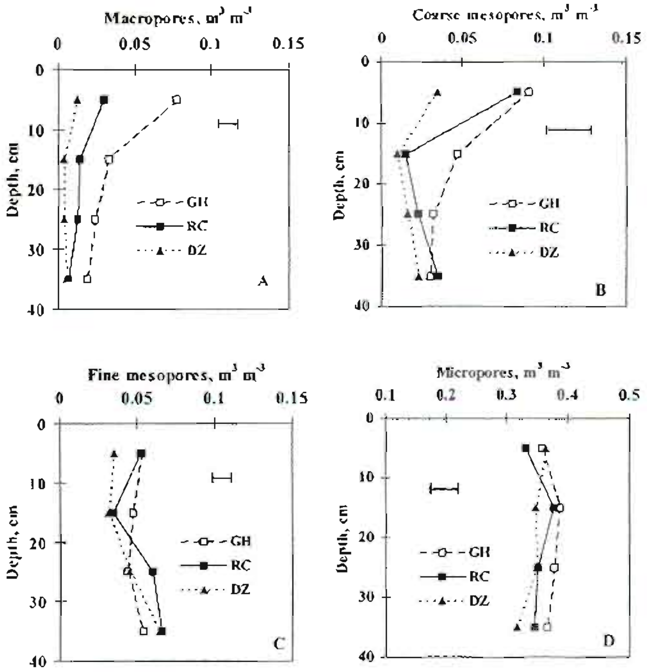

Fig. 4. Effects of position and depth on the distribution of (A) macropores, (B) coarse mesopores, (C) fine mesopores, and (D) micropores. GH = Grass hedge; RC = Row crop; DZ = Deposition zone. Macropores (>1000 μm diam.), coarse mesopores (60–1000 μm diam.), fine mesopores (10–60 μm diam.), and micropores (<10 μm diam.). Bars indicate LSD(0.05) values.

Least significant differences among positions for a specific depth or between depths for the porosity classes are shown in Fig. 4A–D. The grass hedge position had

Table 5. Depth and position means and probability values ($P > F$) from analysis of variance for macropores, coarse mesopores, fine mesopores, micropores, and K_{sat} as affected by position and depth 10 yr after establishment of a grass hedge system ($n = 6$).

Mean	Macropores (>1000 μm)	Coarse mesopores (60 to 1000 μm)	Fine mesopores (10 to 60 μm)	Micropores (<10 μm)	K_{sat}
	m^3 m^{-3}				mm h^{-1}
			Depth mean		
0–10 cm	0.040	0.070	0.047	0.352	273.5
10–20 cm	0.017	0.024	0.037	0.371	7.0
20–30 cm	0.014	0.024	0.049	0.360	3.1
30–40 cm	0.010	0.029	0.061	0.343	4.6
			Position mean		
Grass hedge (GH)	0.038	0.050	0.049	0.373	174.3
Row crop (RC)	0.016	0.039	0.053	0.352	30.8
Deposition (DZ)	0.007	0.021	0.044	0.345	11.0
			Analysis of variance $P > F$		
Position	<0.01	0.014	0.029	0.137	<0.01
GH vs. others	<0.01	0.018	0.669	0.057	<0.01
DZ vs. RC	0.014	0.049	<0.01	0.591	0.272
Depth	<0.01	<0.01	<0.01	<0.01	<0.01
Position by depth	<0.01	0.016	<0.01	0.033	0.028

significantly greater ($P < 0.05$) macroporosity than the row crop and deposition positions in the 0- to 20-cm depth and greater than the deposition position in the 20- to 40-cm depth. While row crop and deposition positions were not significantly different, the deposition position had the lowest macroporosity (Fig. 4A). The largest decrease in macroporosity was found from the 0- to 10-cm to the 10- to 20-cm depths for the grass hedge (57%), row crop (53%), and deposition (69%) positions, with slight decreases at deeper depths. These results suggest that soil under grass hedges has more macropores, which can act in the transport of water into the soil under ponded conditions during rainfall, while the deposition position may produce more runoff compared with the other positions.

Coarse mesoporosity in the grass hedge position was not significantly different than in the row crop position, except for the 10- to 20-cm depth (Fig. 4B). Coarse mesoporosity was found to be significantly different between grass hedge and deposition positions to a depth of 20 cm with the deposition position having the lowest coarse mesoporosity values for all depths. There were no significant differences in coarse mesoporosity found among positions at the 20- to 40-cm depths. Coarse mesoporosity decreased to the lowest values at the 10- to 20-cm depth for the row crop and deposition positions, then increased slightly at deeper depths, while in the grass hedge position coarse mesoporosity decreased with depth. These trends were in accordance with the bulk density values (Fig. 2D).

Position significantly affected fine mesoporosity to a depth of 30 cm (Fig. 4C). In general, fine mesoporosity decreased to the lowest values at the 10- to 20-cm depth for the row crop and deposition positions and at the 20- to 30-cm depth for the grass hedge position, then increased slightly at deeper depths. No significant differences were found among positions for microporosity (Fig. 4D).

Saturated Hydraulic Conductivity

Statistical analyses for K_{sat} were performed on log-transformed values since data for this parameter were not normally distributed. Position and depth were found to significantly affect K_{sat} ($P < 0.01$; Table 5). The contrast of the grass hedge position with the other two positions was significant ($P < 0.01$), while the contrast between the row crop and deposition positions was not significant (Table 5).

Figure 5 shows the depth distribution of K_{sat} for the three positions. The K_{sat} for the grass hedge position decreased with depth with the lowest values occurring at the 20- to 40-cm depth. Consistent with the bulk density data, the K_{sat} was significantly higher in the grass hedge position than in the row crop and deposition positions for the 0- to 20-cm depth. No significant differences were found among the positions in the 20- to 40-cm depth (Fig. 5).

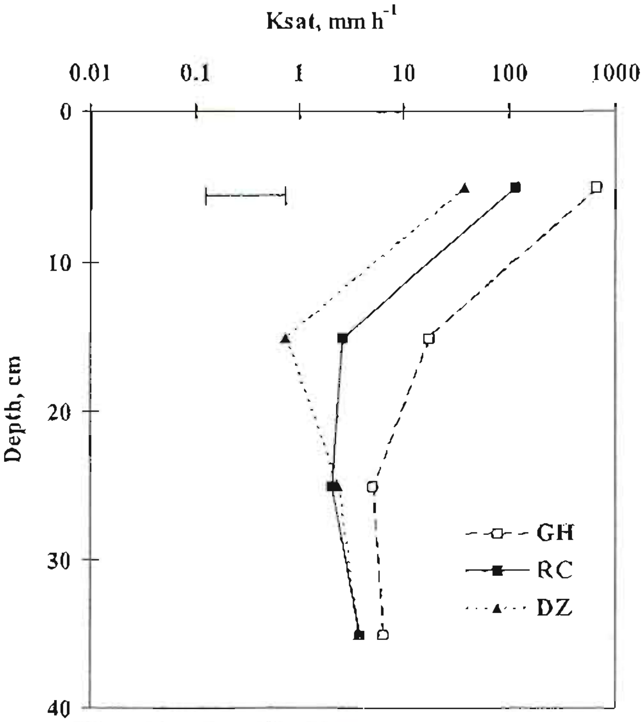

Fig. 5. Effects of position and depth on saturated hydraulic conductivity (K_{sat}). GH = Grass hedge; RC = Row crop; DZ = Deposition zone. Bar indicates LSD(0.05) value.

The K_{sat} in the grass hedge position for the first 10 cm (668 mm h^{-1}) was six times greater than in the row crop position (115 mm h^{-1}) and 18 times larger than in the deposition position (37 mm h^{-1}). This higher K_{sat} in the grass hedge position can be attributed to the abundance of macropores found at the 0- to 20-cm depth (Fig. 4A). These macropores are in part due to the root network of switchgrass remaining intact without annual tillage for the last 10 yr. These conditions will induce the formation of stable soil aggregates (Rachman et al., 2003) and also enhance the formation of macropores. Chan and Mead (1989) found that soil in permanent pasture had a high percentage of water-transmitting macropores, while in the conventionally cultivated soil all macropores were disturbed. The lowest K_{sat} in the deposition position probably was due in part to sedimentation of silt-sized materials and the detachment of surface soil by rain splash that destroyed macropores (Beven and Germann, 1982).

There were no significant differences in K_{sat} among the three positions in the 30- to 40-cm depth increments (Fig. 5). Physical excavation of the soil in the grass hedge position was conducted to qualitatively observe macropores. Qualitative results indicate that a large concentration of switchgrass roots were found in the top 20 cm, a lower concentration between 20 to 30 cm and very few beyond the 30-cm depth. However, some macropores were present below the 40-cm depth to 100 cm (the lowest depth excavated), although the frequency was low.

The K_{sat} for the row crop and deposition positions had the highest values in the surface 10 cm and the lowest in the 10- to 20-cm depth. Soil consolidation occurred as evidenced by increased bulk density (Fig. 2D) and reduced porosity (Fig. 3B and 3C) in the second depth

Table 6. Stepwise regression analysis of log K_{sat} on bulk density, macroporosity, coarse mesoporosity, fine mesoporosity, and microporosity.

Position	Factor	R^2 Partial	R^2 Model
Grass hedge	macroporosity	0.82	0.82
	bulk density	0.02	0.84
Row crop	bulk density	0.66	0.66
	microporosity	0.03	0.69
Deposition	macroporosity	0.36	0.36
	bulk density	0.11	0.47

for the row crop and deposition positions, which in turn reduced K_{sat}.

Prediction of K_{sat} Using Selected Soil Properties

Step-wise regression analysis of log K_{sat} with bulk density and pore-size fractions indicated that bulk density and macroporosity were the best parameters for a two-parameter model. The relationship found was:

$$\text{Log } K_{sat} = 4.46 - 3.19\text{bulk density} + 19.50\text{macroporosity}$$

$$R^2 = 0.68$$

The model explained 68% of the variation with a negative correlation between K_{sat} and bulk density and a positive correlation with macroporosity. These findings are in agreement with Bouma and Hole (1971) and Rawls et al. (1992) who found that the reductions in K_{sat} are paralleled by increases in bulk density and decreases in porosity.

When this regression analysis was partitioned by position, it is clearly seen that macroporosity was the most important factor affecting the K_{sat} in the grass hedge and deposition positions (Table 6). Bulk density was the most important factor affecting K_{sat} in the row crop position. Porosity is an important pathway in the process of infiltration of rainwater into the soil, especially when the macropores are open to the soil surface. If conditions are wet enough to exceed air entry values for the macropores, water flows directly into the soil and initiates lateral infiltration into the soil during ponded conditions, thus increasing surface area for infiltration (Beven and Germann, 1982). This is true for the grass hedge position where many macropores are open to the soil surface. In the row crop position, crusting on the soil surface may block the pores to the surface and mask the effects of macroporosity.

SUMMARY

A study was conducted to characterize and compare soil hydraulic properties at three positions (grass hedge, deposition, and row crop positions) within a grass hedge system that had been in place since 1991. Intact soil samples were removed from four depths (0–10, 10–20, 20–30, and 30–40 cm) and analyzed for bulk density, soil water retention, and saturated hydraulic conductivity measurements. In addition, bulk soil samples were collected for soil texture and organic matter measurements. After 10 yr, the stiff-stemmed grass hedge system had created three distinct zones within the watershed that significantly affected particle-size distributions, pore-size distributions, bulk density, and saturated hydraulic conductivity. The grass hedge position had the lowest bulk density and clay content and had the highest silt content, porosity, and saturated hydraulic conductivity. Bulk density and macroporosity were the most important factors affecting saturated hydraulic conductivity ($R^2 = 0.68$). A negative correlation was found between bulk density and saturated hydraulic conductivity and a positive correlation existed between macroporosity and saturated hydraulic conductivity. The lower bulk density and greater macroporosity in the grass hedges may reduce runoff by acting as a sink for runoff from the upper slope positions.

ACKNOWLEDGMENTS

The authors are grateful to the Agency for Agricultural Research and Development (AARD), Ministry of Agriculture, Indonesia, in providing the first author with financial support to study in the USA and conduct this research. This research was supported in part by the Missouri Agricultural Experiment Station project number MO-NRSL0117. The authors are grateful to Mr. Larry Kramer for sharing the watershed data.

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