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Landscape and Conservation Management Effects on Hydraulic Properties of a Claypan-Soil Toposequence

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Information on the effects of landscape and its interaction with management on soil hydraulic properties is scarce. Our objective was to investigate the effects and interactions of landscape position and conservation management systems (e.g., reduced tillage or permanent grass) on soil bulk density, saturated hydraulic conductivity (K_{sat}), soil water retention, and pore-size distributions for claypan soils in central Missouri. Landscape positions included summit, backslope, and footslope positions. Management included mulch tillage with a corn (*Zea mays* L.)–soybean [*Glycine max* (L.) Merr.] rotation (MTCS); no-till with a corn–soybean–wheat (*Triticum aestivum* L.) rotation (NTCSW) with a red clover (*Trifolium pretense* L.) cover crop following wheat; a Conservation Reserve Program system (CRP); and a hay crop system (HAY). Intact soil cores (76 by 76 mm) were collected from 0- to 10-, 10- to 20-, and 20- to 30-cm depths. Soil properties were affected by management only in the surface 0 to 10 cm, and were controlled by the depth of the claypan horizon. Management and depth effects on soil properties varied with landscape position. Saturated hydraulic conductivity was highest for CRP and lowest for MTCS (20.2 vs. 4.3 mm h^{-1}), averaged across all landscape positions and depths. The management × landscape position interaction indicated that, at the backslope, K_{sat} values for CRP and HAY were 16 and 10 times higher, respectively, than values for MTCS. The CRP retained the most water at soil water pressures from saturation to -1 kPa at the 0- to 10-cm depth. The fraction of larger pores was the highest for CRP at the 0- to 10-cm depth. Results suggest that the use of perennial grasses in rotation (or permanently) will benefit soil hydraulic properties, particularly at slope positions most vulnerable to degradation where soil conditions cannot be improved by row-crop conservation systems.

Abbreviations: CRP, Conservation Reserve Program; HAY, hay crop system; MTCS, mulch tillage with a corn–soybean rotation; NTCSW, no-till with a corn–soybean–wheat rotation.

Conservation tillage, as one of many conservation practices, was developed to reduce soil erosion by crop production. The degree of adoption of conservation tillage varies across the country for agronomic, management, and economic reasons (Uri, 1999). In some geographic regions where economic returns are substantial, however, these conservation practices have become predominant. In its general definition, conservation tillage is a tillage system that leaves at least 30% residue cover after harvest. Specifically, conservation tillage systems include mulch tillage, ridge tillage, and no-till. In mulch tillage, soil is disturbed with tillage tools such as chisels, disks, sweeps, or blades before planting. In ridge tillage and no-till, soil is left undisturbed from harvest to planting; planting is completed in a seedbed prepared on ridges with residue left on the surface between ridges when ridge tillage is practiced, and in a narrow seedbed or slot made by tools such as coulters or disk openers when no-till is practiced (Conservation Technology Information Center, 1998).

The CRP is a governmental soil conservation program, in effect since the early 1980s, in which highly erodible farmland is converted from crop production to perennial vegetative cover. Establishment of perennial vegetation has been shown to reduce water runoff and soil erosion (Davie and Lant, 1994; Gilley et al., 1997), restore soil organic C (Gebhart et al., 1994) and fertility (Karlen et al., 1999), and alter physical properties such as bulk density (Karlen et al., 1999) and water infiltration (Wienhold and Tanaka, 2001; Jung, 2005). Consequently, concerns have risen regarding management of CRP land when the CRP period (usually a 10-yr contract) has expired. Zheng et al. (2004) investigated soil erosion for CRP land converted to a permanent hay and grain crop rotation (spring wheat–winter wheat–dry pea [*Pisum sativum* L.]) managed with NT and disking. The study showed that the hay crop effectively controlled soil erodibility and runoff. For the grain crops, erodibility for no-till was about one-third that of disking, partly due to the wheat-dominated rotation producing durable and effective residues. These results lead to the conclusion that, to maintain the gains in soil conservation made during CRP, a

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Table 1. Selected soil physical and chemical properties for the 12-ha experimental area, Centralia, MO, composed primarily of Mexico silt loam and Adco silt loam. Data were averaged across nine sample locations for each landscape position. Numbers in parentheses are standard deviations.

Soil horizon	Soil depth	Clay	Silt	Cation exchange capacity	Organic C	pH (water)
	cm	——%	——	$cmol_c\ kg^{-1}$	%	
			Summit			
A_p	0–17	21.3 (4.6)	70.3 (6.2)	18.8 (2.1)	1.0 (0.2)	5.9 (0.6)
Bt_1	17–34	45.5 (13.8)	50.2 (12.1)	33.3 (8.6)	0.9 (0.1)	5.0 (0.4)
Bt_2	34–61	49.9 (8.7)	49.0 (8.6)	38.3 (5.3)	0.7 (0.3)	5.0 (0.3)
			Backslope			
A_p	0–12	24.8 (5.8)	65.8 (5.0)	21.9 (3.5)	1.0 (0.1)	6.1 (0.4)
Bt_1	12–35	54.6 (7.8)	42.8 (6.0)	40.2 (4.0)	0.9 (0.1)	4.9 (0.1)
Bt_2	35–61	42.9 (7.7)	55.3 (7.6)	34.8 (4.3)	0.4 (0.3)	5.1 (0.2)
			Footslope			
A_p	0–25	23.0 (8.2)	69.2 (9.2)	20.7 (4.1)	0.1 (0.2)	5.9 (0.6)
AB or Bt_1	25–50	38.3 (13.3)	55.7 (10.3)	29.9 (8.4)	0.9 (0.1)	5.1 (0.3)
Bt_2	50–78	39.7 (11.6)	54.4 (8.3)	30.7 (9.2)	0.5 (0.3)	5.1 (0.2)

carefully designed cropping system with an appropriate tillage method is needed.

Management practices influence soil hydraulic properties such as K_{sat} and water retention. These properties impart a direct impact on soil water conservation. Previous studies have shown that K_{sat} is usually higher for no-till management than for moldboard plowing (Gantzer and Blake, 1978; Azooz et al., 1996) and higher for permanent grass than for row crops (Rachman et al., 2004; Seobi et al., 2005). These effects have been attributed to well-preserved pore networks and better structure formation and, hence, enhanced macropore flow. Water retention has been also found to be higher for conservation tillage than plowed soils (Blevins et al., 1971; Gantzer and Blake, 1978; Lindstrom et al., 1984; Hill et al., 1985) due to improved soil structure and pore arrangements. Information has been scarce regarding the effects of CRP on these soil properties despite their key importance in evaluating CRP efficacy in soil water conservation. Schwartz et al. (2003) compared near-saturated hydraulic conductivity, water retention, and porosity between a 10-yr CRP land and native grassland. Pore volume for CRP was similar to that for native grassland, but near-saturated hydraulic conductivity for CRP was lower than that for grassland. Wienhold and Tanaka (2000) evaluated tension infiltration for CRP land returned to crop production after 5 yr of CRP management and continuous CRP. Within the 2-yr observation period, infiltration for continuous CRP increased an average of 45% at three applied tensions compared with crops after CRP. These results suggested that restoration of soil hydraulic properties to their natural state under CRP is a gradual process and could take much longer than 10 yr.

Effects on soil hydraulic properties of landscape and its interactions with management are important aspects in constructing a soil-water conservation management system. Previous studies have reported these effects to be significant. Landscape position directly affected water storage (McGee et al., 1997; Tomer et al., 2006) and interacted with management to affect spatial water redistribution (da Silva et al., 2001). In a cropped soil landscape, da Silva et al. (2001) found that soil moisture was significantly affected by the spatial distribution of clay content and organic matter along a slope under different tillage systems. As a result, increased clay and organic matter at the footslope position partially compensated for water loss in plowed soils. Direct landscape effects on soil hydraulic properties for various management systems are, however, not well understood. In particular, we were interested in these issues for the claypan soils that spread across about 4 million ha in the Midwest.

Our objective was to study the effects and interactions of landscape position and conservation management systems on basic soil hydraulic properties for a claypan soil toposequence. The studied properties included saturated hydraulic conductivity, water retention characteristics, pore-size distributions, and bulk density.

MATERIALS AND METHODS

Study Site and Experimental Design

The study site was a 12-ha plot area near Centralia in central Missouri (39°13′ N, 92°07′ W). The site lies on a sloping landscape (slopes ranging between 1 and 10%) encompassing three positions: summit, backslope, and footslope. The landscape positions were delineated based on a topographic map and on-site evaluation. The primary soils found at the site are Mexico (fine, smectitic, mesic Aeric Vertic Epiaqualfs), and Adco (fine, smectitic, mesic Vertic Albaqualfs) with a somewhat poorly drained classification. These soils are typical claypan soils characterized by an abrupt occurrence of a clay-rich layer (i.e, a claypan horizon, commonly silty clay or clay in texture) at varying depths from 10 cm at the backslope position to as deep as 40 cm at the footslope position. The clay contents with soil depth at these landscape positions, along with other soil properties, are given in Table 1. The texture of the soil above the claypan is mostly silt loam and silty clay loam. The mean annual temperature is 12°C, and the mean annual precipitation is 96.9 cm (National Climate Data Center, 2002).

These plots, originally including five management systems, were established in 1991 for evaluation of tillage and rotation effects on crop production and environmental impact. The experimental design was a randomized block design with three blocks, and all rotation phases of each management system were present each year in each block. Each plot measures 189 by 30 m (0.35 ha in area) running east–west parallel to the slope direction. In this study, four management systems (two cropped and two grass) were selected for investigation. Description of the selected management systems, along with management information, and time of initiation are given in Table 2. Additional description of these research plots and management systems can be found in Ghidey et al. (2005). To establish the HAY system in 2001, the CRP plots were split longitudinally into three subplots to accommodate two more grass management systems with HAY being one of them. The CRP grasses were sprayed with glyphosate [*N*-(phosphonomethyl)glycine] and then disked twice to a 15- to 20-cm depth before replanting with hay grasses. The grass treatments were randomly assigned to the subplots.

Sampling Procedures

Soil sampling was conducted on 19 and 20 May 2005. For the row-crop treatments (MTCS and NTCSW), the previous crop was corn. The MTCS plots were tilled on 17 March and 2 May using a cultivator. The last harvest cutting on the HAY plots was in October 2004. Undisturbed soil cores (76-mm diam. by 76-mm height) were independently taken from soil depths of 0 to 10, 10 to 20, and 20 to

Table 2. Description of the four management systems selected for the study, along with management information.

Acronym	Description	Initiation	Fertilizer input	Yield goal
MTCS	Mulch tillage with a corn–soybean rotation	1991	190 kg N ha^{-1} for corn; lime, P, and K by soil test.	10 100 kg ha^{-1} for corn; 2500 kg ha^{-1} for soybean
NTCSW	No-till (since 1996) with a corn–soybean–wheat rotation with a red clover cover crop following wheat	1991	150 kg N ha^{-1} for corn; lime, P, and K by soil test	8700 kg ha^{-1} for corn; 2500 kg ha^{-1} for soybean; 4031 kg ha^{-1} for wheat
CRP	Conservation Reserve Program: predominant species ~95% tall fescue by 2000, orchardgrass, and red clover	1991	None	None
HAY	Hay crop: predominant species white clover, orchardgrass, big bluestem, and Canada wild rye	2001	90 kg N ha^{-1} yr^{-1}; lime, P, and K by soil test	9000 kg ha^{-1} yr^{-1}; 2–3 harvest cuttings yr^{-1}

30 cm. In each block, one core sample was collected at each treatment combination (management × landscape position × soil depth). This procedure yielded 108 sample cores. In the cropped plots, samples were taken in the untrafficked interrow position with a consistent distance from nearby crop rows. The soil cores were trimmed and each sealed in a plastic bag on site, and stored at 4°C in the laboratory until measurements were made. A map of the depth to claypan was used to confirm that, at the all sampling locations, the claypan was approximately 20 cm deep at the summit position, 10 cm at the backslope position, and 30 cm at the footslope position. An additional core was collected at the 30- to 40-cm depth, within the claypan horizon, at each footslope location (a total of 12 additional cores). Soil bulk density, K_{sat}, and water retention characteristics were experimentally determined on these soil cores, and pore-size distributions based on water retention information were calculated.

Laboratory Analyses

Cores were covered at the lower end with cheesecloth and saturated gradually from the lower end in tubs for at least 48 h. Then K_{sat} measurements were conducted using either the constant-head method (K_{sat} value ≥1.0 mm h^{-1}) or falling-head method (K_{sat} value <1.0 mm h^{-1}) as described by Reynolds and Elrick (2002). Sample cores were resaturated for water retention measurements. Water retention was measured sequentially at 0, −0.4, −1, −2.5, −5, −10, and −20 kPa soil water pressures in Buchner funnels (Dane and Hopmans, 2002). Subsequently, sample cores were air dried at 37°C to a constant weight. A subsample of about 50 g was oven dried to determine air-dry water content for each sample core. Then bulk density was calculated using air-dry soil mass, water content of the air-dried subsample, and core volume. The remaining sample cores were broken apart, and small aggregates were used to determine water retention at −33 and −100 kPa using pressure chambers.

Effective pore sizes were determined from water retention measurements using the capillary rise equation (Hill et al., 1985). Pore size classes determined were 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.) as used in Anderson et al. (1990). Total porosity was assumed to be equal to volumetric water content at saturation.

Statistical Analyses

The experiment was treated as a split-split-plot design with management (M) being the main plot, landscape position (LP) being a split plot, and soil depth (D) being a split-split plot. Note that landscape position and soil depth cannot be randomized (Tomer et al., 2006; Seobi et al., 2005). Based on the sampling scheme used, however, soil core samples taken from different landscape positions and soil depths were assumed independent. Analysis of variance was conducted for the logarithm of K_{sat} (log-transformed to correct high skewness), bulk density, water retention at all soil water pressures, and four pore sizes using PROC MIXED in SAS (SAS Institute, 2005). Block was treated as a random effect. Mean separations were performed when P values for the F test were ≤0.05 using LSD. Significant interaction effects (P values ≤0.05, unless otherwise indicated) were further analyzed using the SLICE option within the LSMEANS statement in the procedure. The SLICE option partitions the interaction of two factors so that each factor can be tested at different levels of the other factor (Schabenberger and Pierce, 2002; SAS Institute, 2005). A detailed breakdown of degrees of freedom was included with ANOVA results for bulk density and K_{sat} as an example below; these were the same in analyses for all other soil properties.

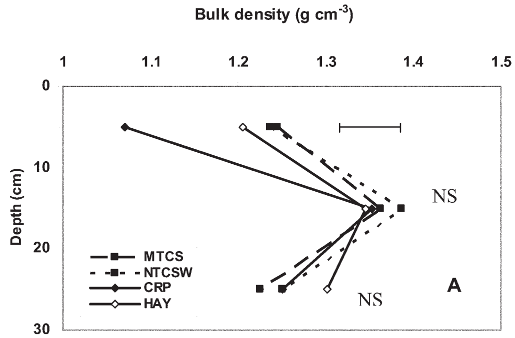
RESULTS AND DISCUSSION

Bulk Density

Bulk density was affected by management systems as shown in Table 3. Slicing the management effect by depth showed that management effects were limited to the 0- to 10-cm depth. At this depth, the ascending order of bulk density was CRP (1.07 g cm^{-3}) < HAY (1.21 g cm^{-3}) = NTCSW (1.24 g cm^{-3}) = MTCS (1.25 g cm^{-3}; Fig. 1A). The CRP treatment exhibited a consistently lower bulk density than other management treatments across landscape positions due to a marked abundance of roots and biopores. The HAY management, however, did not exhibit a statistical difference from the two row-crop management treatments. The HAY treatment had been established for only 4 yr

Table 3. Analysis of variance summary for bulk density and saturated hydraulic conductivity (K_{sat}), along with degrees of freedom (n = 108).

Source of variation	df	ANOVA $P > F$	
		Bulk density	K_{sat}
Block	2	–	–
Management (M)	3	0.021	0.003
Error(1)	6		
Landscape position (LP)	2	<0.001	<0.001
M × LP	6	0.27	0.058
Error(2)	16		
Depth (D)	2	<0.001	<0.001
M × D	6	<0.001	0.28
Error(3)	16		
LP × D	4	<0.001	<0.001
M × LP × D	12	0.14	0.26
Error(4)	32		
Total	107		



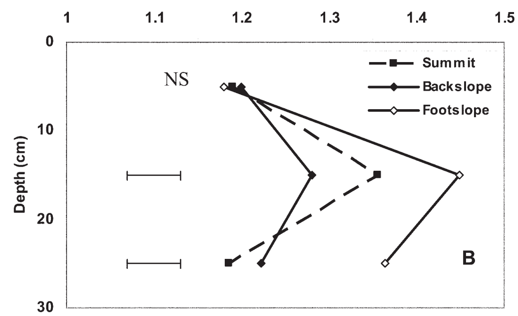


Fig. 1. Effects of (A) management and depth on bulk density (MTCS = mulch tillage, corn–soybean, NTCSW = no-till, corn–soybean–wheat, CRP = Conservation Reserve Program; bar indicates LSD values for management; LSD is identical for all depths; NS = not significant), and (B) landscape position and depth on bulk density (bar indicates LSD values for landscape position; LSD is identical for all depths; NS = not significant).

since being converted from CRP. More importantly, uncontrolled management trafficking for fertilizer applications and harvest (five or more passes per year) could compact the soil relative to CRP. There were no significant differences in bulk density between MTCS and NTCSW treatments in the 0- to 10-cm depth.

Table 4. Main effect means for bulk density and saturated hydraulic conductivity (K_{sat}). Main effects are management, landscape position, and soil depth.

Main effect	Bulk density	K_{sat}
	g cm^{-3}	mm h^{-1}
Management†		
MTCS	1.28b‡	4.3b
NTCSW	1.29b	11.0b
CRP	1.22a	20.2a
HAY	1.28b	11.4b
Landscape position		
Summit	1.24a	15.9a
Backslope	1.23a	3.4b
Footslope	1.33b	19.7a
Depth		
0–10 cm	1.19a	29.3a
10–20 cm	1.36c	13.9b
20–30 cm	1.26b	2.6c

† MTCS, mulch tillage with a corn–soybean rotation; NTCSW, no-till with a corn–soybean–wheat rotation; CRP, Conservation Reserve Program; HAY, hay crop.

‡ Within a column, treatment levels with the same letter are not significantly different.

Among landscape positions, bulk density was the highest at the footslope position (Table 4). The statistical significance came from higher bulk density at the 10- to 20- and 20- to 30-cm depths as shown on the landscape position × depth interaction plot (Fig. 1B). The footslope position receives runoff water, lateral flow, and seepage from upper slope positions. Soil at the footslope positions may remain wetter for more extended time periods, and thus be more susceptible to root-zone compaction when trafficked.

By soil depth, bulk density was the lowest (1.19 g cm^{-3}) at the 0- to 10-cm depth, and highest (1.36 g cm^{-3}) at the 10- to 20-cm depth (Table 4). These values were comparable with values found in a study conducted on similar soils (Vertic Epiaqaulfs) by Seobi et al. (2005).

Saturated Hydraulic Conductivity

Management system effects on K_{sat} were significant (Table 3). The descending order of K_{sat} among management treatments was CRP (20.2 mm h^{-1}) > HAY (11.4 mm h^{-1}) = NTCSW (11.0 mm h^{-1}) = MTCS (4.3 mm h^{-1}; Table 4). Saturated hydraulic conductivity for CRP management at the 0- to 10-cm depth was remarkably high, reaching 125.6 mm h^{-1} (Fig. 2A) due to substantially more connected biopores and a lower bulk density (Fig. 1A), which resulted from intensified perennial grass roots. Studies have shown that the restoration of soil hydraulic conductivity under grass management varied with location and time since establishment of that management system. For example, Mazurak et al. (1960) reported that infiltration rates under perennial grasses within 16 yr of establishment approached those for native grassland on a silt loam soil in Nebraska, while Schwartz et al. (2003) found little impact of CRP management on improving hydraulic conductivity on fine-textured soils after a 10-yr period on the southern Great Plains.

The management × landscape position interaction was marginally significant ($P = 0.058$) and is illustrated in Fig. 2B. Management effects on K_{sat} were of different statistical significance among the landscape positions. The management effects were strongly significant at the backslope position ($P < 0.001$, not shown), and not significant at the other two landscape positions. At the backslope position, the descending order of K_{sat} was CRP (10.9 mm h^{-1}) = HAY (6.6 mm h^{-1}) = NTCSW (2.9 mm h^{-1}) > MTCS (0.64 mm h^{-1}). In general, the backslope is the most eroded landscape position and is characterized by a thinner topsoil layer (varied from 0–10 cm in the study area) and higher clay content and, hence, a lower infiltration rate. Creation of macropores and amendment of soil structure by grasses in CRP and HAY treatments, and possibly by the red clover cover crop in the NTCSW treatment, markedly improved water flow through an otherwise high-clay-content and slowly permeable soil. Conversely, it was the most challenging to improve K_{sat} at the backslope position when managed with tillage (even conservation tillage) and row crop rotation.

Saturated hydraulic conductivity generally decreased with depth, but changes were not consistent for different landscape positions (Table 3). This interaction (landscape position × depth) is illustrated in Fig. 3, which shows that the most dramatic decrease in K_{sat} with depth was at the backslope position because the clay content increased more rapidly with depth than it did at the summit and footslope positions. At the backslope position, K_{sat} was about 29% (6.1 mm h^{-1}) of the average value for the summit and footslope positions (21.0 mm h^{-1}) at the 10- to 20-cm depth, and only about 2.2% at the 20- to 30-cm depth (0.21 vs. 9.4 mm h^{-1}). At the footslope position, K_{sat} decreased to 0.83 mm h^{-1} at the 30- to 40-cm depth (not shown), one-tenth that at 20 to 30 cm, since the claypan occurred at that depth. These results present evidence that the claypan horizon is a controlling factor on soil hydraulic processes based on its differential depth occurrence within a landscape.

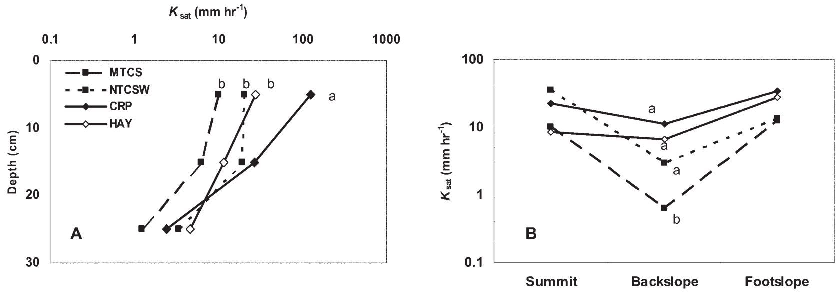


Fig. 2. Effects of (A) management and depth on saturated hydraulic conductivity (K_{sat}) (MTCS = mulch tillage corn–soybean, NTCSW = no-till corn–soybean–wheat, CRP = Conservation Reserve Program; treatment levels with the same letter are not significantly different within a soil depth; LSD = 32.9 mm h^{-1}), and (B) management and landscape position on K_{sat} (treatment levels with the same letter are not significantly different within a landscape position; LSD = 39.6 mm h^{-1}).

Soil Water Retention

Management effects were significant at 0, −0.4, and −1 kPa soil water pressures for the 0- to 10-cm depth (Fig. 4). At the 0- to 10-cm depth, the saturated water content for CRP (0.56 m^3 m^{-3}) was 10, 14, and 19% higher than that for HAY (0.51 m^3 m^{-3}), NTCSW (0.49 m^3 m^{-3}), and MTCS (0.47 m^3 m^{-3}), respectively. Water content was also higher for CRP and HAY management than values for MTCS from saturation to −1 kPa pressure (Fig. 4A). These results agreed with those of Seobi et al. (2005), where statistical differences in water retention among row crop, grass buffer, and tree buffer treatments occurred in the same soil water pressure range. Differences in water retention among management treatments diminished as soil water pressure decreased (less than −1 kPa), confirming that management effects on water retention were limited to the high soil water pressure range (greater than −1 kPa) due to management modifying pore sizes in this range. Between the two row-crop management treatments, even though differences were never significant, water content for the NTCSW treatment was consistently higher than values for the MTCS treatment at all soil water pressures. There was no management effect observed in the 10- to 20- and 20- to 30-cm depths (Fig. 4B and 4C).

Landscape position, soil depth, and lanscape position × depth effects on water retention were significant at all soil water pressures (Table 5). Averaged across management and depth, the backslope position had the highest water content at all soil water pressures, and the summit had higher water content than the footslope position at all soil water pressures except for-20 and-33 kPa (Table 5). Significant differences among landscape positions occurred for the 10- to 20- and 20- to 30-cm depths (Fig. 5). The backslope position had the shallowest claypan occurrence (∼10 cm), which caused more water to be retained at a given soil water pressure than at the summit and footslope positions. Water retention at the backslope

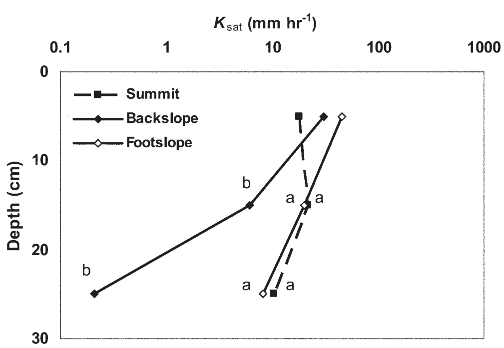


Fig. 3. Effects of landscape position and depth on saturated hydraulic conductivity (K_{sat}) (treatment levels with the same letter are not significantly different within a soil depth; LSD = 32.9 mm h^{-1}). The K_{sat} value decreased to 0.83 mm h^{-1} at 30- to 40-cm depth for the footslope position (not shown).

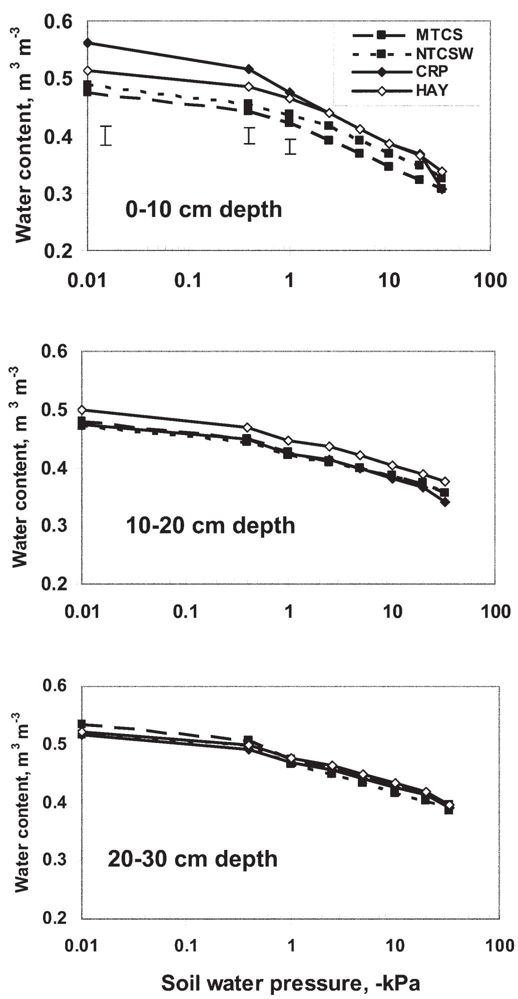


Fig. 4. Management effects on soil water retention by depth (MTCS = mulch tillage corn–soybean, NTCSW = no-till corn–soybean–wheat, CRP = Conservation Reserve Program; bars indicate LSD values, when significant, for management at a given soil water pressure).

Table 5. Analysis of variance summary and main effect means for water content (θ) at soil water pressures ranging from 0.0 to-33 kPa. Main effects are management, landscape position and soil depth (n = 108).

Source of variation	ANOVA $P > F$							
	0.0 kPa	−0.4 kPa	−1 kPa	−2.5 kPa	−5.0 kPa	−10.0 kPa	−20.0 kPa	−33.0 kPa
Block	–	–	–	–	–	–	–	–
Management (M)	0.16	0.14	0.007	0.082	0.18	0.35	0.48	0.52
Landscape position (LP)	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
M × LP	0.15	0.65	0.69	0.70	0.70	0.67	0.63	0.80
Depth (D)	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
M × D	0.002	0.004	0.034	0.12	0.22	0.20	0.13	0.83
LP × D	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	0.013
M × LP × D	0.33	0.44	0.96	0.98	0.99	0.99	1.0	0.98
	θ means†, m^3 m^{-3}							
Management‡								
MTCS	0.50	0.47	0.44b	0.42	0.40	0.39	0.37	0.35
NTCSW	0.49	0.47	0.44b	0.42	0.41	0.39	0.37	0.36
CRP	0.52	0.49	0.46a	0.44	0.42	0.40	0.38	0.35
HAY	0.51	0.48	0.46a	0.45	0.43	0.41	0.39	0.37
Landscape position								
Summit	0.51b	0.48b	0.45b	0.43b	0.41b	0.39b	0.37b	0.35b
Backslope	0.53a	0.50a	0.48a	0.46a	0.44a	0.43a	0.42a	0.39a
Footslope	0.48c	0.45c	0.43c	0.41c	0.39c	0.37c	0.36b	0.33b
Depth								
0–10 cm	0.51a	0.47b	0.45b	0.42b	0.40b	0.37c	0.35c	0.32c
10–20 cm	0.48b	0.45c	0.43c	0.42b	0.40b	0.39b	0.38b	0.36b
20–30 cm	0.52a	0.50a	0.47a	0.46a	0.44a	0.43a	0.41a	0.39a

† Mean comparisons were made only when P values for the main effects were ≤0.05. Treatment levels with the same letter are not significantly different within a main effect for a given soil water pressure.

‡ MTCS, mulch tillage with a corn–soybean rotation; NTCSW, no-till with a corn–soybean–wheat rotation; CRP, Conservation Reserve Program; HAY, hay crop.

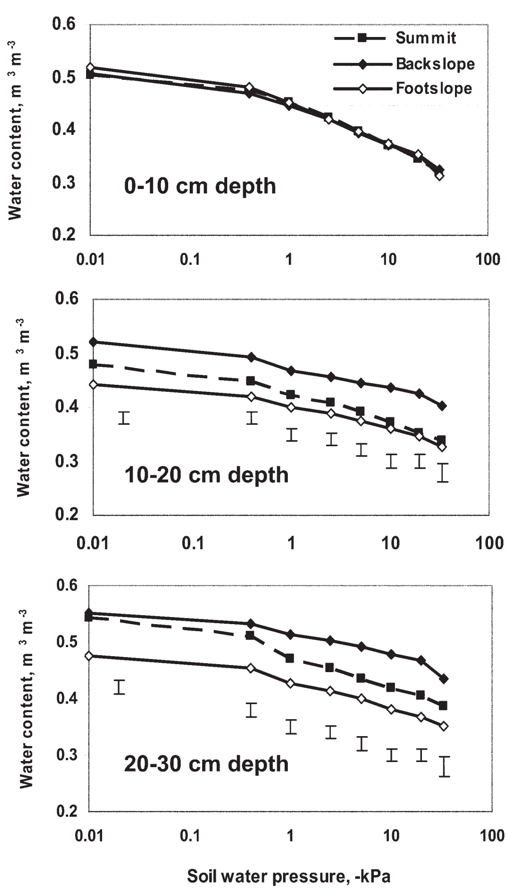


Fig. 5. Landscape effects on soil water retention by depth (bars indicate LSD values, when significant, at a given soil water pressure; LSD is identical for all depths at a given soil water pressure).

continued to increase and to be the highest among landscape positions at 20 to 30 cm as clay content approached or reached its maximum, while this effect only occurred at deeper depths for the summit and footslope positions (Table 1).

Pore-Size Distributions

The three-way interaction (management × landscape position × depth) for macroporosity was significant (P = 0.050; Table 6). Two-way slicing landscape position × depth (to examine management effect) showed that macroporosity was higher for HAY (0.036 m^3 m^{-3}) than for MTCS and NTCSW (both 0.012 m^3 m^{-3}) at the backslope position for the 20- to 30-cm depth, with P values of 0.014 and 0.011, respectively (not shown). This result was probably due to a greater volume of roots and deeper rooting depth of HAY grasses than those of row crops; these grass roots created more fine-root channels and improved soil structure. This effect was most pronounced at the backslope position, where clay content was highest at that depth. Further, macroporosity for MTCS (0.020 m^3 m^{-3}) was the lowest at the summit position for the 0- to 10-cm depth among all management treatments, while it was the highest among all management treatments at the same position for the 20- to 30-cm depth (0.054 m^3 m^{-3}). Soil variability may have caused macroporosity to be higher for the MTCS treatment at this depth for the summit position.

At the 0- to 10-cm depth, the CRP treatment showed a consistent trend of higher macroporosity (0.045 m^3 m^{-3}), coarse mesoporosity (0.105 m^3 m^{-3}), and fine mesoporosity (0.104 m^3 m^{-3}) than values for the other three management treatments, which had averages of 0.032 m^3 m^{-3}, 0.070 m^3 m^{-3}, and 0.068 m^3 m^{-3}, respectively, even though statistical differences occurred only for coarse mesoporosity (Fig. 6A–6C).

Table 6. Analysis of variance summary and main effect means for macroporosity (>1000 μm), coarse mesoporosity (60–1000 μm), fine mesoporosity (10–60 μm), and microporosity (<10 μm). Main effects are management, landscape position, and soil depth (n = 108).

Source of variation	ANOVA $P > F$			
	Macroporosity	Coarse mesoporosity	Fine mesoporosity	Microporosity
Block	–	–	–	–
Management (M)	0.41	0.24	0.12	0.52
Landscape position (LP)	0.49	0.009	0.88	< 0.001
M × LP	0.048	0.19	0.92	0.80
Depth (D)	<0.001	<0.001	<0.001	<0.001
M × D	0.075	0.009	0.060	0.84
LP × D	0.023	0.002	0.078	0.013
M × LP × D	0.050	0.068	0.53	0.98
	Means†, $m^3\ m^{-3}$			
Management‡				
MTCS	0.030	0.066	0.050	0.35
NTCSW	0.027	0.056	0.052	0.36
CRP	0.030	0.068	0.070	0.35
HAY	0.028	0.058	0.058	0.37
Landscape position				
Summit	0.031	0.069a	0.060	0.35b
Backslope	0.029	0.054b	0.057	0.39a
Footslope	0.027	0.063b	0.056	0.33b
Depth				
0–10 cm	0.035a	0.079a	0.077a	0.32c
10–20 cm	0.027b	0.049b	0.048b	0.36b
20–30 cm	0.025b	0.056b	0.051b	0.39a

† Mean comparisons were made only when P values for the main effects were ≤0.05. Treatment levels with the same letter are not significantly different within a main effect for a given pore size class.

‡ MTCS, mulch tillage with a corn–soybean rotation; NTCSW, no-till with a corn–soybean–wheat rotation; CRP, Conservation Reserve Program; HAY, hay crop.

Furthermore, when macroporosity and coarse mesoporosity were summed, the difference between CRP (0.15 $m^3\ m^{-3}$) and the average of the other three management treatments (0.10 $m^3\ m^{-3}$) was significant ($P < 0.001$, not shown). Macropores provide channels for water to move rapidly through the soil profile, with mesopores also contributing to improved water transport within the soil profile (Wilson and Luxmoore, 1988). Collectively, the abundance of these larger pores gave rise to the higher K_{sat} values measured for the CRP treatment as discussed above. Other researchers have also found higher porosity for perennial grass than for cropland. For example, Rachman et al. (2004) found that total porosity, macroporosity, and coarse mesoporosity under warm-season grass hedges were 11, 137, and 28% higher than those under tilled cropland in the top 40 cm of a deep loess soil (Typic Hapludoll). Seobi et al. (2005) found more total porosity and coarse mesoporosity under grass buffers than under no-till corn–soybean management for the first 0 to 10 cm after 8 yr of grass buffer establishment. For the HAY treatment, we did not find a higher macroporosity or mesoporosity than values for MTCS or NTCSW across landscape positions at the 0- to 10-cm depth (Fig. 6A–6C). This suggests that the single seedbed preparation during the initiation of the HAY treatment combined with uncontrolled harvest traffic may have disrupted the improvement in soil structure gained during 10 yr of CRP. Microporosity was not affected by management at any depth (Fig. 6D). An increasing trend of microporosity with depth was observed, which is a result of increasing clay content with soil depth.

On average, macroporosity decreased with depth at the backslope and footslope positions, as the management effect decreased to virtually nill below the surface 10 cm (Fig. 7A). Again, higher macroporosity at the 20- to 30-cm depth for the summit position than for the other two positions was caused by MTCS, as discussed above (Fig. 7A). Coarse mesoporosity was lowest at the backslope position for the 20- to 30-cm depth (Fig. 7B) as a consequence of higher clay content at that position in the landscape. Microporosity was the same for all landscape positions at the surface depth, but significantly increased with

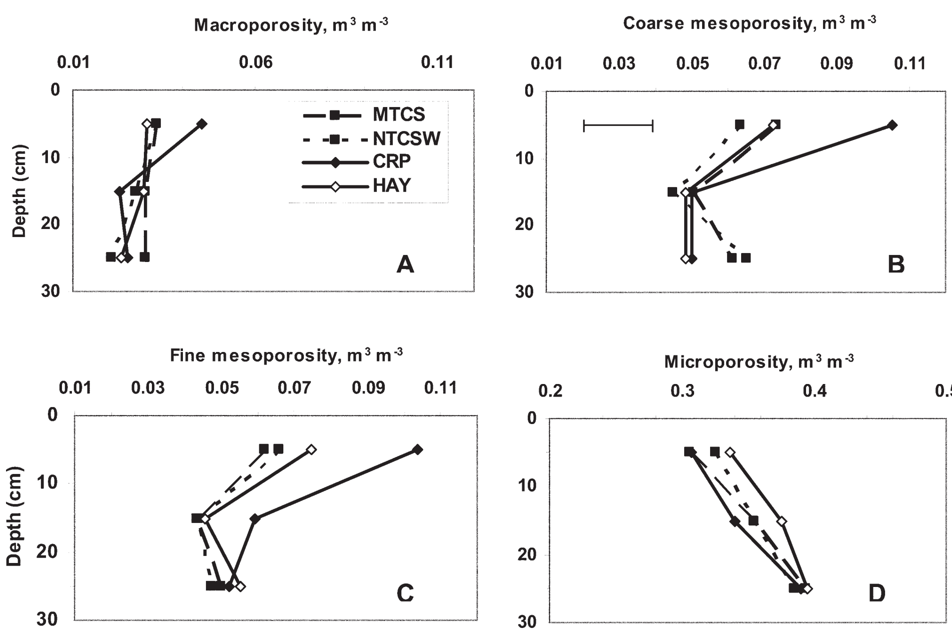


Fig. 6. Effects of management and depth on pore-size distributions of (A) macroporosity (>1000-μm diam.), (B) coarse mesoporosity (60–1000-μm diam.), (C) fine mesoporosity (10–60-μm diam.), and (D) microporosity (<10-μm diam.) (MTCS = mulch tillage corn–soybean, NTCSW = no-till corn–soybean–wheat, CRP = Conservation Reserve Program; bar indicates LSD value, when significant, among management treatments within a depth; LSD is identical for all depths for a given pore size class). Note scale difference in (D).

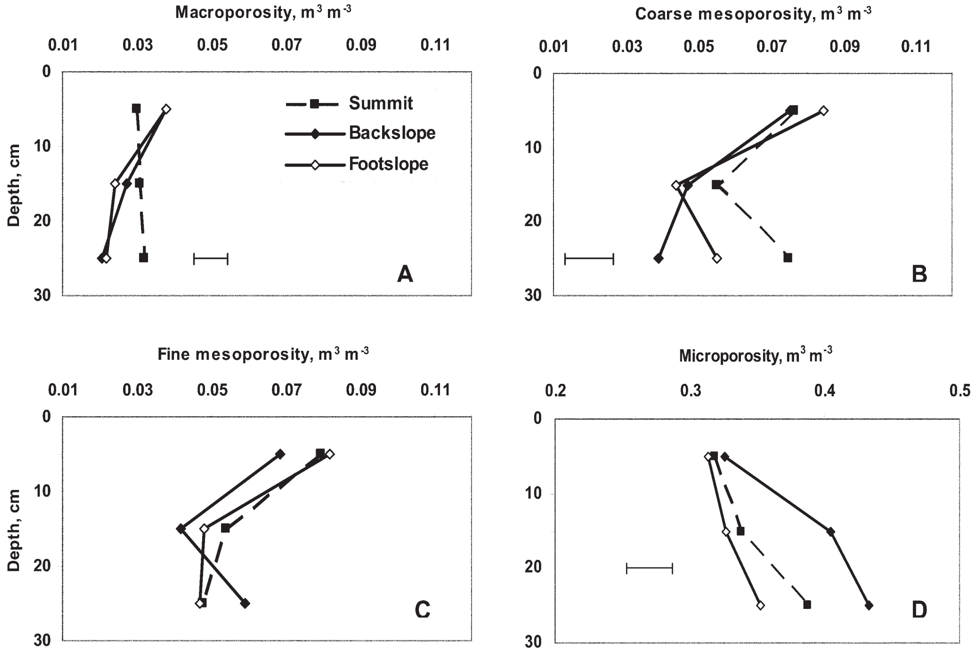


Fig. 7. Effects of landscape position and depth on pore-size distributions of (A) macroporosity (>1000-μm diam.), (B) coarse mesoporosity (60–1000-μm diam.), (C) fine mesoporosity (10–60-μm diam.), and (D) microporosity (<10-μm diam.) (bars indicate LSD values, when significant, among landscape positions within a soil depth; LSD is identical for all depths for a given pore size class). Note scale difference in (D).

soil depth at the backslope position (Fig. 7D). Again, microporosity increased with increasing clay content below the 10-cm depth at the backslope position.

CONCLUSIONS

In a toposequence setting, we examined the effects of four conservation management systems (MTCS, NTCSW, CRP, and HAY) on soil bulk density, K_{sat}, water retention characteristics, and pore-size distributions for three soil depths (0–10, 10–20, and 20–30 cm) as influenced by landscape position (summit, backslope, and footslope). Our results showed that most of the management effects occurred at the surface 0- to 10-cm depth, and that management effects varied among landscape positions. The most noticeable examples were that, at the backslope position, K_{sat} for MTCS was 10% and macroporosity was 33% of the average of the other management treatments. These results show that at the backslope position, where topsoil is the shallowest, even row cropping with conservation tillage such as mulch tillage may further degrade soil hydraulic properties. Alternatively, the backslope position showed the most pronounced improvement in K_{sat} and macroporosity when managed in permanent grass. In this study, the CRP management improved most soil physical properties among the conservation management systems evaluated (i.e., decreased bulk density, increased K_{sat}, increased water retention, and increased fraction of larger pores). The MTCS, on the other hand, was the least favorable management system for the hydraulic properties studied.

The claypan horizon at varying depth in the landscape was the controlling factor for practically all soil hydraulic properties examined below the 10-cm soil depth. The depth where the claypan occurs and the thickness of the surface horizon are not random with regard to landscape position. Usually, the claypan controls hydraulic properties at the backslope position at a shallower depth than it does at the summit and footslope positions. Our findings suggest that for similar claypan soil landscapes, use of perennial grasses in rotation (or permanently) will benefit soil hydraulic properties, particularly at slope positions most vulnerable to degradation where soil condition cannot be improved by row-crop conservation systems.

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