Hydraulic Properties in a Silt Loam Soil under Natural Prairie, Conventional Till, and No-Till

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ABSTRACT

Tillage in the Palouse region of Washington State over the past 100 yr has influenced the soil physical and biological properties. In particular, hydraulic properties are significantly affected by soil cultivation. The objectives of this study were to assess the temporal patterns of soil hydraulic properties under three management systems, natural prairie (NP), conventional till (CT), and no-till (NT), and to compare hydraulic properties between these three systems. Saturated and near-saturated hydraulic conductivities (up to −15 cm-H_2O hydraulic head), and soil water retention curves were determined using intact soil cores taken from the top 10 cm of soil. Soils were sampled at six different times during a period of 1.5 yr from a NP, a long-term (>100 yr) CT, and a 27-yr-old NT system. The NP represented the original soil and natural vegetation of the area. Significant temporal variation in hydraulic conductivity was found. Temporal variation was most evident in the NP soil, where organic matter content was twice as large as under the CT and NT soils. Hydraulic conductivities in the NP were about one order of magnitude larger than in the cultivated soils. In NT, saturated hydraulic conductivities in the top 5 cm of soils were significantly larger than in CT. No-till and CT soils had similar near-saturated hydraulic conductivities, indicating that even 27 yr of continuous NT could not restore the original hydraulic properties of the soil. Restoration of original hydraulic properties in cultivated former prairie soils may take considerably longer.

Hydraulic conductivity depends on soil structure, which varies in both space and time. Temporal variation of hydraulic conductivity is caused by growth and decay of plant roots (Meek et al., 1992), activity of soil organisms (Beven and Germann, 1982; Willoughby et al., 1996), precipitation that forms surface crusts (Messing and Jarvis, 1993), shrinking and swelling (Messing and Jarvis, 1990; Bagarello et al., 1999), freezing and thawing (Scott et al., 1994), and agricultural activities, such as tillage and wheel-traffic compaction (Ankeny et al., 1990; Logsdon and Jaynes, 1996).

Tillage operations affect hydraulic conductivities in contrasting ways. Tillage, especially plowing, creates macropores that cause saturated and near-saturated hydraulic conductivities to increase considerably, but also disrupts pore continuities that reduce hydraulic conductivities between plow layers and subsoils (Bouma, 1991). Shortly after tillage, saturated and near-saturated hydraulic conductivities in the topsoil are usually large and decrease with time due to reconsolidation of soil particles (Cassel and Nelson, 1985; Messing and Jarvis, 1993). No-till systems and nonagricultural soils do not undergo this dramatic cyclic change in soil structure; although seasonal variations in hydraulic conductivities occur through root development, earthworm activity, and other natural processes such as freezing and thawing, or shrinking and swelling.

Soil compaction can also alter hydraulic conductivity. Soil compaction, mostly caused by wheel traffic, destroys large pores, thereby reduces saturated and near-saturated hydraulic conductivities (Ankeny et al., 1990; Heddadj and Gascuel-Odoux, 1999). The effects of soil compaction vary with soil type and management. Under no-till systems, wheel traffic may cause compaction of the soil matrix and results in reduction of saturated and near-saturated hydraulic conductivities, but biological effects, such as root channels and earthworm burrows may counteract the compaction-induced reduction of the conductivities (Gantzer and Blake, 1978; Ankeny et al., 1990).

Because of the many factors affecting the hydraulic conductivity, a temporal pattern may be difficult to observe (Logsdon, 1993). Sometimes, certain factors are more dominant than others, allowing us to discern temporal patterns. For instance, saturated and near-saturated hydraulic conductivities can increase from a wet to dry season due to the formation of cracks, particularly in soils that shrink and swell (Jabro, 1996; Azevedo et al., 1998). Decreases of saturated and near-saturated hydraulic conductivities occur when soil particles reconsolidate, especially after tillage operations, when raindrop impact causes sealing of the soil surface, and when root growth clogs pre-existing pores (Messing and Jarvis, 1993; Angulo-Jaramillo et al., 1997; Suwardji and Eberbach, 1998). The effect of roots on saturated and near-saturated hydraulic conductivities is closely related to the physiological stage of the root system. Living roots can create new pores, but also use pre-existing root or earthworm channels for growth, thereby reducing hydraulic conductivities. When roots decay, they leave behind empty pores through which water can flow rapidly (Murphy et al., 1993). Wetting and drying cycles near to the root systems can also create new pores and cracks (Rasse et al., 2000). The activity and type of root systems can play a pronounced role in temporal variation of hydraulic conductivities. Increases in infiltration rates from spring to late summer in an irrigated montmorillonitic soil have been linked to decaying roots of perennial plants, which can create more stable pores as compared with annual plants (Mitchell et al., 1995).

Most of the studies conducted in cultivated soils have associated the changes in hydraulic conductivities with variations in soil structure due to tillage. Few studies have assessed the long-term effect of farming on hydraulic conductivities. The prairie in eastern Washington, which has been cultivated since the late 1870s (Michal-

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Table 1. Agronomic practices under the conventional tillage (CT) and no-till (NT) sites during the course of the study.

Year	Crop	Planting date	Harvesting date	Type and time of tillage operations prior and during planting: Primary	Secondary
			Conventional till		
2001	Soft white spring wheat	12 Apr. 2001	August 2001	Moldboard plow; 17 Oct. 2000	Field cultivator and harrow; 10 Apr. 2001
2002	Spring peas	17 Apr. 2002	August 2002	Moldboard plow; 20 Oct. 2001	Field cultivator and harrow; 15 Apr. 2002
			No-till		
2001	Soft white winter wheat	28 Sept. 2000	July 2001	None	None
2002	Soft white spring wheat	15 May 2002	August 2002	None	None

son, 1999), offers a unique opportunity to compare hydraulic properties before and after cultivation. Conversion from natural to agricultural systems causes a progressive change in soil properties (Low, 1972; Scott and Wood, 1989). Hydraulic conductivities can decrease considerably in the top soil due to the effect of long-term tillage operations (Scott et al., 1994; Schwartz et al., 2003).

The objectives of this study were (i) to analyze the temporal pattern, both seasonal and from one year to another, of soil hydraulic properties under three different long-term management systems: a NP soil that has never been tilled, a CT soil that is plowed annually, and a NT soil that was under no tillage for 27 yr; and (ii) to compare hydraulic properties between the different management systems. Before farming in the region about 130 yr ago, the soils developed under identical climate, relief, time, parent material, and presumably also vegetation. Differences in hydraulic properties between the soils can therefore be attributed to different management practices.

MATERIALS AND METHODS

Site Selection and Characterization

The soil sites were located in the Palouse region of eastern Washington State, USA, near the city of Pullman. The climate type of this zone is Mediterranean with an annual precipitation averaging 544 mm and mean annual air temperature of 8.3°C from 1940 to 1995 (Earthinfo, 1995). Selected soils were managed as a NP, a CT, and a NT.

The NP and CT soils were located adjacent to each other 32 km south of Pullman (46°34′ N lat., 117°12′ W long.) on an upper-slope landscape position, a 3 to 5% slope, and northeastern aspect. The NP was located in the Kramer Palouse Natural Area owned by Washington State University. The NP soil has never been disturbed, and represents one of the best examples of the natural soil and vegetation of the region (Despain and Harris, 1983). The natural vegetation of the site has been classified as *Festuca idahoensis*/*Symphoricarpos albus* association (Daubenmire, 1988). The natural flora consists of perennial grasses (*Festuca idahoensis*, *Agropyron spicatum*, *Koelaria cristata*), shrubs dominated by snowberry (*Symphoricarpos albus*), wild roses (*Rosa nutkana* and *R. woodsii*), and broad-leaved perennial plants (Despain and Harris, 1983). It is considered that natural and human-induced grazing of the Palouse prairies has been of minor importance for more than 2000 yr (Despain and Harris, 1983). The CT field has been under a continuous 3-yr rotation of winter wheat (*Triticum aestivum* L.), spring wheat, and spring pea (*Pisum sativum*). During the course of this study, the CT soil was under the spring wheat/spring pea portion of the rotation.

The NT soil was located 20 km north of Pullman (46°55′ N lat./117°11′ W long.) and was on a upper-slope landscape position, a 3 to 5% slope, and northeastern aspect. The field had been under no tillage for 27 yr with a 3-yr rotation of winter wheat/spring wheat/lentil (*Lentis culinaris*), with occasional spring barley (*Hordeum vulgare* L.) in place of spring wheat and spring peas in place of lentils. The soil was under the winter wheat/spring wheat portion of the rotation during the course of this study. Previous to the establishment of NT, the soil was managed as CT farmland. Agronomic practices for CT and NT are shown in Table 1.

All three soils belong to the Palouse-Thatuna silt-loam (fine-silty, mixed, mesic Pachic Ultic Haploxerolls) series (Donaldson, 1980). All three soils had a similar soil texture, with the particle-size distribution dominated by the silt fraction (Table 2). The NP soil was higher in pH, higher in organic C content, and higher in total N content than the two cultivated soils (Table 2).

Table 2. Selected properties of the three soils.

Soil depth	pH: $CaCl_2$ (1:1)	Particle-size distribution†: Sand (50–2000 μm)	Silt (2–50 μm)	Clay (<2 μm)	Organic C‡	Total N‡
		% by weight				
			Natural prairie			
0–5 cm	6.3 (0.2)§	16.2 (1.5)	71.5 (1.0)	12.3 (0.6)	3.71 (0.10)	0.34 (0.02)
5–10 cm	6.1 (0.2)	16.3 (2.0)	71.4 (0.7)	12.3 (1.4)	3.19 (0.28)	0.29 (0.03)
			Conventional till			
0–5 cm	5.3 (0.1)	15.9 (0.9)	70.4 (0.1)	13.7 (0.8)	1.47 (0.24)	0.12 (0.02)
5–10 cm	5.3 (0.1)	16.0 (0.3)	70.5 (1.0)	13.5 (1.3)	1.43 (0.07)	0.12 (0.01)
			No-till			
0–5 cm	5.1 (0.1)	13.3 (1.0)	73.6 (1.9)	13.1 (2.2)	1.82 (0.23)	0.17 (0.02)
5–10 cm	4.8 (0.01)	12.8 (2.4)	74.0 (0.6)	13.2 (1.9)	1.34 (0.13)	0.12 (0.01)

† Measured using wet sieving and static light scattering (MasterSizer S, Malvern Instruments Ltd., Malvern, UK) after organic matter was removed by pretreatment.
‡ Measured by dry combustion with a LECO CHN Analyzer (Leco Corp., St. Joseph, MI).
§ Values in parentheses represent the standard deviation of the mean.

Soil Sampling

Soil samples were taken in 2001 on May 16 to 17, and November 30, and in 2002 on April 22 to 25, June 26 to 27, September 18 to 20, and December 7 to 11 from 20 by 20 m plots. At each sampling date, eight intact soil cores of 9-cm diam. and 10-cm depth were taken for hydraulic conductivity analysis, and five cores of 5.4-cm diam. and 9-cm depth were taken for soil water retention analysis. Crop and plant residues on the soil surface were removed before sampling. The cores were taken with a manual hammer-driven core sampler from random locations, which were determined using a random number generator. If the random location fell on a crop row or on a wheel track, then a new random location was chosen. Because of dry soil conditions in September 2002, the soil was wetted 1 d before sampling by infiltrating about 60 mm of well water at the sampling locations. The 10-cm deep soil cores were dissected in two depths (0–5 and 5–10 cm) and the 9-cm deep cores were dissected in three depths (0–3, 3–6, and 6–9 cm), and stored at 4°C.

Measurement of Hydraulic Properties

Hydraulic Conductivity

Saturated hydraulic conductivities (K_s) were measured with the constant-head method (Klute and Dirksen, 1986). Before K_s determination, soil cores were saturated from the bottom by placing the cores in a tray with about 2-cm deep, degased 5 m*M* $CaSO_4$ solution for 48 h.

Near-saturated hydraulic conductivities at low hydraulic heads (−1, −6, and −15 cm-H_2O) were measured with a steady state method using a tension-infiltrometer (Klute and Dirksen, 1986). The water level in the infiltrometer was monitored with a pressure transducer (PX 170, Omega Engineering Inc., Stamford, CT). The tension-infiltrometer was equipped with a nylon membrane of 30 cm-H_2O bubbling pressure (Nylon Mesh No 400, Gilson Company, Inc., Lewis Center, OH). A layer of glass beads (Glass Oxide C.A.S. No 65997-17-3, Potter Industries Inc., Canby, OR), <1 mm thick, was used between the nylon membrane and the soil samples to ensure good hydraulic contact (Reynolds and Zebchuk, 1996). A water manometer was used to check the hydraulic head inside the infiltrometer disk. The bottom boundary condition of the soil core was controlled by a suction table of fine sand, which was hydraulically connected to a hanging water column. The air-entry potential of the fine sand was −15.5 cm-H_2O, that is, the sand remains water saturated for potentials hydraulic heads between 0 and −15.5 cm-H_2O. Steady-state flow conditions were established by adjusting top and bottom boundary conditions to the same matric potential, so that the total potential difference between top and bottom of the column was only due to the gravitational potential difference. This results in a unit gradient condition (Hillel, 1998). Hydraulic conductivities were calculated using Darcy's law after constant flow rate was achieved. Measurements were made in hydraulic head sequences of −1, −6, and −15 cm-H_2O.

Assuming cylindrical pores and applying the Young-Laplace equation using a 0° solid-liquid contact angle, the pore diameters excluded from water flow at the different hydraulic heads are 3 mm at −1 cm-H_2O, 0.5 mm at −6 cm-H_2O, and 0.2 mm at −15 cm-H_2O. All these pores are usually considered macropores in soils, and we therefore denote the corresponding hydraulic conductivities as near-saturated.

Soil Water Characteristic

The soil water characteristic was determined for the range of 0 to −100 kPa (corresponding to hydraulic heads of 0 to −1019 cm H_2O). Before analysis, nylon membranes (Nylon Mesh No 400, Gilson Company, Inc., Lewis Center, OH) were attached at the bottom of each core with rubber bands. Cores were saturated from the bottom with a degased 5 m*M* $CaSO_4$ solution for 48 h. Some swelling was observed in the NP soils during saturation, however, the volume change during saturation was at most 3%, and considered part of the experimental error.

For water potentials ranging from 0 to −4.2 kPa, the measurements were made with the hanging water column method (Townend et al., 2000) using a Buchner funnel with a fritted disk (Pyrex, fritted disk No 36060, ASTM 40-60, Corning Inc., Acton, MA). For water potentials ranging from −10 to −100 kPa, a pressure plate extractor (Soilmoisture Equipment Corp., Goleta, CA) with 1-bar ceramic plates was used. At each pressure, soil cores were equilibrated for 96 h, weighed, and returned to the plate extractor for the next pressure step. At the end, soil cores were oven-dried at 105°C for 48 h to determine the porosity. The volumetric water contents determined at each pressure step were averaged over the five replicated soil cores.

Data Analysis

Soil water characteristics were analyzed using the van Genuchten relationship (van Genuchten, 1980)

$$\theta = \theta_r + (\theta_s - \theta_r)[1 + (\alpha h)^n]^{(1/n-1)} \qquad [1]$$

where θ is the volumetric water content and *h*, the hydraulic head. The parameters α (inverse of the air entry potential), *n* (associated with the pore-size distribution), θ_s (saturated water content), and θ_r (residual water content) were fitted to the experimental data using the RETC program (van Genuchten et al., 1991).

Analysis of variance (ANOVA) was used to test for differences in hydraulic conductivity between management systems (MS) and sampling time (TIME). The analysis made here is similar to the one employed by Scott et al. (1994). The ANOVA model considered a complete randomized design with two-way treatment structure (MS, TIME) with repeated measurements (DEPTH). Significant differences between MS, TIME, and the interaction between MS and TIME were tested using the replications within MS and TIME as the error term. Significant differences in depth (DEPTH) and the interactions DEPTH × MS, DEPTH × TIME, DEPTH × MS × TIME were tested with the total error of the model. Log-transformed (log *K*) data were used for the statistical analysis. Normality of the transformed distributions was examined by the Shapiro–Wilk test. We used the general linear model (GLM) to carry out the ANOVA using SAS 8.0 (SAS Institute, Cary, NC). If significant differences ($P < 0.05$) were found, we further analyzed the means with the least significant differences (LSD) procedure. The means of the logarithmically transformed variables are, if not noted otherwise, reported as geometric means, and the errors of the mean as 95% confidence intervals computed from the logarithmically transformed data (Sokal and Rohlf, 1995).

RESULTS AND DISCUSSION

Temporal Variation of Hydraulic Properties

The measurements of the hydraulic conductivities are summarized in Fig. 1. The statistical analysis indicates that there were significant differences in time (Table 3). Those differences were observed between the first two (May and November 2001) and the remaining sampling

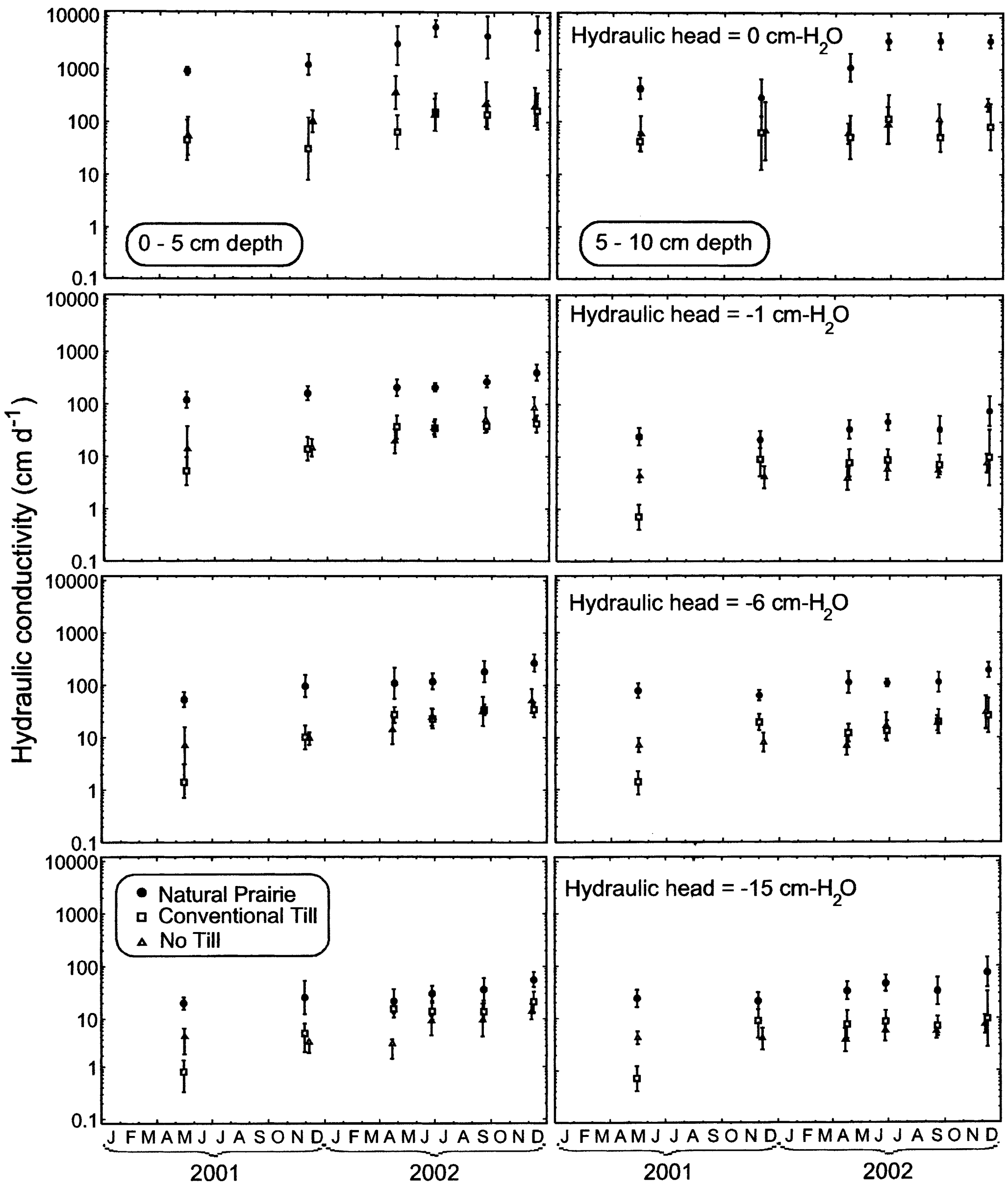

Fig. 1. Temporal variation of hydraulic conductivity for sampling depths 0 to 5 cm (left panels) and 5 to 10 cm (right panels). Symbols represent the geometric mean and the bars are 95% confidence intervals (n = 8).

times (2002). The first two sampling times showed significantly lower hydraulic conductivity than the later sampling periods. This was generally true for each management system, hydraulic head, and depth. We attribute the higher hydraulic conductivities in 2002 to the wetter soil conditions. After October 2001 cumulative precipitation increased considerably until October 2002 (Fig. 2). In soils with high organic matter content, such as the topsoils used in our study, soil pores may expand if soil moisture increases (Tsuboyama et al., 1994). Indeed, bulk density measurements corroborate that soil porosity was generally larger in 2002 than in 2001 (Fig. 2).

Table 3. Significant differences in hydraulic conductivities for the different treatments: management system (MS), sampling time (TIME), sampling depth (DEPTH), and the interactions between treatments.

Hydraulic conductivity	MS	TIME	DEPTH	MS × TIME	MS × DEPTH	TIME × DEPTH	MS × TIME × DEPTH
h = 0 cm-H$_2$O	***	***	***	*	NS†	NS	NS
h = −1 cm-H$_2$O	***	***	***	***	*	NS	NS
h = −6 cm-H$_2$O	***	***	***	***	NS	NS	NS
h = −15 cm-H$_2$O	***	***	NS	***	***	*	*

* $P < 0.05$.
*** $P < 0.001$.
† Not significant.

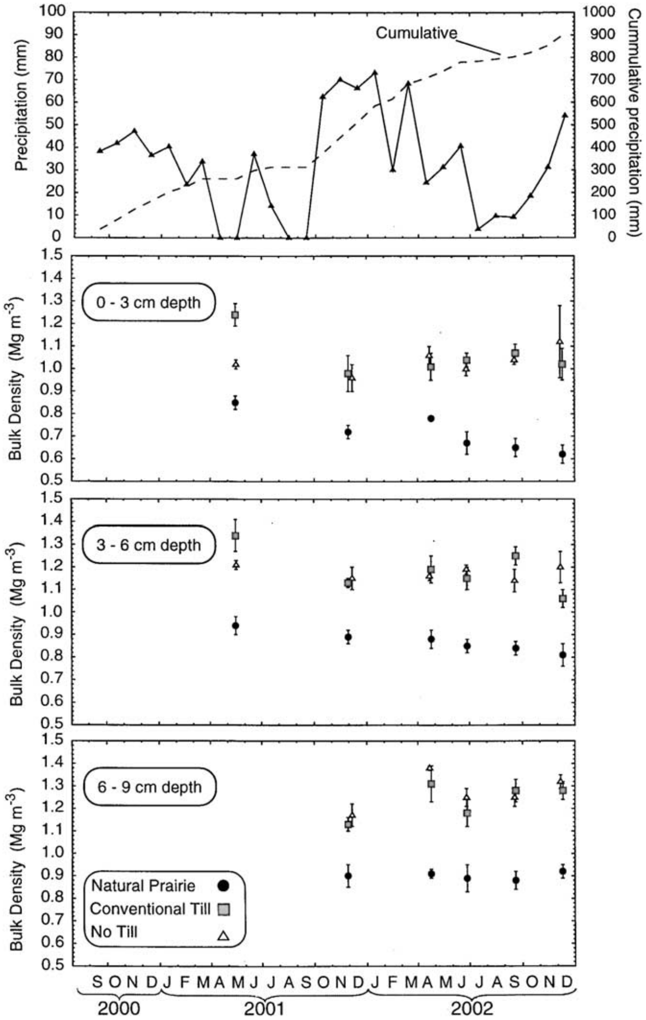

Fig. 2. Monthly precipitation and temporal variation of bulk density for sampling depths 0 to 3, 3 to 6, and 6 to 9 cm. Symbols represent the mean and the bars are one standard error (n = 5). Precipitation data courtesy of Pullman NOAA Weather Station, WA (Jeff Smith, USDA-ARS, Pullman, WA, personal communication, 2003).

The increase in hydraulic conductivities, particularly the saturated hydraulic conductivity, in Year 2002 was most pronounced in the NP, which has the highest amount of organic matter.

The interaction between MS and TIME was significant for the conductivities at all hydraulic heads (Table 3). This shows that the temporal change in hydraulic conductivity depended on the management system. The NP showed greater temporal variation than CT and NT at all hydraulic heads and depths. Such variation was larger at less-negative than at more-negative hydraulic heads. The effect of farming operations, such as planting, tilling, and harvesting, depends on the degree of soil moisture. For planting and tilling, the soil was moist (Spring and Fall) whereas for harvesting (Summer), the soil was dry (Table 1, Fig. 2).

The coefficients of variation for each sampling period indicate that the spatial variation of the hydraulic conductivities ranged from 21 to 151% (Table 4). In general, the spatial variability decreased as the hydraulic head decreased. This result is expected as greater variabilities are commonly found for saturated conditions than under unsaturated conditions (e.g., Nielsen et al., 1973; Azevedo et al., 1998). The saturated hydraulic conductivity often varied over more than one order of magnitude between replicates. Spatial variations of this extent are common (Nielsen et al., 1973; Jury et al., 1987; Russo et al., 1997).

The soil water characteristics were well described with the van Genuchten relationship (Fig. 3). The fitted van Genuchten parameters are listed in Tables 5 through 7. The NP and the NT system did not show much temporal variation in the shape of the water characteristics; however, the CT system showed some temporal variation. From November 2001 to September 2002, the CT system showed an increase in porosity between equivalent heads of 0 and −33 cm H_2O and a decrease in porosity between equivalent heads less than −300 cm H_2O (Fig. 3). The increase in porosity was associated with an increase in saturated hydraulic conductivity (Fig. 1). The increase in porosity between 0 and −33 cm H_2O is attributed to tillage and cultivation operations, which were performed in October 2001 and April 2002. These observations are consistent with findings of others (Mapa et al., 1986; Ahuja et al., 1998). The temporal variation in moisture characteristics decreased with increasing sampling depth, corroborating the observations made with the hydraulic conductivities.

The distribution of pore sizes in NT was fairly constant in time, however, some variation was discerned in NP and CT (Fig. 4). In the NP, the fraction of pores larger than 375 μm increased over time, whereas in CT the opposite trend was observed. The CT system showed the largest temporal variation in pore-size distributions, likely caused by tillage. The magnitude of the variation induced by tillage decreased with depth.

Effect of Soil Management on Hydraulic Properties

Overall, there were significant differences in hydraulic conductivities between management systems (Table 3). The NP had significantly larger hydraulic conductivities than CT and NT for all hydraulic heads, depths, and sampling times, except for the saturated hydraulic conductivity for the 5- to 10-cm depth in November 2001 and the unsaturated conductivity at −15 cm-H_2O for the 0- to 5-cm depth in April 2002, where no statistical differences were detected (Table 3, Fig. 1).

Hydraulic conductivity measurements of all sampling times were averaged for each depth and management system (Fig. 5). The conductivities of the NP for all hydraulic heads and depths were significantly different and about one order of magnitude larger than those of CT and NT. Significant differences between CT and NT were observed for saturated hydraulic conductivity, but not for unsaturated conductivities. It is also apparent from Fig. 5 that the hydraulic conductivity for all hydraulic heads decreased with soil depth. The conductivities at the 0- to 5-cm depth were significantly larger than at the 5- to 10-cm depth (Table 3), which was most pronounced for the saturated hydraulic conductivity in

Table 4. Arithmetic mean (M), geometric mean (G), and coefficients of variation, CV, for hydraulic conductivity at different hydraulic heads, sampling times, and sampling depths.

Hydraulic head *h*	Sampling time: May 2001 M	May 2001 G	May 2001 CV	Nov./Dec. 2001 M	Nov./Dec. 2001 G	Nov./Dec. 2001 CV	Apr. 2002 M	Apr. 2002 G	Apr. 2002 CV	Jun. 2002 M	Jun. 2002 G	Jun. 2002 CV	Sep. 2002 M	Sep. 2002 G	Sep. 2002 CV	Dec. 2002 M	Dec. 2002 G	Dec. 2002 CV
cm-H_2O	— cm d^{-1} —		%	— cm d^{-1} —		%	— cm d^{-1} —		%	— cm d^{-1} —		%	— cm d^{-1} —		%	— cm d^{-1} —		%
								Natural prairie 0- to 5-cm depth										
0	941.4	922.4	(21.1)	1412.7	1233.3	(58.6)	4192.4	2889.1	(79.8)	6650.7	6151.1	(41.0)	6413.6	4112.7	(90.9)	6330.5	5007.1	(58.2)
−1	129.2	119.2	(44.5)	166.0	157.9	(28.9)	221.7	203.5	(45.2)	210.2	205.6	(23.1)	274.7	266.3	(26.1)	418.9	397.4	(30.5)
−6	56.0	52.5	(36.7)	109.4	95.5	(53.3)	135.0	107.7	(74.3)	125.9	116.9	(40.8)	198.3	180.3	(41.2)	288.7	264.5	(43.7)
−15	20.4	19.6	(25.8)	32.4	25.2	(60.8)	25.3	21.5	(58.7)	32.5	30.1	(48.4)	41.4	35.9	(52.9)	58.5	54.9	(36.2)
								Natural prairie 5- to 10-cm depth										
0	489.6	429.8	(51.5)	430.5	288.7	(92.0)	1334.7	1096.9	(62.4)	3808.9	3478.0	(52.1)	3845.7	3547.0	(41.0)	3681.5	3495.7	(34.5)
−1	126.1	122.4	(26.8)	97.1	93.2	(29.7)	191.0	169.8	(55.6)	187.9	180.9	(28.0)	221.8	208.1	(36.9)	305.9	298.9	(23.9)
−6	81.5	77.0	(32.8)	65.4	63.2	(27.6)	131.6	111.4	(74.0)	109.9	108.0	(19.4)	126.4	112.7	(48.7)	203.9	193.3	(33.5)
−15	25.8	23.8	(36.4)	22.8	21.3	(32.5)	36.7	33.2	(50.0)	49.1	45.9	(35.2)	41.4	32.9	(73.7)	99.5	74.4	(93.3)
								Conventional till 0- to 5-cm depth										
0	61.5	44.7	(62.3)	49.8	30.8	(103.5)	77.1	64.7	(57.5)	230.9	154.3	(94.7)	180.8	138.6	(86.2)	234.1	164.4	(104.2)
−1	6.6	5.2	(75.4)	14.7	13.6	(46.3)	39.3	35.9	(41.6)	37.5	34.5	(42.1)	39.2	37.7	(33.1)	45.0	41.7	(36.3)
−6	2.4	1.4	(142.7)	10.8	10.0	(43.9)	28.1	26.8	(37.2)	25.4	22.6	(53.8)	35.1	33.8	(28.2)	36.1	33.9	(35.3)
−15	1.2	0.8	(129.7)	4.7	4.3	(45.0)	16.1	15.2	(36.6)	14.8	13.6	(41.2)	14.7	13.4	(48.5)	23.5	20.7	(56.2)
								Conventional till 5- to 10-cm depth										
0	46.1	41.6	(46.4)	154.2	62.4	(128.8)	69.8	50.9	(80.3)	175.6	113.3	(84.8)	65.9	50.5	(88.2)	112.5	80.3	(79.5)
−1	5.2	3.9	(76.4)	29.5	25.3	(68.2)	14.0	13.0	(47.5)	22.8	21.7	(33.4)	25.6	22.1	(59.4)	39.3	30.2	(92.5)
−6	1.6	1.4	(59.7)	19.6	19.2	(24.3)	12.8	12.0	(39.7)	14.6	13.1	(44.9)	23.6	19.7	(67.4)	33.6	25.9	(92.6)
−15	0.8	0.7	(57.3)	10.8	8.9	(62.8)	8.7	7.6	(59.6)	9.7	8.6	(46.5)	8.0	7.0	(59.7)	17.7	9.6	(135.0)
								No-till 0- to 5-cm depth										
0	75.4	53.5	(72.7)	118.1	101.6	(62.2)	500.7	365.8	(83.5)	196.0	138.8	(99.7)	366.8	220.9	(96.0)	283.3	198.8	(78.6)
−1	24.6	13.6	(105.1)	15.8	14.3	(50.6)	23.2	19.3	(66.6)	36.4	34.5	(37.8)	60.9	49.3	(77.3)	98.4	83.5	(66.7)
−6	11.0	7.0	(108.9)	9.9	9.4	(35.0)	17.9	13.9	(82.7)	26.3	24.4	(41.6)	40.3	31.3	(80.5)	56.9	49.6	(55.5)
−15	4.5	3.7	(70.0)	3.0	2.9	(37.2)	2.9	2.7	(54.5)	8.3	7.3	(63.6)	13.3	9.2	(100.2)	14.2	13.3	(35.4)
								No-till 5- to 10-cm depth										
0	89.5	58.1	(108.7)	182.8	66.3	(151.1)	67.4	60.1	(48.1)	119.7	87.0	(81.3)	144.1	112.0	(66.2)	222.8	211.6	(35.0)
−1	12.5	11.6	(37.9)	10.5	8.7	(84.4)	9.0	8.7	(29.6)	25.8	21.1	(74.9)	27.3	26.5	(25.9)	42.8	37.5	(63.5)
−6	7.3	6.9	(31.8)	9.0	7.9	(59.9)	7.6	6.8	(45.3)	19.6	16.2	(59.8)	19.5	18.4	(35.9)	38.9	30.0	(76.9)
−15	4.4	4.2	(30.0)	4.7	4.1	(67.9)	4.5	3.8	(67.2)	6.4	5.7	(50.1)	5.9	5.5	(33.8)	8.5	7.5	(58.5)

Table 5. Fitted van Genuchten parameters of soil moisture characteristics for the natural prairie soil.

Soil depth	Fitted parameter†	May 2001	Nov./Dec. 2002	Apr. 2002	Jun. 2002	Sept. 2002	Dec. 2002
cm							
0–3	θ_r	0.275 (0.221, 0.328)‡	0.213 (0.200, 0.227)	0.243 (0.225, 0.261)	0.174 (0.124, 0.224)	0.236 (0.229, 0.243)	0.226 (0.206, 0.246)
	θ_s	0.654 (0.641, 0.668)	0.613 (0.600, 0.626)	0.649 (0.634, 0.664)	0.667 (0.654, 0.680)	0.674 (0.668, 0.680)	0.696 (0.675, 0.716)
	α	0.171 (0.084, 0.258)	0.188 (0.135, 0.242)	0.205 (0.138, 0.273)	0.277 (0.170, 0.384)	0.237 (0.209, 0.265)	0.317 (0.211, 0.423)
	n	1.389 (1.216, 1.563)	1.438 (1.369, 1.507)	1.428 (1.347, 1.510)	1.325 (1.229, 1.422)	1.505 (1.463, 1.547)	1.473 (1.377, 1.569)
3–6	θ_r	0.229 (0.191, 0.268)	0.174 (0.130, 0.217)	0.242 (0.221, 0.262)	0.116 (0.035, 0.198)	0.215 (0.204, 0.227)	0.229 (0.205, 0.254)
	θ_s	0.596 (0.587, 0.605)	0.570 (0.561, 0.579)	0.616 (0.612, 0.621)	0.645 (0.631, 0.658)	0.647 (0.642, 0.652)	0.655 (0.647, 0.664)
	α	0.109 (0.077, 0.142)	0.143 (0.096, 0.190)	0.164 (0.139, 0.189)	0.216 (0.128, 0.303)	0.226 (0.195, 0.257)	0.194 (0.151, 0.237)
	n	1.430 (1.295, 1.565)	1.329 (1.235, 1.424)	1.419 (1.349, 1.488)	1.252 (1.164, 1.340)	1.375 (1.339, 1.410)	1.417 (1.335, 1.500)
6–9	θ_r	na§	0.153 (0.135, 0.171)	0.214 (0.185, 0.244)	0.119 (0.031, 0.207)	0.119 (0.093, 0.144)	0.175 (0.145, 0.205)
	θ_s	na	0.590 (0.588, 0.593)	0.609 (0.599, 0.620)	0.654 (0.645, 0.664)	0.614 (0.611, 0.617)	0.670 (0.661, 0.679)
	α	na	0.134 (0.122, 0.146)	0.156 (0.104, 0.207)	0.161 (0.108, 0.213)	0.285 (0.249, 0.320)	0.162 (0.129, 0.194)
	n	na	1.339 (1.304, 1.374)	1.384 (1.290, 1.478)	1.277 (1.175, 1.380)	1.235 (1.208, 1.261)	1.315 (1.264, 1.366)

† Units of parameters: θ_r, cm^3 cm^{-3}; θ_s, cm^3 cm^{-3}; α, cm^{-1}; n (−).
‡ Values in parentheses are 95% confidence intervals.
§ Data not available.

Table 6. Fitted van Genuchten parameters of soil moisture characteristics for the conventional-till soil.

Soil depth	Fitted parameter†	May 2001	Nov./Dec. 2002	Apr. 2002	Jun. 2002	Sept. 2002	Dec. 2002
cm							
0–3	θ_r	0.181 (0.019, 0.342)	0.152 (0.070, 0.234)	0.049 (0.000, 0.099)	0.026 (−0.050, 0.102)	<0.001¶	<0.001
	θ_s	0.508 (0.497, 0.519)	0.556 (0.544, 0.568)	0.597 (0.590, 0.604)	0.608 (0.599, 0.618)	0.565 (0.559, 0.572)	0.534 (0.527, 0.540)
	α	0.301 (0.091, 0.511)	0.289 (0.156, 0.422)	0.076 (0.063, 0.088)	0.056 (0.040, 0.072)	0.052 (0.044, 0.060)	0.069 (0.056, 0.082)
	n	1.163 (1.023, 1.300)	1.259 (1.141, 1.377)	1.296 (1.240, 1.351)	1.303 (1.213, 1.393)	1.271 (1.258, 1.284)	1.277 (1.261, 1.293)
3–6	θ_r	<0.001	<0.001	0.125 (0.048, 0.203)	0.012 (−0.041, 0.066)	<0.001	<0.001
	θ_s	0.485 (0.479, 0.491)	0.527 (0.514, 0.539)	0.530 (0.526, 0.534)	0.606 (0.603, 0.609)	0.534 (0.524, 0.543)	0.544 (0.535, 0.553)
	α	0.133 (0.079, 0.187)	0.062 (0.043, 0.081)	0.055 (0.045, 0.066)	0.051 (0.046, 0.056)	0.056 (0.046, 0.066)	0.068 (0.053, 0.083)
	n	1.086 (1.077, 1.095)	1.174 (1.160, 1.187)	1.290 (1.187, 1.394)	1.266 (1.222, 1.310)	1.218 (1.209, 1.226)	1.252 (1.235, 1.269)
6–9	θ_r	na§	0.069 (0.037, 0.102)	0.175 (0.135, 0.215)	<0.001	<0.001	<0.001
	θ_s	na	0.531 (0.529, 0.533)	0.505 (0.501, 0.509)	0.565 (0.558, 0.572)	0.516 (0.509, 0.522)	0.537 (0.528, 0.545)
	α	na	0.034 (0.032, 0.036)	0.056 (0.046, 0.065)	0.040 (0.035, 0.045)	0.052 (0.044, 0.061)	0.044 (0.035, 0.053)
	n	na	1.293 (1.256, 1.330)	1.297 (1.225, 1.369)	1.244 (1.233, 1.256)	1.196 (1.188, 1.204)	1.220 (1.207, 1.234)

† Units of parameters: θ_r, cm^3 cm^{-3}; θ_s, cm^3 cm^{-3}; α, cm^{-1}; n (−).
‡ Values in parentheses are 95% confidence intervals.
§ Data not available.
¶ If residual water content <0.001, the model assumes a value of zero for fitting purposes.

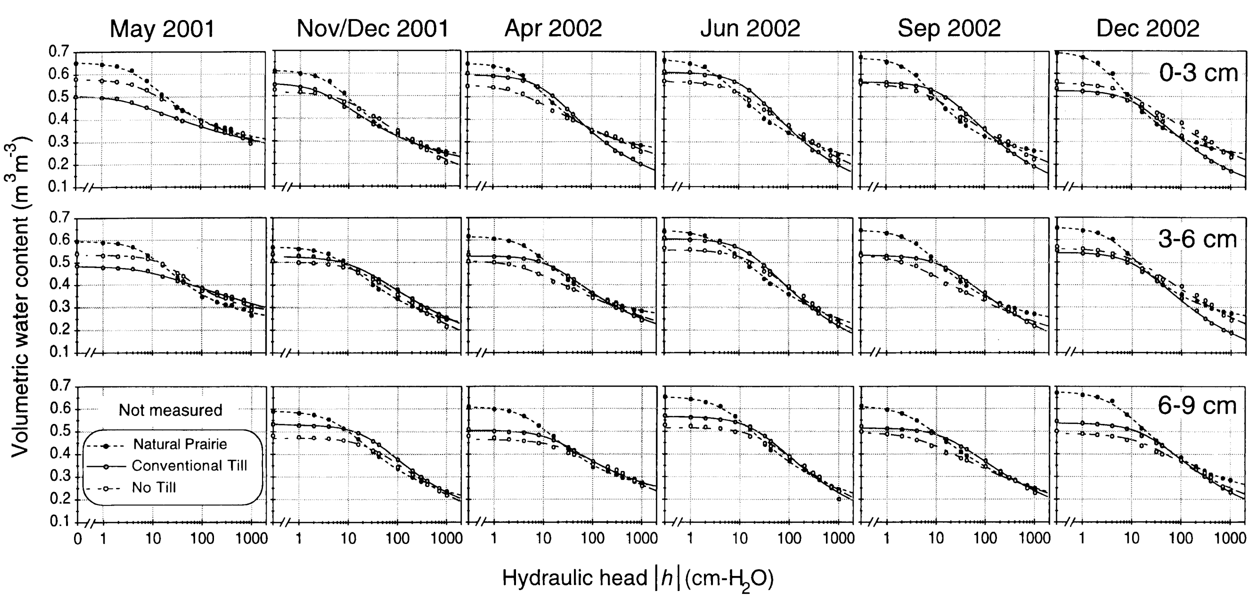

Fig. 3. Measured soil moisture characteristic (symbols) and fitted van Genuchten relationships (lines) for different sampling times and depths.

Table 7. Fitted van Genuchten parameters of soil moisture characteristic for no-till soil.

Soil depth	Fitted parameter†	May 2001	Nov./Dec. 2002	Apr. 2002	Jun. 2002	Sept. 2002	Dec. 2002
cm							
0–3	θ_r	0.204 (0.107, 0.300)‡	<0.001¶	<0.001	<0.001	<0.001	<0.001
	θ_s	0.581 (0.575, 0.587)	0.503 (0.498, 0.507)	0.555 (0.538, 0.573)	0.567 (0.559, 0.576)	0.558 (0.538, 0.579)	0.559 (0.538, 0.581)
	α	0.140 (0.080, 0.200)	0.045 (0.033, 0.057)	0.319 (0.153, 0.484)	0.074 (0.052, 0.097)	0.140 (0.057, 0.222)	0.114 (0.049, 0.179)
	n	1.250 (1.118, 1.382)	1.208 (1.189, 1.228)	1.126 (1.115, 1.138)	1.210 (1.190, 1.229)	1.173 (1.151, 1.196)	1.171 (1.147, 1.194)
3–6	θ_r	0.262 (0.215, 0.310)	<0.001	<0.001	<0.001	<0.001	<0.001
	θ_s	0.534 (0.527, 0.541)	0.503 (0.498, 0.507)	0.510 (0.490, 0.530)	0.555 (0.541, 0.569)	0.536 (0.517, 0.554)	0.561 (0.536, 0.585)
	α	0.046 (0.035, 0.057)	0.045 (0.033, 0.057)	0.257 (0.079, 0.435)	0.041 (0.026, 0.057)	0.362 (0.171, 0.553)	0.086 (0.026, 0.147)
	n	1.496 (1.284, 1.709)	1.208 (1.189, 1.228)	1.120 (1.104, 1.137)	1.226 (1.199, 1.254)	1.137 (1.123, 1.152)	1.174 (1.146, 1.203)
6–9	θ_r	na§	<0.001	<0.001	<0.001	<0.001	<0.001
	θ_s	na	0.473 (0.451, 0.494)	0.464 (0.442, 0.486)	0.517 (0.503, 0.530)	0.496 (0.480, 0.512)	0.490 (0.475, 0.505)
	α	na	0.028 (0.015, 0.042)	0.037 (0.007, 0.067)	0.029 (0.019, 0.039)	0.201 (0.073, 0.330)	0.053 (0.022, 0.085)
	n	na	1.225 (1.192, 1.258)	1.156 (1.126, 1.187)	1.225 (1.201, 1.250)	1.132 (1.113, 1.151)	1.168 (1.137, 1.199)

† Units of parameters: θ_r, cm^3 cm^{-3}; θ_s, cm^3 cm^{-3}; α, cm^{-1}; n (−).
‡ Values in parentheses are 95% confidence intervals.
§ Data not available.
¶ If residual water content <0.001, the model assumesa value of zero for fitting purposes.

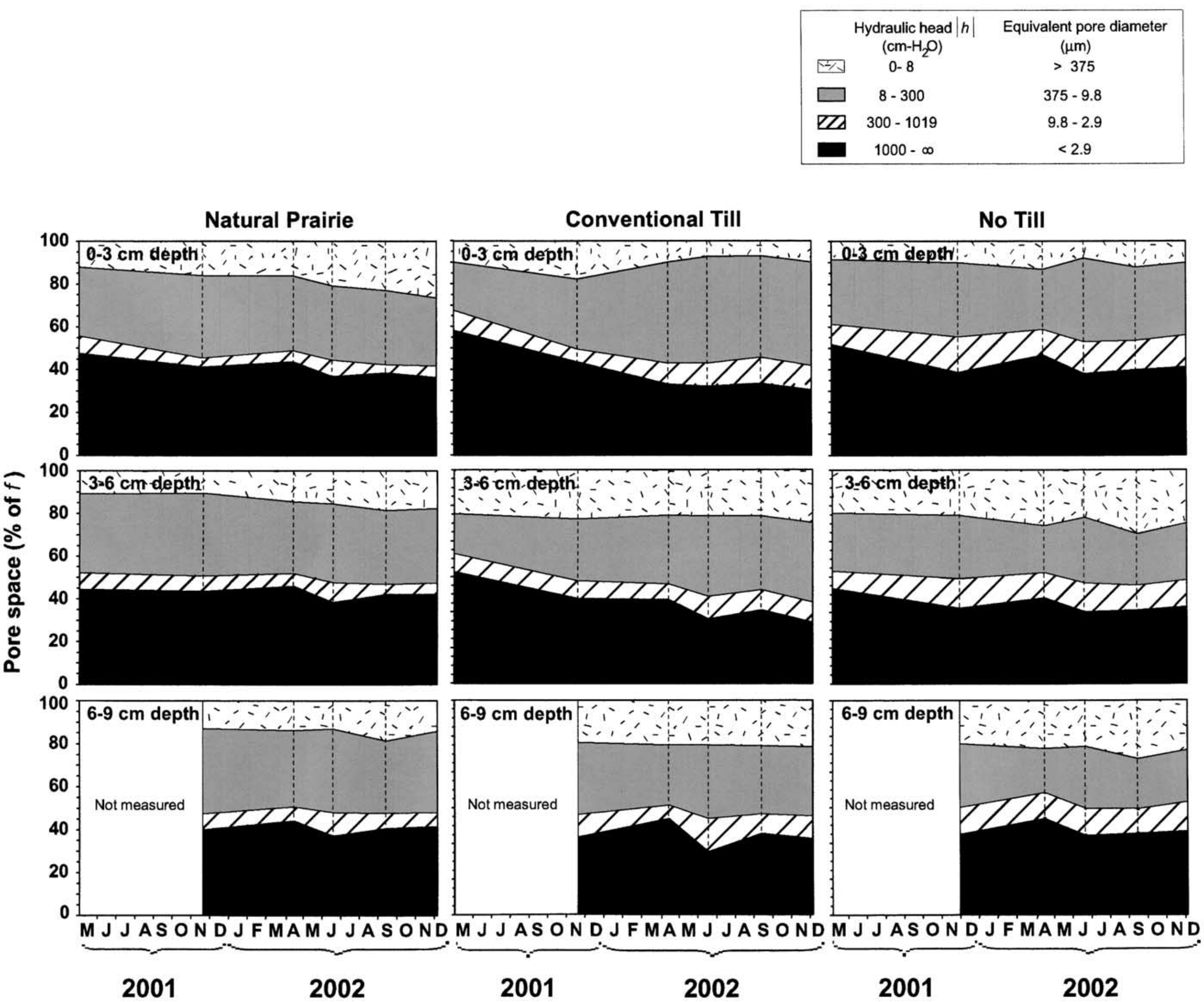

Fig. 4. Variation in time and depth in the distribution of pore sizes (expressed as percentage of total porosity *f*), determined from the soil moisture characteristic.

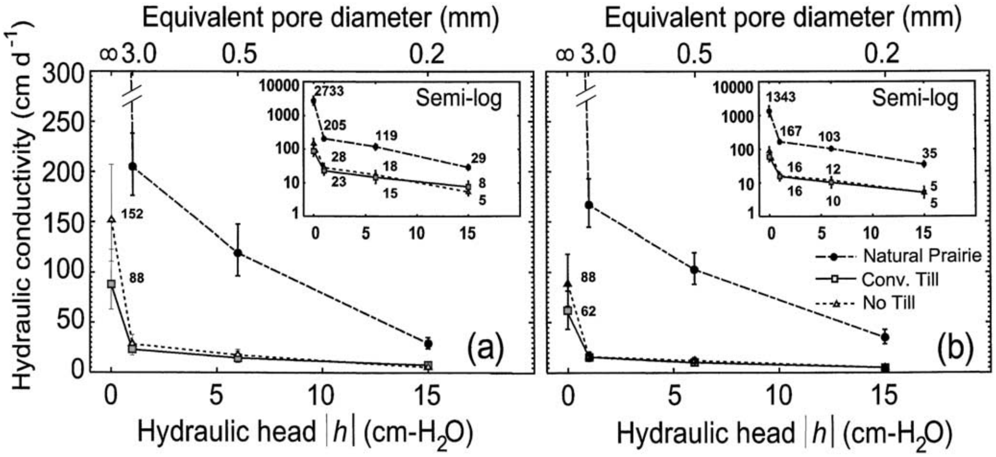

Fig. 5. Hydraulic conductivity averaged over all sampling periods for sampling depths (a) 0 to 5 cm and (b) 5 to 10 cm. Symbols represent the geometric mean and the bars are 95% confidence intervals (*n* = 48). Inserts show data on a semi-logarithmic plot, with the same units of the axes as the linear-linear plots.

the NP. This decrease of conductivity with depth was associated with an increase in bulk density (Fig. 2). As an exception, no significant differences were found for the conductivities at −15 cm H_2O hydraulic head between depths (Table 3), which indicates that equivalent pore diameters <0.2 mm were not affected by soil depth.

In terms of equivalent pore diameters that are effective for transmission of water, the NP not only showed a larger fraction of large pores, but also a more uniform distribution (Fig. 5). The differences in the distribution of pore sizes between the management systems were most pronounced at the very top (0–3 cm) and diminished with increasing soil depth (Fig. 4). The NP had the largest fraction of large pores (>375-μm diam.) in the 0- to 3-cm depth, likely due to the higher organic matter content.

CONCLUSIONS

The Palouse Region of Washington State is characterized by intensive dry-land agriculture, which is primarily supported by the deep and fertile soils of the area. Such intensive use of the soil has increased the need for a better understanding of soil water dynamics. The results of this study showed that hydraulic conductivity varied in time. The main factor responsible for this temporal variation was the expansion of soil pores caused by wetter soil conditions. This phenomenon was more pronounced in the NP where the amount of organic matter was considerably greater than in the CT and NT soils. The effect of tillage practices on the temporal variation of hydraulic conductivity seemed to be small. Soils under CT had a weak aggregate stability (Pierson and Mulla, 1989) so that the effect of tillage operations was counterbalanced by natural reconsolidation.

After 27 yr of continuous NT, the hydraulic conductivities increased as compared with CT; however, except for saturated hydraulic conductivities, this effect was not significant. Unsaturated hydraulic conductivities at all measured tensions were similar between the two cultivated systems. The hydraulic conductivity under NP was about one order of magnitude greater than under CT and NT. It seems that 27 yr of no tillage have only slightly contributed to the recovery of the hydraulic conductivity that existed previous to cultivation.

Due to the unique characteristics of the Palouse NP, its hydraulic properties might be difficult to restore. No till seems to help in the process of restoring some of the original properties of the natural soils of the area. However, a restoration of the original hydraulic conductivity may need a much longer period of time. The implementation of other management practices that help to increase soil water flow and minimize soil erosion, should consider the formation of more continuous and long-lasting pores. The introduction of perennial plants that favor a more continuous and enduring root system may potentially contribute to this purpose. Implementation of long-lasting conservation reserve programs as well as the introduction of perennial crops can be a promising approach to restore original hydraulic properties.

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