DIVISION S-6—SOIL & WATER MANAGEMENT & CONSERVATION

Porosity and Pore-Size Distribution in Cultivated Ustolls and Usterts

A. Eynard, T. E. Schumacher,* M. J. Lindstrom, and D. D. Malo

ABSTRACT

Soil management systems affect soil porosity and pore sizes, changing soil hydraulic properties by loosening or by compacting different soil layers. Changes in porosity and pore-size distribution following cultivation were studied in six Ustolls and two Usterts of the prairie in the Upper Missouri River Basin. Soil pores were morphologically described. Water infiltration was measured at 0.03- and 0.06-m tensions. Soil bulk density and moisture retention at 1-m tension were determined in undisturbed and in remolded soil cores. In Ustolls, cultivation decreased soil porosity and pore sizes. Steady-state water infiltration rates were higher in grasslands than in cultivated soils. In no-till and till systems, both very fine macroporosity and microporosity were reduced when compared with grasslands. No-tillage relative to tillage increased soil porosity between the 0.05- and 0.30-m depth. More very fine tubular pores were present in no-till than in tilled Ustolls, indicating increased biological activity in pore formation. In Usterts, total pore space, quantity, shape, and size of macropores, water infiltration under tension, and moisture retention at 1-m tension did not show significant changes related to different management systems.

P ORE GEOMETRY and size distribution control water transmission and storage, and provide air and space for root growth. Internal and external stresses cause pore structure to be dynamic (Oades, 1993). A primary goal of soil management is the development and maintenance of an optimal pore structure for crop production. Sustaining crop productivity in agricultural soils requires a high degree of pore stability. Thus, describing soil structure in terms of stable pores is very important (Lynch and Bragg, 1985).

Agricultural management affects pore-size distribution as well as pore continuity and tortuosity. Traffic reduces macroporosity and tillage mechanically breaks pore continuity and hinders biopore formation (Boersma and Kooistra, 1994). No-till has been shown to decrease the number of 30- to 100-μm pores with a resultant increase in 100- to 500-μm diameter pores within 4 yr (VandenBygaart et al., 1999). Soils managed using no-till show a greater number of horizontally oriented elongated macropores in the top 5 to 15 cm due to the combination of no-tillage and freezing–thawing (VandenBygaart et al., 1999). In addition, cylindrical macropores increase with no-till duration. After 6 yr, more

A. Eynard, T.E. Schumacher, and D.D. Malo, NPB 247A NPB, South Dakota State Univ., Box 2410C, Brookings, SD 57007-2141; M.J. Lindstrom, USDA-ARS, 803 Iowa Ave, Morris, MN 56267. Received 18 Apr. 2003. *Corresponding author (thomas_schumacher@sdstate.edu).

biopores >500 μm were present in no-till than in till systems (VandenBygaart et al., 1999). As a result of these differences in porosity and pore characteristics, resistance to fracture by compression decreases more rapidly with increasing ped size in no-till than in tilled systems (Perfect et al., 1998). Pore strengthening by organic matter, especially in clayey soils, is associated to stability of non-cultivated or virgin soils in the soil structure model of Quirk and Panabokke (1962).

Swelling and shrinking from wetting and drying affect soil porosity and pore sizes in soils with significant quantities of smectitic clays (Coughlan et al., 1991). Hydraulic soil properties change if pore volume and size distribution change in space and time due to management practices. In the presence of swelling clays, soil moisture characteristic curves cannot provide unique estimates of the pore-size distribution because water loss results from a combination of pore drainage and pore shrinkage (Bouma et al., 1977). Pores collapse in slaking soils directly immersed in water at air-dry moisture content. Additionally, changes in bulk density occur during wetting and drying, and proper techniques need to be applied to obtain representative samples of cracking soils (Chan, 1981). In these conditions of soil heterogeneity and anisotropicity, morphological techniques are particularly helpful in explaining erratic physical measurements and establishing major differences between structural features in native and cultivated soils (Bouma, 1992).

Water infiltration, retention, and flow depend on the quantity, interconnectivity, and size of interpedal, intrapedal, and transpedal pores (Bouma and Anderson, 1973). Tension infiltration measurements can directly provide information on the size distribution of pores that conduct water into the soil at a particular tension. Tension infiltration measurements allow detection of surface structural changes caused by different management practices (Coughlan et al., 1991).

Pore quantity and sizes may be greatly reduced in soils subjected to cultivation or heavy loads in wet conditions. Soil remolding can be used to simulate this reduction (Muller and Schindler, 1998). Self-mulching soils may regenerate a finely aggregated soil surface on wetting and drying, and intense soil cracking may improve deep structural damage caused by wet cultivation despite harsh compactive stresses (McGarry, 1996).

The objective of this study was to compare the effects of different management systems on total porosity and pore-size distribution in Ustolls and Usterts on farms of central South Dakota (USA). The susceptibility to soil structural alteration due to stress under wet condi-

tions was tested by determining changes in porosity and pore sizes after remolding samples from grassland, no-till, and tilled fields. This experiment tested the hypothesis that total porosity, very fine macroporosity, water infiltration under tension, water retention, and structural stability of the topsoil are greater in grasslands than in no-till and tilled fields, and in no-till when compared with tilled fields.

MATERIALS AND METHODS

Experimental Design

Eight locations were selected in the Upper Missouri River Basin in central South Dakota. Ustolls were present at six locations and Usterts were present at two locations. Seven soil series were considered in the study (Table 1). Highmore silt loams were present at two locations. At each location there were three treatments: no-till, conventional-till (till), and grasslands (grass). Treatments were applied to fields in close proximity on the same soil series and with similar topography (backslope position with slope <2%). Site selection was dependent on finding land with the same soil series, three management systems, and cooperating producers. Only sites where subsequent morphological and laboratory analysis confirmed the initial site selection criteria are used in this study. Grasslands were typically used for hay or pasture and had never been tilled. Dominant grass species were bromes (*Bromus sp.*), wheatgrasses (*Agropyrum sp.*), and Kentucky bluegrass (*Poa pratensis* L.). Conventional-till systems (recently using chisel-plowing as primary tillage and tandem-disking as secondary tillage) had been practiced for over 80 yr. The depth of tillage varied between 0.07 and 0.20 m. No-till management systems (minimal soil disturbance by slot-planting) had been in place for 6 to 16 yr (average 10 yr) after conversion from conventional tillage. Cropping systems included wheat (*Triticum aestivum* L.), corn (*Zea mays* L.), and soybean [*Glycine max* (L.) Merr.]. The eight locations were used as replications with each of the three management systems compared as treatments in a randomized complete block design (Table 2).

Sampling

Four representative sampling areas with similar soil profiles and landscape positions were selected within each of the individual fields at each location. A hydraulic 75 mm-diam. soil probe was used to take soil cores to the 1- to 1.5-m depth. The surface of the soil in the sampling tube was compared with the surface of the surrounding soil. Samples showing a lowering of the sample surface or other evidence of disturbance were discarded. Each soil profile core was morphologically described. Soil cores were air-dried and stored for further analyses. Four cores for the morphological description were taken in fall after harvest in each field at each location. All other determinations were performed on samples taken in spring in the four sampling areas where the profiles were taken earlier in fall in each field at each location. Sampling time

Table 1. Soil series sampled in the study (Soil Survey Staff, 1998b).

Soil Series	Classification
Lowry	coarse-silty, mixed, superactive, mesic Typic Haplustoll
Uly	fine-silty, mixed, mesic Typic Haplustoll
Reeder	fine-loamy, mixed, superactive, frigid Typic Argiustoll
Highmore	fine-silty, mixed, superactive, mesic Typic Argiustoll
Williams	fine, smectitic, frigid Typic Argiustoll
Millboro	fine, smectitic, mesic Typic Haplustert
Promise	very-fine, smectitic, mesic Typic Haplustert

Table 2. Experimental design.

Parameter	Description	Number
Treatment structure	one-way treatment	
Design structure	randomized complete block design	
Treatments	management systems	3
Replicates	locations	8
Experimental units	farm fields	$24 = 3 \times 8$
Sampling units	field areas	$96 = 24 \times 4$

relative to tillage operations in tilled fields varied with location. Time of tillage and specific tillage operation were not controlled factors in this on-farm experiment. Soil moisture content at sampling was gravimetrically determined to a 0.30-m depth. When tension infiltration was measured, mean soil moisture content was 0.20, 0.21, and 0.19 kg water kg^{-1} soil, respectively, in grass, no-till, and till Ustolls (standard error 0.009, $N = 6$), and 0.29, 0.33, 0.31 kg kg^{-1} in grass, no-till, and till Usterts (standard error 0.034, $N = 2$). Soil moisture content was not significantly different between management systems. Soil cores of a 50-mm diam. were taken for bulk density and for soil moisture retention determinations in metal rings in each sampling area. Four additional cores were taken from each treatment and replication at three depth intervals (0.02–0.07, 0.15–0.20, and 0.25–0.30 m) for measuring bulk density. Four other cores were taken from each treatment and replication at the 0- to 0.05-m depth for measuring moisture retention.

Four bulk soil samples were collected from the topsoil with a spade to the 0.20-m depth for measuring moisture retention on subsequently remolded soil. Bulk samples were air-dried at room temperature and stored until analysis without any presieving, grinding, or removal of organic materials. Bulk samples were thoroughly mixed and pooled by treatment at each location.

Bulk Density

Cores for bulk density measurements were cylindrical cores of 0.05 by 0.05 m size. Bulk density was also determined on the undisturbed and remolded soil cores used for measuring moisture retention. Total porosity was calculated from bulk density, assuming a particle density of 2.65 Mg m^{-3} (Blake and Hartge, 1986).

Macroporosity

Soils were morphologically described according to the Natural Resources Conservation Service methods (Soil Survey Staff, 1998a). Morphological results are presented to a depth of 0.8 m. Pores from the 1- to 0.050-mm size were detected by visual observation and recorded in the very fine size-class in the morphological description without finer size distinctions (Soil Survey Staff, 1998a).

The morphological description of very fine macropores was quantified according to the scale developed by Lin et al. (1999) in relation to soil hydraulic properties. Ratings are reported in Table 3. The scale was based on relationships between steady infiltration rates and morphological features, taking as a reference, a massive clay without any macropores, and at a fully saturated state. Scores increase as the capacity of vertical water transmission increases. The macroporosity index was calculated as product of macropore quantity, size, and shape. For each pore shape a partial index of macroporosity was calculated as the product of quantity and size. When different pore shapes were present in the same horizon, the total macroporosity index was calculated by adding the partial indexes for each shape. In this study, the soil area of each horizon available for pore observation was too small for a reliable assessment of medium, coarse, and very coarse pores because the soil profiles were

Table 3. Scores used for quantifying morphological features of soil structure in relation to water transmission (modified after Lin et al., 1999).

Morphological feature	Class	Score
Macroporosity quantity	few	2
	common	10
	many	45
Macroporosity size	very fine (<1 mm)	1
	fine (1 to <2 mm)	9
	medium (2 to <5 mm)	49
	coarse (5 to <10 mm)	60
	very coarse (≥10 mm)	70
Macroporosity shape	irregular, vesicular	1
	tubular	8
	cracks	10
	interstitial	25

morphologically described on soil cores of a 75-mm diam. Therefore, results refer only to very fine macroporosity.

Tension Infiltration

Water infiltration was measured with 80-mm diam. tension infiltrometers (Soil Measurement Systems, Tucson, AZ) according to Ankeny et al. (1988). Unconfined steady-state infiltration was measured at -0.03- and -0.06-m water potentials at the soil surface, after leveling vegetation and soil irregularities with clippers and trowel with minimum disturbance to avoid smearing. Silica sand (0.10–0.25 mm) was used to assure a smooth contact between the soil and the nylon membrane of the infiltrometer without major modification of the soil surface. The sand was moistened by spraying water before setting the tension infiltrometer above the sand. A discussion about the use of a thin (<2 mm) layer of fine sand as a capping material can be found in Perroux and White (1988). Water was supplied in ascending sequence of potentials (from -0.06 to -0.03) to exclude hysteresis effects due to continued wetting at the infiltration front while the layer above is draining (Reynolds and Elrick, 1991). Measurements were made with two infiltrometers per sampling area placed 1 to 2 m apart (for a total of eight measures for each treatment and each replication) for 20 min at each tension. Constant infiltration rate was usually reached in <10 min.

The ratio of the difference between the flow rate at the -0.03- and -0.06-m water potentials to the flow rate at the -0.03-m water potential was calculated as a measure of the contribution of 0.5- to 1-mm pores to the total flow in pores <1 mm. Pores of 0.5 to 1 mm in diameter can be called very fine macropores or coarse mesopores depending on the definition of limits for macropore and mesopore sizes (Luxmore, 1981). In this study we refer to them as very fine macropores.

To estimate the mean characteristic pore dimension, the microscopic pore radius was calculated from the macroscopic capillary length, based on the capillary theory (White and Sully, 1992). The macroscopic capillary length is defined as the mean soil water potential weighted by the hydraulic conductivity of every water potential considered (White and Sully, 1987). Hydraulic conductivities were estimated from the measured flux densities, which can be used as a valid approximation of hydraulic conductivities (Lin and McInnes, 1995).

Moisture Retention at the -1-m Water Potential

Undisturbed soil cores taken from the 0- to 0.05-m depth were frozen at field moisture and stored frozen until measurement. We froze undisturbed cores for measuring moisture retention at low tension to maintain soil structure as natural as possible despite long storage (9 mo). Bacterial growth in moist samples may affect water retention (Dane and Hop-

mans, 2002). Samples taken out of the freezer were directly saturated without air-drying before draining to 1-m tension on the sand table. We tried to avoid the evident changes produced by air-drying due to pore collapse and shrinking, and consequent hysteresis in water retention. We assumed that changes during freezing were affecting all compared management systems to the same extent and that the interaction of freezing and management system was negligible. The clay mineralogy of the studied Ustolls and Usterts is dominated by smectitic clays (Table 1). Swelling and reorientation of particles upon thawing tend to rebuild the initial structural arrangement, even though this may not completely restore the original structure (Yuen et al., 1998). In the presence of smectitic clays, changes are less severe than in case of less expansive clays like illite (Schwinka and Mortel, 1999). Structural changes for smectitic clays are more similar to vermiculitic transitions from tactoid to swollen phases (Hatharasinghe et al., 2000).

Moisture retained at 1-m tension was determined by desorption on a sand table. The cores were initially saturated from the bottom. Swelling of soil cores occurred in both Usterts and Ustolls. In Usterts swelling was more pronounced than in Ustolls. Soil cylinders were free to expand at the top because metal rings limited the expansion only on the sides. A nylon mesh was used to provide the contact between the sand table and the bottom of the soil cores.

Remolded cores were prepared by packing topsoil samples into metal rings (50-mm diam., 50 mm high) with a technique similar to the disk preparation of McKenzie and Dexter (1985). Air-dry soil was wetted to a gravimetric moisture content (0.30 kg water kg^{-1} soil in Ustolls and 0.35 kg kg^{-1} in Usterts) greater than the plastic limit (≤ 0.26 kg kg^{-1} in Ustolls and ≤ 0.32 in Usterts) and worked with a spatula to break down macroaggregates. The soil paste was pressed with the spatula to fill metal rings. The moisture retention at 1-m tension of remolded cores was determined with the same procedure used for undisturbed cores. For both types of cores, the air-filled porosity was determined at the moisture content of -1 m water potential.

Statistical Analysis

Data were analyzed using the SYSTAT 9 statistical program (SPSS Inc., 1999). Data analyses were separately done for Ustolls (six replications) and for Usterts (two replications). Orthogonal contrasts were made between the grass and cultivated treatments and between the no-till and till treatments. Means grouped by management system and soil order were compared by t tests.

For very fine macropores, data of the four repeated measures per site and management system were averaged using horizon depths as weighing factors and analyzed by depth layer. Five depth increments were considered (0–0.05, 0.05–0.20, 0.20–0.40, 0.40–0.60, and 0.60–0.80 m). Weighed averages were also calculated for the top 0 to 0.20 m of soil for comparative purposes with analyses of spade samples. The top 0.20-m layer included the surface horizon (A or Ap) and part of the underlying horizon in pedons where the surface horizon was less thick. Regular increments of a 20-cm depth were used for the calculation of macroporosity indexes because actual horizon boundaries varied in depth for each pedon. We separately calculated values for the top 0.05 m to individuate soil surface differences. All calculations were based on the morphological description of the pores done by horizon in each pedon.

RESULTS AND DISCUSSION

Bulk Density

In Ustolls, the bulk density in grass fields was less than in cultivated (till and no-till) fields (Fig. 1). Loosening
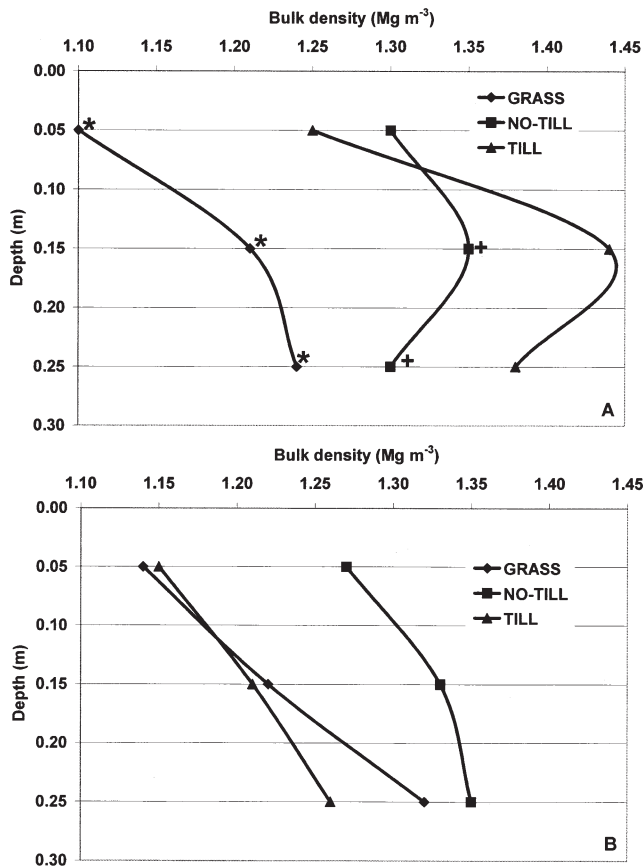
Fig. 1. Bulk density means as a function of soil depth in (A) Ustolls and (B) Usterts of central South Dakota (USA). Standard errors for Ustolls ($N = 6$) were 0.032, 0.025, and 0.019 Mg m^{-3} at 0.02- to 0.07-, 0.15- to 0.20-, and 0.25- to 0.30-m depth, respectively. Standard errors for Usterts ($N = 2$) were 0.070, 0.053, and 0.071 Mg m^{-3} at 0.02- to 0.07-, 0.15- to 0.20-, and 0.25- to 0.30-m depth, respectively. *Significant ($P < 0.05$) difference in the orthogonal contrast between grass and cultivated soils. + Significant ($P < 0.05$) difference in the orthogonal contrast between no-till and till soils.

parallel with decreasing root density (Eynard, 2001) and macroporosity. The bulk density was greatest below the tillage depth where a tillage pan (0.10–0.20 m) had been formed in both cultivated treatments. Differences in bulk density between no-till and till reported in the literature vary because of variable tillage types, tillage duration, and depth of measurements. For example, similar bulk densities in the top 0 to 0.30 m of no-till and conventional-till were reported by Voorhees and Lindstrom (1984) and by Arshad et al. (1999) for fields that have been in no-till for >5 yr. VandenBygaart et al. (1999) observed a reduction of total pore volume and in total number of pores in the top 0 to 0.25 m of soils after 11 yr of no-till. However, increased biological activity with biopore formation may facilitate aeration and water entry, and decrease the bulk density in no-till fields in the long term (Boersma and Kooistra, 1994; VandenBygaart et al., 1999). Increased biopore formation may explain significantly lower bulk density in no-till when compared with tilled soils below the depth loosened by tillage in Ustolls of our study.

Management systems did not significantly affect soil bulk density of Usterts (Fig. 1). Organic C and wet aggregate stability were relatively high in the two cultivated Usterts (Eynard, 2001) and are likely to have contributed to prevent compaction relative to grasslands. Usterts are cracking soils due to a swelling clay content >35% so that self-mixing and self-tilling are natural processes limiting differences due to management practices. Differences in bulk density of Australian Usterts were not significant after 13 yr of no-till as compared with conventional tillage (Dalal, 1989). The trend for higher bulk density in no-till in this study suggests the risk of compaction due to uncontrolled use of heavy machinery. Compaction may increase with time after conversion of intensively tilled Usterts to minimum tillage (Chan and Hulugalle, 1999).

Very Fine Macroporosity

Very fine macropores (1–0.050 mm) are involved in water flow at negative water potential. Very fine macropores were more abundant in topsoils of grass than of till or no-till systems (Table 4). In Ustolls, differences in very fine macroporosity between grass and cultivated soils were significant. In Usterts, grasslands tended to have greater very fine macroporosity than cultivated soils, although differences were not significant. More very fine macropores were present in the topsoil of no-till than in tilled Ustolls (Table 4). Differences in very fine

by tillage did not compensate for the loss of pedality, biological activity, and organic matter found under perennial grasses, as already observed in other soils (Haynes, 2000). Greater values of bulk density in no-till vs. grass can be attributed to the collapse of interpedal pores after conversion from tillage and compaction by heavy equipment. Total soil porosity was on the average 56% for grass and 50% for no-till and till in the top 0.20 m. The initial effect of minimum tillage may be a decrease in soil porosity relative to plowed soils (Boersma and Kooistra, 1994). In Ustolls under grass, bulk density gradually increased with depth in

Table 4. Means of very fine macropore rating and distribution in shape classes in the top 0 to 0.20 m of soil in Ustolls ($N = 6$) and in Usterts ($N = 2$) of central South Dakota (USA). Probabilities of significant differences in the contrasts between grass and cultivated soils (A) and between no-till and till (B) are reported in the last two columns.

Soil order	Pore shape	Grass	No-till	Till	A	B
Ustolls	tubular	360	306	183	$P \leq 0.019$	$P \leq 0.028$
	cracks	38	67	19	$P \leq 0.888$	$P \leq 0.248$
	interstitial	33	18	7	$P \leq 0.033$	$P \leq 0.279$
	all	431	391	209	$P \leq 0.048$	$P \leq 0.022$
Usterts	tubular	305	144	162	$P \leq 0.206$	$P \leq 0.868$
	cracks	22	64	40	$P \leq 0.266$	$P \leq 0.413$
	interstitial	38	67	19	$P \leq 0.074$	$P \leq 0.323$
	all	378	217	227	$P \leq 0.112$	$P \leq 0.897$

macropores between management systems were not significant below the 0.20-m depth.

In Ustolls, there was a significant management $\times$ depth interaction ($P \leq 0.025$). Very fine macropores decreased with depth in no-till and grass, whereas in tilled Ustolls very fine macropores were fewer in the topsoil than deeper and increased below tillage depth. This distribution was mainly determined by the distribution of very fine tubular macropores (Fig. 2). In cultivated Usterts very fine macropores reached a maximum between the 0.20- and 0.40-m depth. Tubular pores increased in cultivated soils in the same depth interval (Fig. 2).

Tubular pores dominated very fine macropore shape distribution (Table 4), although the rating of macropores based on Lin et al. (1999) lessens the incidence of tubular pores on the total macroporosity (Table 3). Cracks were present and not significantly affected by management in any soil (Table 4). Tubular pores are formed by biological activity, and they are likely to play a major role in water movement because they may stay open when cracks close upon swelling (Bouma et al., 1977). In this study tubular pores were mainly derived
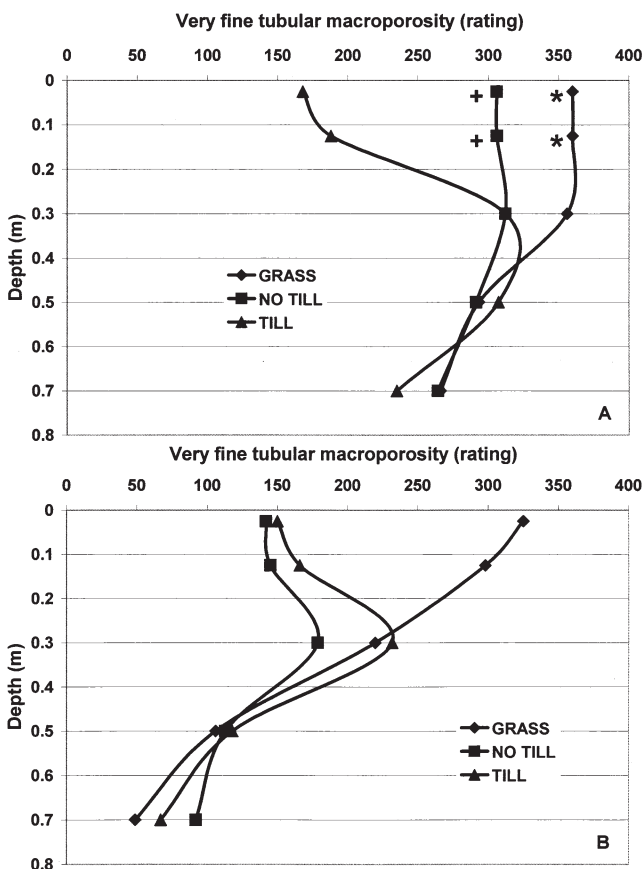

Fig. 2. Very fine tubular macropore means as a function of soil depth in (A) Ustolls and (B) Usterts of central South Dakota (USA). Standard errors for Ustolls ($N = 6$) were 36, 34, 19, 25, and 44 at 0- to 0.05-, 0.05- to 0.20-, 0.20- to 0.40-, 0.40- to 0.60-, and 0.60- to 0.80-m depth, respectively. Standard errors for Usterts ($N = 2$) were 77, 65, 48, 50, and 29 at each depth interval respectively. *Significant ($P < 0.05$) difference between grass and cultivated soils. + Significant ($P < 0.05$) difference between no-till and till soils.

from root channels of the herbaceous vegetation grown, as observed during the morphological characterization. Tubular porosity was greater in grass than in till and no-till, and more tubular pores were present in topsoils of Ustolls in no-till than in till, indicating increasing biological activity with no-till systems relative to intensive tillage (Fig. 2 and Table 4). In silt loams of The Netherlands, 7 yr were needed for structural improvements after implementation of minimum tillage because of the major role of soil organisms in pore formation (Boersma and Kooistra, 1994). In our study an average of 10 yr of no-till showed increased very fine macroporosity in Ustolls of central South Dakota (Table 4, Fig. 2).

Tension Infiltration

The description of macroporosity showed macroscopic structural changes consequent to cultivation. Water infiltration under tension provided further information on very fine pores. Infiltration rates under tension reflect different soil porosity, pore-size distribution, and stability. Measurements of water infiltration at the 0.03- and 0.06-m tensions refer to <1- and <0.5-mm equivalent cylindrical diameter pores active in water transmission, respectively. We focused on pores larger than micropores with the purpose of comparing soils under different land use because micropores are much less susceptible to changes in management than macropores.

In Ustolls, water entered the topsoil of grass fields at a significantly greater rate than in till and no-till both at the 0.03- and 0.06-m tensions (Table 5). Pores of 0.5- to 1-mm diam. contributed to the total water flux through pores <1-mm in diameter to a greater extent in grass than in no-till and till. The macroscopic capillary length was minimum in grass, intermediate in no-till, and maximum in till in the range of applied tensions, although differences were not significant. The macroscopic capillary length is an estimate (relative to the tested range of water potentials) of the mean capillary rise above a water table, corresponding to a mean microscopic capillary radius. The microscopic capillary radii (estimate of the mean conductive pore size) were 0.30 mm in grass, 0.28 mm in no-till, and 0.20 mm in till, showing a trend toward increasing mean size of pores conductive to water after conversion of management system from till to no-till. No-till management was shown to increase pore continuity as compared with conventional tillage, despite a decrease of the mean pore size of the topsoil (0–0.30 m) in some loam soils (Azooz et al., 1996). Increasing the volume fractions of <1- and <0.5-mm continuous pores may result in improved water flow in the soil under tension. In a heavy clay soil of Finland, a greater volume fraction of pores <0.3 mm was found in no-till soils when compared with plowed soils (Aura, 1988 as cited in Rasmussen, 1999). Improved hydraulic properties in no-till soils may be a result of better pore continuity more than a change in size distribution.

In the two Usterts of this study, the large variability of measurements did not allow distinctions between management systems (Table 5). The average clay content was 58% in Usterts vs. 25% in Ustolls (Eynard, 2001).

Table 5. Water infiltration at 0.03- and 0.06-m tension in Ustolls ($N = 6$) and Usterts ($N = 2$) of central South Dakota (USA). Mean values are followed by standard errors inter parentheses. Probabilities of significant differences in the contrast between grass and cultivated soils and between till and no-till management systems are reported in the last two columns (G = grass, NT = no-till, T = till).

	Grass	NT	T	G vs. NT & T	NT vs. T
			Ustolls		
Flow rate at 0.03 m, μm s^{-1}	22 (3.9)	6 (1.2)	13 (2.0)	$P \leq 0.005$	$P \leq 0.128$
Flow rate at 0.06 m, μm s^{-1}	11 (2.3)	4 (0.8)	7 (0.6)	$P \leq 0.011$	$P \leq 0.179$
Macroscopic capillary length, mm	50 (8.7)	54 (7.9)	76 (19.2)	$P \leq 0.363$	$P \leq 0.265$
			Usterts		
Flow rate at 0.03 m, μm s^{-1}	15 (1.2)	17 (6.2)	19 (1.4)	$P \leq 0.607$	$P \leq 0.723$
Flow rate at 0.06 m, μm s^{-1}	7 (1.8)	7 (3.5)	6 (0.7)	$P \leq 0.846$	$P \leq 0.677$
Macroscopic capillary length, mm	29 (4.7)	37 (21.9)	20 (3.3)	$P \leq 0.997$	$P \leq 0.366$

Increasing variability of soil mechanical and hydraulic behavior with increasing clay contents was expected (Lin et al., 1997). Structural characteristics have greater impact on the physical behavior of clay soils than in sandy soils. In soils rich in smectitic clay, the macroporosity varies with structural changes and the structure spatially varies with irregular pattern in relation to cracks, presence of roots, and animal burrows. The variability of water infiltration cannot be attributed to differences between initial moisture content in different management systems because measurements were performed with uniform initial water content for the three treatments in each block. Large variability of unsaturated hydraulic conductivity data and consequent lack of significant differences between management systems was reported for Vertic Haplustolls with >65% clay of New Zealand (Sparling et al., 2000).

The relative flow rate (estimate of the contribution of very fine macropores of 0.5–1 mm in diameter to the flow in pores <1 mm) was significantly lower ($P \leq 0.014$) in Ustolls (44%) than in Usterts (57%). A greater contribution of pores >0.5 mm to water infiltration in soils richer in clays than in coarser-textured soils has already been observed (Lin et al., 1997).

Moisture Retention at −1-m Water Potential and Pore Stability to Soil Remolding

The development and stability of structure dominates over texture in determining physical properties of fine and very fine textured soils (Gee and Bauder, 1986), as in the majority of soils in this study. Information on the stability of macropores and mesopores was obtained by comparing total porosity and amount of micropores (pores of <0.030-mm equivalent cylindrical diameter)

between undisturbed soil cores and remolded samples. Micropore volume was estimated by measuring water retention at the −1-m water potential (defined as field water capacity).

In both Ustolls and Usterts, the bulk density tended to be less, but not significantly, in undisturbed than in remolded soil for any management system (Table 6). Ustolls showed significant differences between management systems both in remolded and in undisturbed samples (nonsignificant undisturbed-remolded × management-system interaction). The remolded soil bulk density of Ustolls was 1.20 Mg m^{-3} and was significantly less ($P \leq 0.001$) in grass than in no-till (1.29 Mg m^{-3}) and till (1.33 Mg m^{-3}). The bulk density of remolded soil was similar in all management systems in Usterts. The bulk density of remolded samples was significantly less in Usterts than in Ustolls.

The gravimetric water content retained at 1-m tension in undisturbed cores was similar between Ustolls and Usterts in the case of grass (approximately 0.37–0.38 g g^{-1}), but it was significantly less in Ustolls than in Usterts in the case of no-till and till soils (Table 7). Water retention was greater in grass when compared with cultivated treatments ($P \leq 0.005$) in Ustolls, without significant differences between no-till and till. Contrary to our findings, water retention was observed to be higher in no-till relative to till in silt loam soils of southwestern Ontario (Azooz et al., 1996). No significant differences between water retention in different management systems were found in Usterts.

In Usterts, remolding did not significantly affect total pore space (approximately 60%), but changed the pore-size distribution, decreasing the amount of >0.030-mm diam. pores (Table 6). Differences in moisture retention before and after remolding may have been enhanced by incomplete water filling of undisturbed cores due to air pockets left in micropores. Yet, significant differences in gravimetric moisture content at field capacity

Table 6. Mean bulk density (Mg m^{-3}) and mean moisture retention at −1 m water potential (g g^{-1}) in Ustolls and in Usterts of central South Dakota (USA) in undisturbed and remolded samples.

Parameter	Sample type	Ustolls	Usterts	Probability†
Bulk density		—— Mg m^{-3} ——		
	undisturbed	1.23	1.04	$P \leq 0.009$
	remolded	1.27	1.05	$P < 0.001$
	probability‡	$P \leq 0.230$	$P \leq 0.817$	–
Water retention at −1 m		—— g g^{-1} ——		
	undisturbed	0.31	0.38	$P \leq 0.005$
	remolded	0.32	0.52	$P < 0.001$
	probability‡	$P \leq 0.532$	$P < 0.001$	–

† Probability of significant differences between Ustolls and Usterts.
‡ Probability of significant differences between undisturbed and remolded samples.

Table 7. Mean moisture retention at −1-m water potential in undisturbed soil cores (g g^{-1}) of Ustolls and Usterts in central South Dakota (USA). Moisture retention was greater in grass when compared with cultivated treatments ($P \leq 0.005$) in Ustolls. No other differences in moisture retention between management systems were significant ($P > 0.05$).

Management	Ustolls	Usterts	Probability†
Grass	0.37	0.38	$P \leq 0.747$
No-till	0.30	0.39	$P \leq 0.015$
Till	0.28	0.38	$P \leq 0.027$

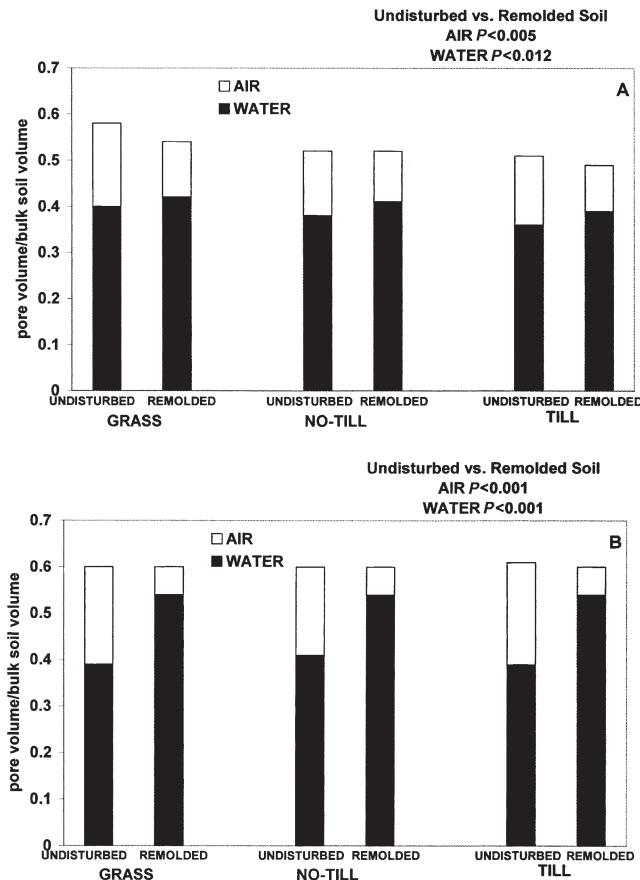† Probability of significant differences between Ustolls and Usterts.

Fig. 3. Air and water distribution in undisturbed and remolded soil at −1-m water potential in (A) Ustolls and (B) Usterts of central South Dakota (USA). Undisturbed-remolded × management interactions were not significant ($P \geq 0.05$). In the top right corner, probability of differences between undisturbed and remolded sample means are reported for air-filled pore volume (AIR = pores of >0.030-mm diam.) and water-filled pore volume (WATER = pores of <0.030-mm diam.). Standard errors for air and water were 0.016 and 0.011, respectively, in Ustolls ($N = 18$). Standard errors for air and water were 0.036 and 0.021, respectively, in Usterts ($N = 6$).

between undisturbed cores and remolded samples were not observed in Ustolls (Table 7). The increase of moisture retention was significant only when expressed as volumetric water content (Fig. 3). This increase corresponded to a significant decrease in air-filled pores with >0.030-mm diam.

Remolding reduced field-air capacity (air-filled porosity at the −10-m water potential) from 21 to 6% in all management systems in Usterts (Fig. 3). Working these soils at high moisture content risks decreasing the field-air capacity below the level of 10% of air-filled pore space that severely limits plant growth (Hillel, 1998). Risk of compaction and decreased pore sizes due to traffic and heavy loads in both grasslands and cultivated soils was shown by morphological observations in other soils (Boersma and Kooistra, 1994). In Ustolls, the decrease of field-air capacity was less evident (Fig. 3). Field-air capacity was ≥10% after remolding Ustolls. In remolded Ustolls both field-air capacity and field-water capacity were significantly higher in grass than in

cultivated soils ($P \leq 0.010$ and $P \leq 0.004$, respectively), with no significant differences between no-till and till.

Soils with different clay content are expected to behave differently because clay platelets in quasi-crystals can be reoriented from flecked (random) to striated (parallel) upon soil puddling (McGarry, 1989). Reorientation of particles under stress results in changes in pore-size distribution (Dexter, 1990). Usterts contain significantly greater amounts of clay that can be reoriented when compared with Ustolls as shown by remolded soil data. On the other hand, Usterts within this experiment showed a high structural stability, significantly higher than Ustolls (Eynard, 2001). In soils with strong stable aggregates such as Usterts, a significant period of time and energy is required to break down soil structure. Prolonged remolding is required to breakdown particularly stable aggregates (Campbell, 2001). Moreover when soil structure is damaged in Usterts, the forces associated with shrinking and swelling are able to restore soil structure (McGarry, 1996).

CONCLUSIONS

The use of several methods to quantify soil pore characteristics showed the effect of different land use on farms of central South Dakota. In Ustolls of central South Dakota, soil porosity and very fine pore-size distribution were affected by management systems. Differences between management systems were most evident in the surface horizons (0–0.30 m). Total pore space decreased in cultivated soils when compared with grasslands. No-tillage increased total soil porosity relative to tillage between the 0.05- and the 0.30-m depth below the surface. More very fine macropores (1- to 0.050-mm diam.) and, in particular, more tubular very fine macropores (indicating greater biological activity) were observed in grass than in cultivated soils, and more in no-till than in tilled soils. More <1- and <0.5-mm diam. pores conducted water under grass than in cultivated fields, allowing higher infiltration rates of water supplied under tensions of 0.03 and 0.06 m. Micropores (<0.030-mm diam.) as well as meso and macropores (>0.030-mm diam.) were reduced by cultivation in Ustolls. More micropores were present in grass than in till and no-till, both in undisturbed and in remolded soil samples. The reduction of field air-capacity upon remolding wet soil was greater in no-till and till than in grass. In grass, more pores >0.030 mm maintained aeration above 10% of the total bulk soil.

In contrast, in Usterts total pore space, very fine macropores, water infiltration under tension, moisture retention at field capacity, and field air capacity did not show significant changes due to differences in management system. However, grasslands tended to present more very fine tubular macropores and greater infiltration rates than cultivated soils, similar to Ustolls. The risk of compaction, decreasing air-filled porosity below the minimum needed for good plant growth, was higher in Usterts than in Ustolls.

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