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Effects of aggregate structure and organic C on wettability of Ustolls

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Abstract

Soil wettability is especially important for rainfed agriculture in climates with a dry period during the growing season. The effect of aggregate structure and soil organic C content on wettability of soil aggregates was determined for grassland (grass) and tilled fields (tillage). Soil organic C, plastic limit, aggregate total porosity, and wettability at 100 mm (rapid wetting) and 300 mm (slow wetting) water tension were measured on soil at 0–0.2 m depth. Natural aggregates from tillage and grass were compared to soil pellets formed by remolding aggregates. At both tensions, wettability of grass aggregates was significantly greater than that of tillage aggregates ($P \leq 0.001$). Pellets were significantly less wettable than natural aggregates at 300 mm tension and during the initial wetting at 100 mm tension, but became significantly more wettable with time at 100 mm tension. Cumulative water uptake during 60 min exceeded the initial total porosity of pellets and natural tillage aggregates, suggesting incipient failure (formation of microcracks) during fast wetting. Grass aggregates contained twice as much organic C as tillage aggregates (26 g kg^{-1} versus 13 g kg^{-1}). Organic C was linearly and positively related to plastic limit, total porosity, and the wettability of natural aggregates at 300 mm tension. At 100 mm tension, organic C was negatively related to wettability of natural aggregates under grass, but unrelated to wettability under tillage. Aggregate wettability was positively related to organic carbon content, except when the arrangement of soil constituents reduced or prevented incipient failure and soil dispersion during rapid wetting resulted in cumulative water uptake (60 min) similar to initial aggregate total porosity. Organic C increased wettability of grass aggregates when compared to tillage aggregates and also stabilized natural aggregates during fast wetting (100 mm tension). Both soil organic C content and aggregate structure were key factors controlling aggregate stability and wettability.

Keywords: Soil structure; Soil management; Aggregation; Water repellency; Soil carbon

1. Introduction

Relatively high and uniform wettability, defined as the opposite of repellency, is a desirable quality for agricultural soils, because water repellent zones

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prevent rapid and uniform soil wetting and hinder optimal crop growth (Blackwell, 2000). Wettability can be measured as a wetting rate, which is affected by organic and mineral composition of soil surfaces (hydrophilic and/or hydrophobic) and by structural arrangement of soil components (solids, water solution, and air). The term hydrophilicity (opposite of hydrophobicity), in contrast to wettability, is used to strictly refer to the molecular origin of soil surface–water interactions. At a molecular level, composition of solid surface-exposed chemical groups (hydrophilic and/or hydrophobic) and their packing density determine wettability. At a soil aggregate level, composition of soil and aggregate structure defined as the spatial distribution of soil particles and pores determine wettability.

Lack of soil wettability favors water runoff and surface erosion (Shakesby et al., 2000). On the other hand, some degrees of water repellency (sub-critical water repellency, Tillman et al., 1989) may stabilize soil against slaking and aggregate breakdown. Soil stability under natural vegetation has been related to relatively low wettability. Grass and/or forest soils have shown lower wettability than cultivated soils in previous studies (Quirk and Panabokke, 1962; Ellies et al., 1995; Chenu et al., 2000; Hallett et al., 2001; Sonneveld et al., 2003).

Both soil structural stability and wettability appear related to soil organic matter quantity and quality. Hydrophobic organic constituents, particularly aliphatic hydrocarbon units in the soil organic fraction, may be a primary cause of soil water repellency (Peng et al., 2003; McKissock et al., 2003). Production of long chain aliphatic compounds and lipids has been attributed to fungal populations favored by the absence of soil disturbance (Hu et al., 1995; Beare et al., 1997). Hydrophobicity of organic matter increased from bare fallow, to single crop, to crop rotation, and to permanent grass in a Luvisol (Alfisol) from Bavaria (Germany), as measured by diffuse reflectance infrared Fourier transform spectroscopy (Capriel, 1997). Specific flora covering the land is a major determining factor of soil wettability due to changes in litter amount and composition, root development, and associated rhizospheric organisms (Doerr et al., 1996; Scott, 2000; Buczko et al., 2002).

Water-repellent and water-soluble organic fractions affect soil wettability (Horne and McIntosh, 2000). Hydrophilic organic constituents dominate the composition of organic matter of most soils (Cheshire, 1979; Monreal et al., 1995). Large changes of water repellency can occur without removal of any compounds from soil, due to conformational changes of solid surfaces. According to Ma'Shum and Farmer (1985), hydrophilic functional groups of solid surfaces can interact with water molecules when the soil is wet and with each other when dry. The structure of natural hydrophobic organic compounds is not suitable for attaching to ion-exchanging clay minerals (Farmer, 1978). Therefore, soils with $\geq$15–20% silicate clay minerals are not likely to become water repellent through natural hydrophobic compounds.

Due to the considerable quantity of smectitic clay minerals that do not favor manifestation of water repellency, data on wettability of Mollisols are scarce. Studies of water repellency have usually dealt with soils expressing severe water repellency, such as volcanic ash (Andosols), sandy soils, soils contaminated by oil spills, or soils, covered by forests or bushes, especially in xeric or aridic moisture regimes favorable to fire. We studied Mollisols of central South Dakota (USA) under different agricultural management systems.

In prairie soils with smectitic clays, swelling of clay minerals and organic matter during wetting modifies porosity, pore characteristics, and hydraulic properties (Tillman et al., 1989). Soil management practices change soil composition and spatial distribution of soil components. The arrangement of organic matter within soil structure may control soil wetting more than the amount or quality of organic matter (Quirk, 1979; Franzluebbers, 2002). Macroscopic changes in soil porosity and aggregation due to tillage may contribute to differences in wettability between natural and cultivated soils and along cultivation intensity sequences (Ellies et al., 1995). Hydrophobic surfaces may play a minor role in explaining sub-critical water repellency observed in agroecosystems (Hallett et al., 2001). Instead, crusts, compaction, aggregate disruption, and slaking may strongly affect soil wettability that includes water entry into inter-aggregate and intra-aggregate pore spaces.

Intensive agroecosystem management can increase, or decrease aggregate wettability depending on the situation. Ellies et al. (1995) found that in forest, range, and agricultural soils, increased management intensity appeared to decrease wettability. In the northern Andes, intensive grazing strongly decreased soil organic matter content and broke down macro-aggregates, creating a highly water repellent soil structure (Podwojewski et al., 2002). In a study by Hallett et al. (2001), plowed soil showed much higher wettability than pasture soil. In soils where coatings are common, tillage may increase wettability by abrasion (Tillman et al., 1989). Aggregates from soils under no-tillage were less wettable than from plowed soils (Hallett et al., 2001). Higher water repellency was measured in topsoil of grasslands than in tilled corn (*Zea mays* L.) fields (Sonneveld et al., 2003).

Wettability is a function of antecedent water content and water tension (de Jonge et al., 1999; Doerr et al., 2002), and is affected by aggregate mellowing and slaking (Quirk and Panabokke, 1962). Slaking and mellowing may occur during wetting as a function of soil water tension and structural stability. Slaking is the process of fragmentation that occurs as a consequence of differential swelling and pressure by entrapped air when the aggregate is exposed to water at zero tension. At lower rates of wetting and under tension, aggregates are weakened by mellowing (McKenzie and Dexter, 1985; Grant and Dexter, 1990). Incipient failures (microcracks) occur at the boundaries between assemblages of clay particles (Murray and Quirk, 1990). Formation of microcracks with mellowing and slaking opens pathways for water entry during wetting (Grant and Dexter, 1989). Most soils are not affected by slaking at water tensions <10 kPa (Chan and Mullins, 1994). Some soils are stable at antecedent water tensions >100 kPa (Panabokke and Quirk, 1957). In general, slaking increases with increasing water tension (Chan and Mullins, 1994). However, in very dry soil (e.g., at 1000 kPa water tension) slaking may decrease due to decreased wetting rate from entrapped air in the aggregate (Panabokke and Quirk, 1957).

The objective of this study was to distinguish the effects of organic C content from aggregate structure on the wettability of soil aggregates of prairie (grass) and intensively tilled fields (tillage).

2. Materials and methods

2.1. Site description, experimental design, and sampling

Five locations were selected in the Upper Missouri River Basin (Fig. 1). Conventionally, tilled fields (tillage) and grasslands (grass) sharing similar topography and the same soil series were sampled at each site. All soils were Ustolls (Table 1). Highmore soils were present at two locations. Grasslands were typically used for hay or pasture and had never been tilled. Dominant grass species were bromes (*Bromus*

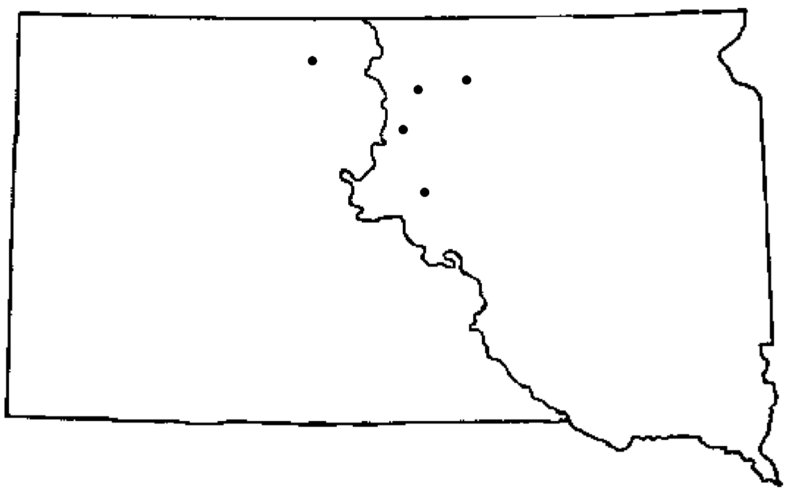

Fig. 1. Location of the studied Ustolls in the Upper Missouri River Basin of the northern Great Plains in South Dakota (USA).

Table 1
Soil series (Soil Survey Division, 2003; FAO, 1974) and clay (<2 μm) content (g kg^{-1}) of Ustolls sampled in central South Dakota (USA)

Soil series	Classification	Clay (g kg^{-1})	Organic C	
			Grass (g kg^{-1})	Tillage (g kg^{-1})
Lowry	Coarse-silty, mixed, superactive, mesic Typic Haplustoll (Haplic Chernozem)	208	21.0	7.6
Reeder	Fine-loamy, mixed, superactive, frigid Typic Argiustoll (Luvic Chernozem)	196	31.6	14.0
Highmore	Fine-silty, mixed, superactive, mesic Typic Argiustoll (Luvic Chernozem)	282	24.5	14.0
Williams	Fine-loamy, mixed, superactive, frigid Typic Argiustoll (Luvic Chernozem)	289	29.4	16.3

The FAO classification is given in parentheses.

sp. pl.), wheatgrasses (*Agropyrum* sp. pl.), and Kentucky bluegrass (*Poa pratensis* L.). Conventional tillage was the management system of tilled fields for >80 years. Chisel plow and tandem disk operations in the spring have been used as primary and secondary tillage, respectively, for at least the last 20 years. Depth of tillage varied between 0.07 and 0.20 m. Cropping systems included wheat (*Triticum aestivum* L.), corn, and soybean [*Glycine max* (L.) Merr.]. The experiment was carried out according to a randomized complete block design with five replications. Locations were used as replications. Land uses (tillage and grass) were compared as treatments.

A hydraulic, 76 mm diameter, soil probe was used to sample soils to 1–1.5 m depth. Profiles were compared according to standard procedures (Soil Survey Staff, 1998). Four sampling areas with similar soil profiles and landscape positions were selected within each of the individual fields at each location. At each sampling area, soil samples were collected from 0 to 0.20 m depth with a spade. Samples were air-dried at room temperature, thoroughly mixed, and pooled by treatment at each location. Samples were stored dry at relative humidity (p/p_0) ~ 0.28 until analysis without any removal of organic particles, pre-sieving, or grinding.

2.2. Organic C and texture

The fine earth fraction (<2 mm diameter) of each sample was ground prior to textural and organic C determinations. Soil particle size distribution was determined by the pipette method (Gee and Or, 2002). Soil organic C was determined by dry combustion of total C (Nelson and Sommers, 1982) followed by subtraction of inorganic C (Wagner et al., 1998).

2.3. Plastic limit

Soil plastic limit was determined as the mean of three repeated measurements by the rod standard procedure (Russel and Wehr, 1928; Archer, 1975). Soil was considered at its plastic limit when a 3 mm diameter rod started breaking into 5–10 mm long pieces.

2.4. Total porosity

Bulk density was measured on air-dry aggregates by the clod method (Grossman and Reinsch, 2002). Total porosity of air-dry aggregates was calculated from bulk density, assuming a particle density of 2.65 Mg m^{-3}.

2.5. Pellet preparation

Soil pellets were prepared by remolding soil from natural aggregates wetter than the plastic limit (McKenzie and Dexter, 1985). Gravimetric moisture content was 0.05 kg water kg^{-1} soil greater than the plastic limit of each sample. Remolded soil was pressed in a rigid cylinder to a constant bulk density (1.70 Mg m^{-3}) equal to the average bulk density of air-dry natural aggregates from tilled soil. Cylindrical pellets of 1 cm^3 volume were made and air-dried at room temperature before wettability tests.

2.6. Wettability

Natural soil aggregates of 10 ± 5 mm size were selected from air-dry topsoil and were gently scraped with fine sandpaper on one side to assure good contact during wetting. Wetting rate was measured with an apparatus consisting of Büchner funnels (60 mm diameter) with the sintered glass base connected by a flexible tube to a horizontal graduated glass capillary (Quirk and Panabokke, 1962). The system was filled with de-ionized water. Different wetting tensions were obtained by adjusting the vertical distance between the glass capillary tube and the top of the sinter. Largest pores of the glass sinter were 40–60 μm diameter in order to support a tension of 0.30 m. Ten natural or remolded aggregates (∼16–20 g) were placed on the sinter over a filter paper of high permeability with the flattened face of each aggregate in contact with the wetting paper. Care was taken to assure uniform contact area of all aggregate beds (approximately 10 cm^2). Aggregates were initially air-dry ($p/p_0 \sim 0.28$). Rate of wetting was measured by movement of the meniscus in the graduated capillary and amount of water taken up by the aggregates checked by oven drying. Management system (grass versus tillage) and type of aggregate (natural versus pellet) treatments were organized in a two-factor factorial arrangement. In each trial, four treatment combinations were compared (grass natural aggregates, grass pellets, tillage natural aggregates, and tillage pellets). Measurements were repeated three times (sub-samples) for each treatment combination in each block. Two wetting tensions were separately tested (100 and 300 mm).

2.7. Statistical analysis

Data were analyzed using the SYSTAT 11 statistical program (SYSTAT, 2004). Relationships between measured soil properties were tested by regression. A log–log transform was applied to the water uptake data to remove heteroscedasticity (heterogeneity of variance), normalize the data for analysis, and linearize the time curve. A power function of the form $y = \alpha x^{\beta}$, linear form $\log y = \log \alpha + \beta \log x$, was fit to the data points where y = cumulative water uptake (g kg^{-1}); x = time (min); α = base water uptake rate (g kg^{-1} min^{-1}) (i.e., water uptake rate at $x = 1$); $\beta = a$ unitless curve fitting parameter that modifies the effect of time on cumulative water uptake. A repeated measures analysis of variance was used to evaluate the contribution of treatment factors to water uptake rates. Comparisons between all four-treatment combinations were made using Tukey's HSD test for pairwise comparisons. The results of the two tension measurements were analyzed separately since these measurements were made at separate times. Significance was considered at $P \leq 0.05$.

2.8. Critical comparisons

Natural and pellet aggregates were compared to test the effects of changes in aggregate structure in the absence of a change in organic C content. Aggregate structure included the combined effects of total porosity, pore size distribution, and carbon arrangement between grass natural and pellet treatments. The test of aggregate structure between tillage natural and pellet included the combined effects of pore size distribution and C arrangement since total porosity was the same between the two treatments. The comparison of grass natural versus pellet tested the combined effect of organic C content and aggregate structure as did the sub-comparison of natural grass versus natural tillage treatments. Grass pellet compared to tillage pellet tested the effect of organic C content since both pellets were assumed to have similar structures after remolding.

3. Results

Particle size distribution was similar between grass and tillage systems within each site. Clay content was 241 g kg^{-1} soil on average (Table 1). Smectitic clay minerals dominated the clay fraction.

Tillage decreased the organic C of the natural prairie. Topsoil under grass contained, on average, twice as much organic C as under tillage (26 g kg^{-1} versus 13 g kg^{-1}; $P \leq 0.001$). Total porosity of natural aggregates was greater under grass than under tillage (0.46 m^3 m^{-3} versus 0.36 m^3 m^{-3}; $P \leq 0.004$) and linearly related to soil organic C content (Fig. 2).

Soil plastic limit was also greater under grass than under tillage (254 g water kg^{-1} soil versus 222 g water kg^{-1} soil; $P \leq 0.005$) and linearly related to soil organic C ($P < 0.001$). On average, plastic limit increased 2.5 times for each organic C unit (g kg^{-1}) increase. Organic C content explained 89% of variation in soil plastic limit (Fig. 3).

At 300 mm tension there was a significant three-way interaction between time, management, and aggregate type based on the repeated measures analysis (Fig. 4). However, there was no significant

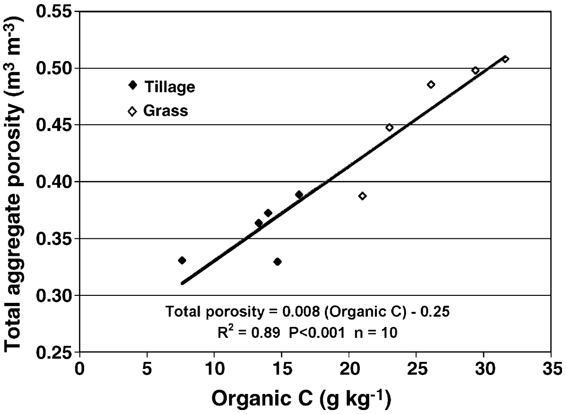

Fig. 2. Relationship between aggregate total porosity and soil organic C content in natural aggregates under grass and tillage of Ustolls from the northern Great Plains in South Dakota (USA).

interaction between management and aggregate type in either of the fitting parameters, although the probability of the α parameter for the grass and tillage comparison was significant (Table 2). The three-way interaction appeared to be primarily related to significant accumulation of water over time in the grass natural aggregate treatment (Fig. 4; Table 4). At 300 mm tension, wetting was slow and natural aggregates from grass had the highest wettability.

Fig. 5 illustrates the differences in cumulative water uptake at 100 mm of tension. Repeated measures analysis at 100 mm tension showed significant differences in wettability between grass and

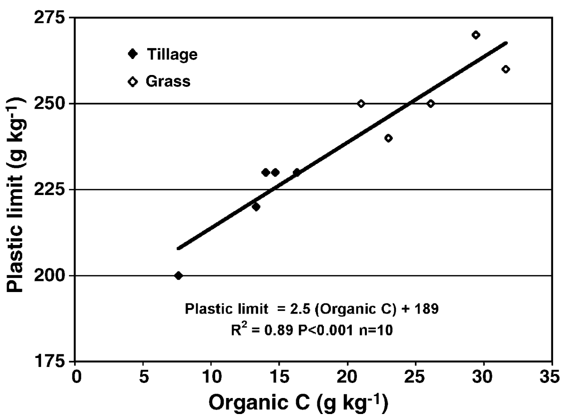

Fig. 3. Relationship between soil plastic limit and organic C content in natural aggregates under grass and tillage of Ustolls from the northern Great Plains in South Dakota (USA).

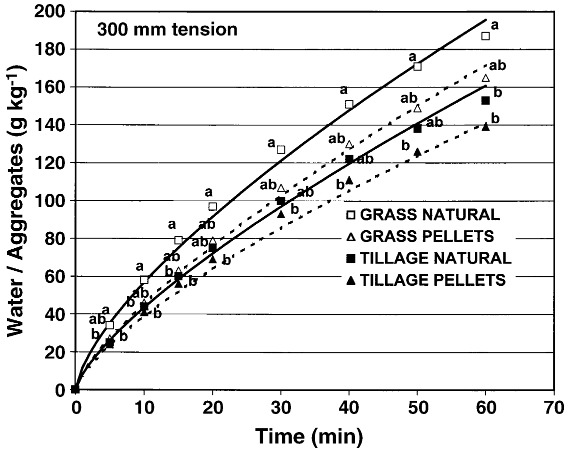

Fig. 4. Wetting at 300 mm tension of Ustolls from the northern Great Plains in South Dakota (USA). Means of three repeated measurements per site ($n = 15$) per time are shown in the graph. Lines represent a fit of the model curve, $y = \alpha x^{\beta}$. Model parameters are reported in Table 2. Means followed by the same letter are not significantly different within each time ($P < 0.05$). Solid lines represent natural aggregates. Dashed lines represent remolded aggregates (pellets).

tillage aggregates with no interactions with aggregate type or time. The probability of the difference between grass and tillage for base water uptake rate, α, was <0.06, but it was <0.67 for the time-water-uptake parameter β as shown in Table 2.

There was a significant management-aggregate type interaction for the difference between volumetric water content at 60 min of wetting at 100 mm tension and initial total porosity ($P \leq 0.006$). Grass natural aggregates had a cumulative water uptake during 60 min similar to initial aggregate total porosity. The difference between volumetric water content and initial total porosity was greater than zero and not significantly different among tillage natural, pellet, and grass pellet treatments (Table 3).

Aggregate type (natural versus pellet) interacted with time for wettability at 100 mm tension. The α and β parameters were both highly significant, indicating a difference in water uptake rates over time between natural and pellet treatments. The nature of interaction was related to an initially greater rate of water uptake during the first 5 min by the natural aggregates followed by reduced water uptake compared to the pellet treatments (Fig. 5; Table 3). During 1 h of fast wetting (100 mm tension) (Table 3), the average rate

Table 2
Curve fitting parameters for cumulative water uptake from soil aggregates from central South Dakota (USA) Ustolls at 300 and 100 mm tensions during a 60 min time period

Tension	Treatment	α	β	R^2
300 mm	Grass natural aggregates	11.6	0.69	0.92
	Grass pellets	8.3	0.74	0.83
	Tillage natural aggregates	8.1	0.73	0.95
	Tillage pellets	7.4	0.72	0.77
	Grass vs. tillage	$P < 0.02$	$P < 0.37$	–
	Natural vs. pellet	$P < 0.32$	$P < 0.34$	–
100 mm	Grass natural aggregates	166	0.17	0.68
	Grass pellets	119	0.29	0.79
	Tillage natural aggregates	136	0.19	0.63
	Tillage pellets	101	0.29	0.78
	Grass vs. tillage	$P < 0.06$	$P < 0.67$	–
	Natural vs. pellet	$P < 0.006$	$P < 0.001$	–

The regression equation was (cumulative water uptake = α (time)$^{\beta}$) where α = base water uptake rate (g kg^{-1} min^{-1}) and β = unitless time-water-uptake modification parameter. Coefficients of determination (R^2) of all regressions were significant at a probability level $P < 0.001$. Interactions between management (grass, tillage) and aggregate type (natural, pellets) for α or β were not statistically significant.

of water intake was greater in pellets than in natural aggregates ($P \leq 0.003$).

Wettability of natural aggregates in the case of slow wetting (300 mm tension) was positive and linearly related to soil organic C (Fig. 6). No relationship between soil organic C and wettability of natural aggregates was found when water was supplied at low tension (100 mm) when tillage and grass management systems were considered together (Fig. 7). However, a negative linear relationship was evident in soil under grass (Fig. 7), showing a >5-fold decrease in water intake per unit increase of organic C. A negative linear relationship was also found for the difference between volumetric water content at 60 min of wetting and initial total porosity, and organic C of the natural grass aggregates ($R^2 = 0.87$, $N = 5$, $P \leq 0.013$), but no relationship in the case of tillage.

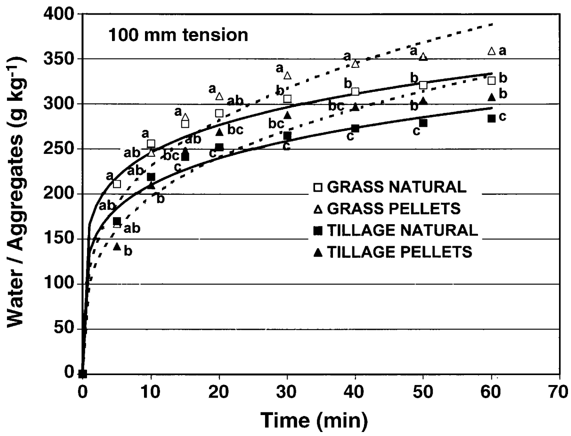

Fig. 5. Wetting at 100 mm tension of Ustolls from the northern Great Plains in South Dakota (USA). Means of three repeated measurements per site ($n = 15$) per time are shown in the graph. Lines represent a fit of the model curve, $y = \alpha x^{\beta}$. Model parameters are reported in Table 2. Means followed by the same letter are not significantly different within each time ($P < 0.05$). Solid lines represent natural aggregates. Dashed lines represent remolded aggregates (pellets).

4. Discussion

Natural aggregates under grass and tillage differed both in organic C content and aggregate structure. Aggregates were remolded at water contents greater than the plastic limit in order to dismantle the original aggregate arrangement. An increase of the plastic limit with increasing organic C suggests that soil under grass would maintain more favorable structural properties in wetter conditions than under tillage.

We infer that organic C content differences were the principal reason for the differences in cumulative water uptake during 60 min between grass and tillage pellets (Table 3; Fig. 5) since both were packed to the same bulk density with the same procedure. Organic

Table 3
Gravimetric ($g\ kg^{-1}$) and volumetric ($m^3\ m^{-3}$) water content at 60 min of wetting at 100 mm tension (water) and difference between this volumetric water content and total porosity (porosity) of air-dry aggregates (water-pores) of Ustolls from central South Dakota (USA)

Treatment	Water[a]		Porosity ($m^3\ m^{-3}$)	Water-pores ($m^3\ m^{-3}$)
	$g\ kg^{-1}$	$m^3\ m^{-3}$		
Grass natural aggregates	338ab	0.48b	0.47a	0.02b
Grass pellets	366a	0.62a	0.36b	0.26a
Tillage natural aggregates	289c	0.49b	0.36b	0.13ab
Tillage pellets	314bc	0.53b	0.36b	0.18a
Grass vs. tillage	$P < 0.001$	$P \leq 0.08$	$P < 0.001$	$P \leq 0.63$
Natural vs. pellet	$P \leq 0.003$	$P \leq 0.001$	$P < 0.001$	$P < 0.001$

[a] Within a column means followed by the same letter are not significantly different ($P \leq 0.05$).

components of soil under grass were more abundant and showed similar or more hydrophilic behavior and increased wettability relative to soil under tillage.

In soils under tillage, natural aggregates did not show similar wettability to pellets for fast wetting (100 mm tension) (Tables 2 and 4). Both pellets and natural aggregates of soil under tillage contained the same amount of organic C and total pore space in air-dry conditions, so that differences in wettability may have been due to differences in pore size distribution and pore stability. The significant difference in the base water uptake rate (α) between the tillage natural and pellet treatments suggests an initial difference in pore size distribution. The significant difference in the time-water-uptake modification parameter (β) could be related to changes in pore stability occurring during the wetting process.

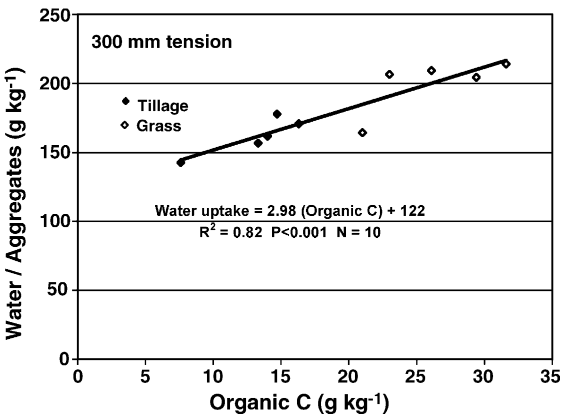

Fig. 6. Relationship between water uptake at 60 min of wetting at 300 mm tension and organic C in natural aggregates under grass and tillage of Ustolls from the northern Great Plains in South Dakota (USA).

Natural grass aggregates and grass pellets had the same organic C content, but different aggregate structure including differences in total porosity. Natural grass aggregates were stable during rapid wetting, while grass pellets were not stable (Table 3). The cumulative water intake after 60 min at low tension in natural grass aggregates was close to the total pore space, implying reduced swelling and/or reduced creation of failures within the aggregate matrix. Pores act as zones of weakness in aggregates and large unstable pores can trigger aggregate break down. Most grassland pores appeared to be biopores formed as root channels with dark organic coatings when the topsoils were morphologically described. This observation suggests that pores in grass natural

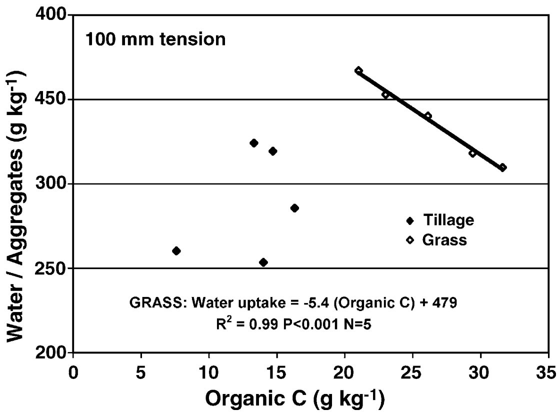

Fig. 7. Relationship between water uptake at 60 min of wetting at 100 mm tension and organic C in natural aggregates under grass and tillage of Ustolls from the northern Great Plains in South Dakota (USA). No significant ($P \leq 0.05$) linear relationship was found between water intake at 60 min of wetting at 100 mm tension and organic C in natural aggregates of tilled Ustolls.

Table 4
Wetting rate (g water kg^{-1} soil min^{-1}) during the first 5 min of wetting (0–5 min) and during the following 5 min (5–10 min) of Ustolls from central South Dakota (USA)

Treatment	300 mm tension[a]		100 mm tension[a]	
	0–5 min (g kg^{-1} min^{-1})	5–10 min (g kg^{-1} min^{-1})	0–5 min (g kg^{-1} min^{-1})	5–10 min (g kg^{-1} min^{-1})
Grass natural aggregates	6.7a	4.9a	42.2a	8.9b
Grass pellets	5.4ab	3.8ab	33.4ab	15.8a
Tillage natural aggregates	5.0b	3.7ab	34.1ab	9.7b
Tillage pellets	4.8b	3.4b	28.5b	13.5a
Grass vs. tillage	$P \leq 0.006$	$P \leq 0.02$	$P \leq 0.01$	$P \leq 0.34$
Natural vs. pellet	$P \leq 0.05$	$P \leq 0.03$	$P \leq 0.007$	$P < 0.001$

[a] Within a column means followed by the same letter are not significantly different ($P \leq 0.05$).

aggregates were likely to have been strengthened by organic matter deposited along pore walls. Linkage between clay domains on the periphery of coarse pores (e.g., 15–50 μm equivalent cylindrical diameter; Quirk and Williams, 1974) was indicated in the model of soil structure of Quirk and Murray (1991). Especially, coarse pores need support for the stability of soil structure, because rapid water entry involves coarse pores (Quirk and Panabokke, 1962).

The initial time lag for water intake in pellets of both grass and tillage treatments (Table 2; Fig. 5) can be explained by the incipient failure of the pellets. Creation of failures most likely accompanied clay swelling in pellets. Formation of microcracks would allow water entry into pores that were not existent in dry pellets. Failures probably also formed in tillage natural aggregates although to a lesser extent than in pellets. Some biopores from crop and weed roots were left after tillage in cultivated fields and may have favored initial water intake, which tended to be quicker in tillage natural aggregates relative to pellets. Only in grass natural aggregates was the difference between pore volume of dry aggregates and water volume of wet aggregates negligible (Table 3), indicating absence of incipient failure.

New voids disrupting unstable aggregates would cause incipient failure. Low aggregate stability and low water tension (rapid wetting) would favor aggregate failure and slaking. In the presence of smectitic clays, mechanisms of air entrapment (compression of occluded air in capillary pores) and differential swelling would act simultaneously during fast wetting, since destruction by air pressurization increases the surface accessible to the swelling action of water (Grant and Dexter, 1990). Pore occlusion by clay swelling would favor air entrapment (Panabokke and Quirk, 1957). Stresses from rapid wetting would be enhanced by the rapid release of heat of wetting and by the mechanical action of moving water (Chan and Mullins, 1994). A result of incipient failure is that a greater amount of water could be retained by soil in an open network of clay domains as compared to water held between aggregates of domains bound together by organic matter (Quirk and Panabokke, 1962). Clay domains are defined in this context as compound units of oriented primary clay particles of 1–2 μm diameter. This would explain why higher water content was retained by soil when wetting rate was faster and aggregates underwent incipient failure and subsequent slaking (Chan and Mullins, 1994).

Virgin and cultivated Australian Haploxeralfs with similar porosity and different organic C content and arrangement were tested by Quirk and Panabokke (1962). In our experiment, remolded aggregates of Ustolls under grass and tillage had similar porosity, and different organic C content, but similar arrangement of organic C. With rapid wetting at 100 mm tension, creation of microcracks in cultivated aggregates of Haploxeralfs resulted in greater wettability of cultivated soils when compared to virgin soils, which did not mellow. Instead, the presence of large interconnected stable pores in natural aggregates of in our Ustolls under grass was able to maintain the highest rate of water intake at both low and high wetting tension during the first 10 min of wetting. In contrast, structural breakdown had to occur for rapid water intake into soil pellets.

Adsorbed polysaccharide networks on soil minerals have mechanical properties that can significantly withstand pressures created in aggregates by rapid wetting (Czarnes et al., 2000; Ferruzzi et al., 2000). In natural aggregates under grass, loose networks of polysaccharides, which are highly hydrophilic, could have provided reinforcement against slaking, allowing air to escape through the largest pores without disrupting the aggregates. Air release through the largest pores could slow down the rate of water entry that would be fastest through the largest pores (Ferruzzi et al., 2000). Decreased wetting rate was shown in experiments with soils amended with polygalacturonic acid, which is abundant in the rhizosphere, as compared to non-amended soils (Czarnes et al., 2000). Thus hydrophilic organic compounds can slow down wetting and increase soil stability.

The hydrophilic nature of organic compounds in Ustolls was shown by the greater wettability in the presence of greater organic C (grass versus tillage). Rearrangement of mineral and organic materials determined the different wettability of grass pellets relative to grass natural aggregates.

The conclusion of other studies (Harper et al., 2000; McKissock et al., 2003) that management practices increasing soil organic C content increase water repellency did not hold for these Ustolls of South Dakota. Increased amounts of organic C increased soil wettability of soils under grass (as shown by the greater water intake of soil under grass relative to tillage), except when location of the organic soil constituents prevented incipient failure and soil dispersion during rapid wetting (as shown by the lower water intake of natural aggregates relative to pellets).

Stability against incipient failure of aggregates due to aggregate structure (pore characteristics and C arrangement) was also supported by a linear negative relationship between wettability and organic C content at 100 mm tension in grass natural aggregates which was not observed in grass pellet aggregates. Direct relationships between organic C and soil wettability are often hidden by other variables, such as soil bulk density and texture. At low water tension, total pore volume has a major impact on wettability because pores of most sizes are involved in the wetting process, while pore size distribution and soil surface area and chemistry tend to control water flow and retention with increasing water tension (Hajnos et al., 2002). In our study, aggregate organic C content was closely related to total porosity of natural aggregates. Total organic C gave a limited prediction of wettability ($R^2 = 0.36$) in sandy soils of western Australia, where texture dominated over amounts and forms of organic C in determining soil water repellency (McKissock et al., 2003). In our experiment, other variables were similar, such that organic C and wettability formed a closer relationship.

Grasses of the mid-tall prairie in the Upper Missouri River Basin produce organic matter and recycle nutrients resulting in topsoil accumulation of basic humus (Soil Survey Staff, 1999). This pool of organic matter is quickly lost upon cultivation due to enhanced decomposition through aeration, erosion, and low return with subsequent crop harvest removal. Abundance of divalent cations (Ca^{2+} in particular) favors the formation of smectitic clay minerals, which are dominant and slowly illuviated. High content of swelling clay minerals of Ustolls is favorable to high wettability, because of hydrophilic silicate clay surfaces. In other experiments, none of the soil clay fractions ($<2\ \mu m$) extracted from soils containing $>10\ g\ kg^{-1}$ organic C appeared truly hydrophobic since contact angles were $\leq 60^\circ$ (Chenu et al., 2000). Further characterization of organic matter (e.g., extraction of polysaccharides) may provide detailed information on the molecular mechanisms supporting the macroscopic structural differences between soils under grass and tillage.

5. Conclusions

Aggregate wettability tests conducted at different water tensions measured intra-aggregate water flow and aggregate stability to water transmission. Hydrophilic components of organic matter were able to both increase and decrease aggregate wettability depending on aggregate structure and water tension. Hydrophilic organic components deposited along a network of inter-connected pores strengthened natural aggregate structure under grass. If water enters aggregates faster than intra-aggregate pore stability can withstand, soil structure could be disrupted and water infiltration hindered by pore sealing.

The relationship between organic C and wettability was a function of water tension during wetting. The negative relationship between organic C and wettability observed under grass for rapid wetting (100 mm tension) agreed with the common finding that an increase in organic matter decreases wettability. Some degree of water repellency (sub-critical water repellency) may be expressed in different soils at different initial moisture contents. Sub-critical water repellency appeared important for soil structural stability and hydrological characteristics of Ustolls of central South Dakota. As previously noted for soils of New Zealand (Wallis et al., 1991), the term sub-critical may not be the best to indicate a soil property of major importance. Measuring wettability may be useful in characterization of soil quality in addition to other aggregate stability measurements.

This study demonstrated that a relatively high rate of water uptake at low water tension could take place within aggregates with stable intra-aggregate pore structure. Intra-aggregate pores are critical for plant available water storage and exchange of gases and water-soluble products between the aggregate exterior and interior. Our findings have important implications for soil hydrology and for microbial ecology within aggregates. More information is needed about the C dynamics involved in the development of a stabilized pore architecture including spatial arrangement of C compounds, and intra-aggregate pore formation.

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