Soil Water Hysteresis in Water-Stable Microaggregates as Affected by Organic Matter

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Interaction of water and organic matter (OM) in pores affects the capacity for long-term C sequestration and water retention in soils. This study investigated the effects of the amount and distribution of OM in microstructures on water retention in soil microaggregates. The focus of the study was on the hysteretic soil water characteristic (i.e., the difference between the main drying and wetting curves), which has been largely ignored in previous studies on water–OM relations. The main drying and wetting branches of the water retention curve were measured using a water activity meter on water-stable microaggregates (53–250 μm), which were collected from surface soils (0–15 cm) subject to different management practices: tallgrass prairie restoration on a Mollisol, and tillage with and without N fertilization on an Alfisol. The results show that the presence of OM in <5-μm-diameter pores increases water retention in microaggregates, while management practices that either increased or decreased the abundance of OM-filled pore volume in the microaggregates promoted hysteresis of water retention characteristics due to changes in soil pore structure. Comparison of the drying and wetting curves between intact and combusted (OM removed) microaggregates indicated a strong retention of water by pore-filling OM. This retention suggests that the high water saturation in microaggregates from soils under management practices that increased OM-filled porosity, which also offered physical protection of the OM, may be a positive feedback mechanism that retards OM decomposition in micropores. The water retention data measured on intact and combusted microaggregates were consistent with results from ultra-small-angle x-ray scattering, and indicated that management practices have a great potential for facilitating the synergistic retention of water and organic C in soils.

Abbreviations: ANCOVA, analysis of covariance; OC, organic carbon; OM, organic matter; SSA, specific surface area.

Stability and turnover of organic matter (OM) in soils is an important issue for global C management. Soil OM favors the formation of stable soil structure, high soil water retention, and balanced nutrient dynamics (Oades, 1984; Elliot, 1986; Bronick and Lal, 2005). A number of studies have found that, as a feedback effect, the formation of microaggregates, especially those relying on OM as a binding agent, is crucial for long-term sequestration of organic C (OC) in soils (Six et al., 1999, 2000a; Bossuyt et al., 2005). Organic matter can be protected against decomposition in microaggregates, resulting in substantially slower average turnover times compared with OM in macroaggregates (Monreal et al., 1995; Angers and Giroux, 1996; Besnard et al., 1996; Jastrow et al., 1996; Skjemstad et al., 1996; Balesdent et al., 2000). Therefore, processes controlling the dynamics of soil aggregate formation and stability can have a profound influence on OC sequestration in soils (Blanco-Canqui and Lal, 2004). Six et al. (2000a,b) concluded that no-till management reduced the rate of macroaggregate turnover compared with conventional tillage cropping systems and promoted the formation of stable microaggregates in which OC is stabilized and sequestered over the long term.

Various mechanisms of OM stabilization in soils have been proposed, including chemical, biochemical, and physical protection (Sollins et al., 1996; Baldock and Skjemstad, 2000; Christensen, 2001). An important factor that is involved in these mechanisms is the water content associated with the microaggregate structure. The small pores in soil microaggregates favor strong water retention. Thus, the effects of soil drying and wetting conditions on water dynamics and microbial activities in microaggregates can differ from those in the bulk soil. Because of the relatively strong anaerobic environment often present in the micropores, pore-scale OM–water interactions can substantially affect biochemical transformation of soil OM. The OM distribution in soil microstructures can also change soil pore connectivity, leading to changes in soil water flow among pores. All of these processes suggest that OM preservation closely interacts

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with water characteristics within soil micropores (Rawls et al., 2003; Mikha et al., 2005; Ojeda et al., 2006).

At present, a major limitation to understanding the relationship between soil water and OC is the lack of information on hysteretic effects on soil water. The relationship between water content and matric potential differs depending on whether the soil is wetting or drying; this path dependence is known as *hysteresis*. Hysteresis occurs mainly because of differences in pore shape, size, and interconnectivity (Hillel, 1998, p. 771). In natural porous media, especially structured soils, a certain percentage of the pore space does not drain because pores are either completely disconnected or are only connected to the atmosphere via smaller pores. With irregularly shaped pores, drainage is determined by the smallest opening or neck, while water entry is controlled by the dimensions of the main pore body. Small pores fill up first and empty last, while large pores empty first and fill up last. Large pores that are connected to the atmosphere via smaller ones will not empty, however, until the smaller ones have drained. The OM content and distribution in soil microstructures has been found to influence pore-size distributions (McCarthy et al., unpublished data, 2005). Thus, it is essential to quantify the relationship between soil OM and the hysteretic characteristics of soil water retention to improve our mechanistic understanding of the turnover of soil OC under cyclical drying and wetting conditions.

Given the importance of water–C interactions to long-term OC sequestration, the objective of this study was to determine the effect of OM amount and distribution on the hysteretic characteristics of water retention in soil microaggregates. The overall hypothesis driving the study was that pore filling of OM is a critical mechanism determining soil water retention and the associated hysteretic characteristics. If so, hydrologic effects may be an additional mechanism that can promote long-term preservation of OC in soil structures. In this study, we investigated the hysteretic water retention characteristics of water-stable microaggregates isolated from soils subjected to agronomic management systems that affect OM accumulation (e.g., tillage vs. no-till at two levels of N fertilizer inputs) and land use options for enhancing OM sequestration (e.g., prairie restoration).

MATERIALS AND METHODS

Sources and Preparation of Soil Microaggregates

Soil samples were collected from two field sites representing different soil orders and land use or management practices that can alter soil OM stocks. One site, located at the National Environmental Research Park at Fermi National Accelerator Laboratory (Fermilab), Batavia, IL, consisted of plots in a chronosequence of tallgrass prairie restorations initiated in 1975 on land previously cultivated for >100 yr (Jastrow, 1987, 1996; Allison et al., 2005). Five plots in this chronosequence were sampled in mid-September 2002. A variously cultivated agricultural field was used as the baseline point (time zero) of the chronosequence. In the decade before sampling, this field had been rotated between corn (*Zea mays* L.) and soybean [*Glycine max* (L.) Merr.] using conservation tillage and was in corn when sampled. Three restored prairie plots planted in spring 1993, spring 1984, and fall 1978 were completing 10, 19, and 24 growing seasons at the time of sampling. The fifth sampled plot was a remnant of virgin (i.e., never cultivated) tallgrass prairie, which was used to represent the steady-state condition for the chronosequence. Vegetation in the restored and remnant prairies was a mixture of C_4 grasses and C_3 forbs and sedges. The dominant grasses were big bluestem (*Andropogon gerardii* Vitman) and Indian grass [*Sorghastrum nutans* (L.) Nash]; members of the Compositae contributed significantly to the forb component. All soil samples were taken from areas classified as Drummer silty clay loam (fine-silty, mixed, superactive, mesic Typic Endoaquolls).

The second study site, with different agricultural management systems, was located at the University of Kentucky's Spindletop experimental farm (Lexington, KY). This site was established with the aim of comparing the long-term influence of tillage and fertilization practices on an Alfisol's OM content. The soil is a Maury silt loam (fine, mixed, semiactive, mesic Typic Paleudalf). Experimental treatments include conventional tillage (CT) vs. no-till (NT) at two levels of N fertilization (0 and 336 kg N ha^{-1}) (Frye and Blevins, 1997). The experiment was started in 1970, 32 yr before we collected soil from replicate subplots for microaggregate isolation. The site was a bluegrass (*Poa pratensis* L.) pasture for horses for about 50 yr before the treatments were established. The treatments are designated as CT0, CT336, NT0, and NT336 to indicate the tillage system and fertilizer level.

Six to eight replicate soil cores (4.8 cm in diameter) were taken to a depth of 15 cm from randomly selected locations in each of the plots at each field site. Samples were pooled in the field and refrigerated at 4°C for 1 mo before they were processed by passing the field-moist soil gently through an 8-mm sieve. Roots, rhizomes, and larger pieces of organic debris were removed during the sieving; when pieces of these materials longer than 8 to 10 mm passed through the sieve, they were removed manually. The sieved soils were air dried and stored in polyethylene bags at room temperature for 3 mo before isolation of microaggregates.

Water-stable microaggregates (53–250 μm) were isolated from the 8-mm sieved soil by using a microaggregate isolator (Six et al., 2000a). For whole soils exhibiting aggregate hierarchy, as in this study, this device isolates microaggregates from within water-stable macroaggregates in addition to collecting any "free" microaggregates present outside of stable macroaggregates. Briefly, 10 g of air-dry soil was immersed in a column of flowing deionized water maintained at a height of 2.5 cm above a 250-μm mesh screen in the microaggregate isolator and shaken with 50 stainless steel beads (4-mm diameter). The continuous and steady water flow through the device while shaking caused free microaggregates and microaggregates released from within macroaggregates to be immediately flushed through the screen onto a 53-μm sieve, avoiding further disruption. After all macroaggregates were broken up, the material caught on the 53-μm sieve was wet sieved for 2 min (50 up–down strokes) to ensure that isolated microaggregates were water stable. Because Fermilab soils exhibit a high level of aggregate stability under perennial vegetation (Jastrow and Miller, 1998), the procedure was modified for these soils to facilitate breakdown of macroaggregates. Thus, air-dry Fermilab soil samples were first slaked by immersion in deionized water in an aluminum pan for 10 min and then subjected to the microaggregate isolator. To collect sufficient amounts of microaggregates for study, five to eight replicate subsamples of soil from each treatment at each site were processed through the microaggregate isolator and composited. The isolated microaggregates comprised 60 to 70% of the whole soil mass for all treatments at both field sites. The isolated microaggregates were dried at 55°C and stored at 4°C in capped glass bottles that were sealed in plastic bags.

Soil OC content of the microaggregates was measured by dry combustion using a Shimadzu TOC-V analyzer in conjunction with a SSM-5000A solid sample combustion unit (Shimadzu Scientific Instruments, Columbia, MD). To evaluate the effect of OM on soil water retention, subsamples of the isolated microaggregates from selected plots were combusted at 350°C for 24 h to remove OM from pores within the microaggregates. Our measurements indicated that a consistent 96 to 98% of the total OM originally in the microaggregates of both the Fermilab and Kentucky samples was removed after combustion. Specific surface area (SSA) of the microaggregate samples was measured using the N_2 adsorption method (Mayer and Xing, 2001). The particle density, ρ_s, was determined on one sample of the bulk soil before and after combustion at 350°C using the pycnometer method as described by Flint and Flint (2002).

Measurements of Water Retention Curves

Main drying and wetting branches of the water retention curve were measured on the soil microaggregates before and after combustion at 350°C 1 yr after the field sampling by using the chilled mirror dew point method (Scanlon et al., 2002). A WP4 Dew Point PotentiaMeter (Decagon Devices, Pullman, WA) was used to measure soil water tension, ψ (MPa). For the drying branch, ~1 g of microaggregates was placed as a complete single layer in a stainless steel container (3-cm diameter, 1 cm high) and wetted to saturation via a capillary wick (filter paper) in contact with a reservoir of tap water at the same elevation as the sample. The sample was then allowed to slowly air dry at room temperature. Paired measurements of ψ and gravimetric water content, θ_g (kg kg^{-1}), were made over time as described by Perfect et al. (2004). The microaggregates were capped and allowed to equilibrate overnight before each reading. A duplicate sample was run in exactly the same way to fill in any gaps in the ψ measurements. For the wetting branch, ~1 g of microaggregates was slowly wetted up using an ultrasonic humidifier (Model 693–12/809996, Sunbeam Products, Hattiesburg, MS) as described by Ojeda et al. (2006). Following each addition of water vapor, the sample was capped and allowed to equilibrate overnight before measuring ψ and θ_g as described for the drying branch. Once again, a duplicate sample was run to fill in any gaps in the ψ measurements.

Both the drying and wetting branches of the water retention curve determined with the WP4 water activity meter were fitted separately using the gravimetric form of the Rieu and Sposito (1991) prefractal model: $\theta_g = a\psi^{D-3} - \rho_w/\rho_s$, which was previously derived and then used to analyze soil water desorption data by Perfect et al. (2004). In the equation, ρ_w is the density of water, D is the mass fractal dimension that is related to pore size distribution and connectivity, and a is a compound parameter, $a = \rho_w/(\rho_b\psi_a^{D-3})$, including bulk density (ρ_b) and the air entry tension (ψ_a) that is related to porosity or the presence of large pores. The fitting was accomplished using the Newton method in nonlinear regression (PROC NLIN) with the SAS/STAT statistical software program (SAS Institute, 1999). The a and D parameters were estimated, while ρ_w was fixed at 1.00 Mg m^{-3} and ρ_s was experimentally measured for each sample (Table 1). Convergence was achieved according to the SAS/STAT default criterion for all of the fits.

Statistical Analysis

Soil cores collected from multiple locations within each field treatment were composited to represent the variation within these treatments; however, the lack of replicate plots for each treatment at the field sites precluded the collection of true replicate samples. Therefore, our measurements on duplicate samples indicate analytical rather than treatment error. The significance of differences in measured properties between samples does not necessarily indicate a cause-and-effect relationship due to the different management practices. Nevertheless, our results still yield insights into, or create an opportunity to infer, soil water–C relationships across the gradient of conditions created by tallgrass prairie restoration, tillage, and N fertilization. Overall, the conclusions of this study were made with the knowledge from past studies at these sites (Jastrow, 1996; Frye and Blevins, 1997; Six et al., 1999) that the consistent management history of the different treatments significantly changed soil C content and the assumption that these treatments also affected water characteristics.

For the OC measurements, duplicate samples were analyzed and the differences between samples from different treatments within the same site were significant at $P < 0.05$ (Table 1). One-way analysis of covariance (ANCOVA; PROC GLM, SAS Institute, 1999) was used to determine whether the slopes and intercepts of the water retention curves differed between the samples from differently treated plots, between the drying and wetting branches for each plot, and between intact and combusted microaggregate samples (SAS Institute, 1999). For these analyses, the ψ–θ_g curves were linearized by using log(ψ). In ANCOVA comparisons of θ_g for the drying and wetting branches at the same water potential or between the intact and combusted microaggregate samples, log(ψ) vs. difference in θ_g was evaluated. When more than two water retention curves were compared by ANCOVA and found to be significantly different (P < 0.05), multiple Student's t-tests were used to identify treatment differences

Table 1. Organic C (OC) content and physical properties of the soil microaggregates.

Field site	Treatment	OC	SSA†	OC/SSA‡	Relative OM-filled porosity§	Particle density
		g kg^{-1}	m^2 g^{-1}	mg C m^{-2}	%	Mg m^{-3}
Fermilab	Cultivated	24.1 d¶	15.6	1.6	42	2.56 (2.58)#
	10-yr restoration	49.0 b	33.5	1.5	16	2.54 (2.76)
	19-yr restoration	44.1 c	27.8	1.6	36	2.46 (2.61)
	24-yr restoration	43.4 c	28.9	1.6	62	2.54 (2.58)
	Virgin prairie	86.1 a	40.2	2.2	76	2.41 (2.52)
Kentucky	CT0	14.6 d	16.6	0.5	13	2.76 (2.74)
	CT336	16.1 c	15.5	0.6	21	2.74 (2.73)
	NT0	23.1 b	12.5	0.9	24	2.71 (2.81)
	NT336	32.8 a	9.5	1.4	34	2.54 (2.50)

† Specific surface area of microaggregates measured by N_2 adsorption.

‡ The ratio of the total soil OC to the SSA of the combusted (OC-free) microaggregates.

§ Ratio of organic-matter-filled pore volume to total pore volume for ≤5-μm pores measured using ultra-small-angle x-ray scattering technique (McCarthy et al., 2005,unpublished data).

¶ Means followed by the same letter within a site not significantly different at $P < 0.05$ according to a protected t-test.

Values in parentheses are for the combusted samples.

between slopes and intercepts. To protect against Type I errors associated with multiple comparisons, Bonferroni corrected α probabilities (α/*k*, where *k* is the number of comparisons) were used to assess significance. Measurements of the SSA and ρ_s were performed on single samples; however, a separate study using three bulk soil samples from the four different Kentucky treatments indicated a reproducibility error of 1.77 and 2.63% for the SSA and ρ_s measurements, respectively.

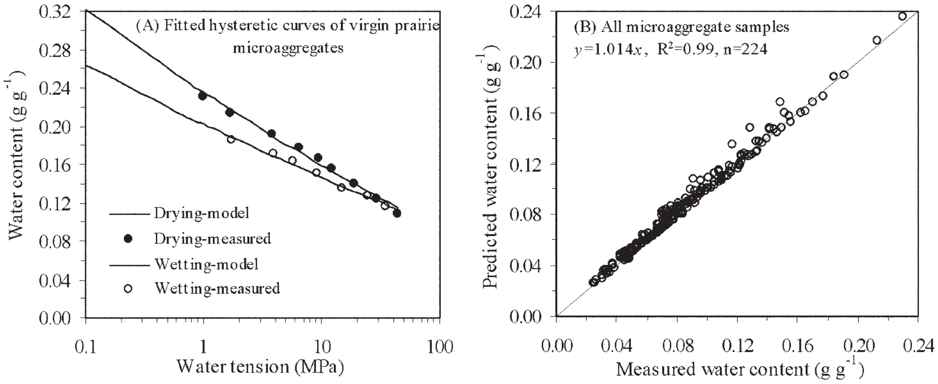

Fig. 1. Validation of the model on the measured drying and wetting data of water characteristics.

RESULTS AND DISCUSSION

Management Practice Effects on Organic Matter

Both OC content and its distribution in micropores (<5 μm) varied with land use and tillage management. At Fermilab, long-term cultivation reduced microaggregate OC to <30% of the OC concentration in virgin prairie microaggregates (Table 1). Restoration of the cultivated soils to tallgrass prairie, however, essentially doubled microaggregate OC levels within 10 yr. Whether the apparent decline in microaggregate OC levels between the youngest (10-yr) and oldest (24-yr) sites in the prairie restoration chronosequence is meaningful or simply reflects plot-to-plot variability requires further investigation. For the Kentucky site, the cessation of tillage resulted in a substantial increase in OC levels of the microaggregates (Table 1). Higher levels of N fertilizer application led to a small increase in OC level for the CT treatment and a larger increase in the NT treatment. In general, these trends in microaggregate OC followed the chronosequence gradient and treatment differences previously reported for whole-soil OC at these sites (Jastrow, 1996; Frye and Blevins, 1997; Six et al., 1999).

The ultra-small-angle x-ray scattering approach (McCarthy et al., unpublished data, 2005) applied to the same microaggregates showed that incorporation of OM into pores <5 μm appeared to be an important protective mechanism of OM in microaggregates. Apparent differences in the relative OM-filled porosity among the different treatments were observed for both the Fermilab and Kentucky microaggregates (Table 1). For the Fermilab chronosequence, the proportion of pores <5 μm that was filled with OM apparently declined after conversion of the cultivated soil to prairie. But, as the prairie restoration proceeded (10, 19, and 24 yr), OM re-established in <5-μm pores, and a trend for increasing OM-filled porosity relative to the total porosity in this size range occurred with little change in the total OC of the microaggregates. Compared with the Fermilab microaggregates, OM filled a smaller fraction of the pores <5 μm in the Kentucky soil microaggregates, which probably resulted from differences in factors such as aggregate dynamics, clay mineralogy, base cation status, and vegetative inputs between the two sites. No-till and N-fertilization treatments, however, appeared to influence the distribution of OM in soil microstructure. Further analyses of microaggregates from additional chronosequence plots, replicate plots at the Kentucky site, and additional field sites will be needed to confirm the trends in pore-filling dynamics identified by these initial observations and to determine their general applicability across a range of soils.

Modeling the Hysteretic Characteristics of Water Retention

An example of the hysteretic phenomenon observed for the water retention is shown in Fig. 1A, along with the corresponding relations predicted using the modified fractal model. The predicted results for the entire data set of all samples (Fig. 1B) indicate an excellent fit of the model to the observed data, with minimal deviations from the 1:1 relationship. Best-fit estimates of the model parameters are summarized in Table 2 for different treatments, where the subscripts *d* and *w* denote the drying and wetting curves, respectively. The parameters obviously varied with samples that were different in both soil management practice and the wetting–drying history. For any microaggregate sample, the value of a_d was consistently greater than the value

Table 2. Hysteretic water retention parameters† fitted using the modified fractal model.

Treatment	a_d	a_w	D_d	D_w
Cultivated	0.482 (0.001)‡	0.470 (0.002)	2.978 (0.001)	2.984 (0.001)
10-yr prairie restoration	0.556 (0.003)	0.537 (0.003)	2.962 (0.003)	2.970 (0.002)
19-yr prairie restoration	0.545 (0.003)	0.529 (0.002)	2.973 (0.003)	2.980 (0.002)
24-yr prairie restoration	0.555 (0.003)	0.537 (0.002)	2.961 (0.003)	2.970 (0.002)
Virgin prairie	0.650 (0.004)	0.617 (0.003)	2.946 (0.003)	2.959 (0.002)
Cultivated, combusted	0.454 (0.001)	0.441 (0.001)	2.977 (0.001)	2.984 (0.001)
24-yr restoration, combusted	0.512 (0.002)	0.489 (0.001)	2.963 (0.002)	2.972 (0.001)
Virgin prairie, combusted	0.559 (0.002)	0.515 (0.003)	2.956 (0.002)	2.970 (0.002)
Conventional tillage, 0 N	0.454 (0.002)	0.451 (0.001)	2.974 (0.002)	2.976 (0.001)
Conventional tillage, 336 kg N ha^{-1}	0.453 (0.002)	0.446 (0.001)	2.970 (0.002)	2.975 (0.001)
No-till, 0 N	0.463 (0.002)	0.459 (0.002)	2.972 (0.002)	2.975 (0.002)
No-till, 336 kg N ha^{-1}	0.491 (0.001)	0.483 (0.003)	2.974 (0.001)	2.979 (0.002)

† *a* is a fitted compound parameter and *D* is the mass fractal dimension; subscripts d and w refer to drying branch and wetting branch, respectively.

‡ Values in parentheses are approximate standard error from nonlinear regressional analysis.

Table 3. Correlation coefficients (*r*) between soil properties and water retention parameters† of nine microaggregate samples.

Properties/parameters	a_d	$a_d - a_w$	D_d	$D_w - D_d$
Organic C (OC)	0.987***	0.957***	−0.877**	0.944***
Specific surface area (SSA)	0.916***	0.883**	−0.838**	0.864**
OC/SSA	0.871**	0.861**	−0.588	0.883**
Relative organic-matter-filled porosity	0.760*	0.782*	−0.653	0.801**
$\theta_{g,d} - \theta_{g,w}$ at ψ = 1 MPa‡	0.982***	0.991***	−0.857**	0.986***

* Significant at P = 0.05.

** Significant at P = 0.01.

*** Significant at P = 0.001.

† *a* is a fitted compound parameter and *D* is the mass fractal dimension; subscripts d and w refer to drying branch and wetting branch, respectively; $a_w - a_d$ and $D_w - D_d$ are the differences in the respective parameters between the drying and wetting curves.

‡ $\theta_{g,d} - \theta_{g,w}$ is the difference is gravimetric water content between the drying and wetting curves.

of a_w, but the value of D_d was smaller than the value of D_w. These inequalities are indicative of hysteresis in the water retention curves, in that the water content associated with a particular tension on the drying branch was always equal to or greater than that on the wetting branch. Such hysteresis was expected since drainage (i.e., soil drying) is controlled mainly by the size of narrow pore necks or small pores, whereas wetting up occurs in response to the size of pore bodies or large pores (Hillel, 1998, p. 771). The difference in the values of the *a* and *D* parameters between the main drying and wetting branches (i.e., $a_d - a_w$ or $D_w - D_d$) was positively correlated with the magnitude of hysteresis of the water retention curves (Table 3); the hysteresis is represented by the difference in water content between the drying and wetting branches ($\theta_{g,d} - \theta_{g,w}$) at the same water tension (e.g., 1 MPa). Similar correlations also existed when the hysteresis was measured by the difference in water content at 0.5 MPa (R^2 = 0.986 for $a_d - a_w$; R^2 = 0.975 for $D_w - D_d$; both $P < 0.001$) or 2 MPa (R^2 = 0.978 for $a_d - a_w$; R^2 = 0.967 for $D_w - D_d$; both $P < 0.001$). As reported by Perfect et al. (2004), the *a* parameter was found to be inversely correlated with the *D* parameter (R^2 = −0.658, $P < 0.01$), suggesting that lower bulk density or air-entry values were associated with more rapid capillary drainage.

The direct effects of soil properties on hysteretic water retention were confirmed by the observed strong correlations (Table 3) between the model parameters and the levels of OC, SSA, OC/SSA, and the relative OM-filled porosity in the microaggregates. These soil properties were positively proportional to the *a* parameter or its difference between the drying and wetting branches ($a_d - a_w$). Since an increase in *a* can be the result of a decrease in bulk density (ρ_b) or air-entry tension (ψ_a), this parameter should be sensitive to changes in soil structure, including any shrink–swell processes (Perfect et al., 2004). Assuming there was little impact of soil disturbance on the $\theta_g(\psi)$ curve, which was measured at tensions >300 kPa in this study, we infer from changes in the *a* parameter that OC accumulation in soil pores due to tallgrass prairie restoration, N fertilization, or no-till management increased total porosity (leading to a decrease in ρ_b), or increased the size of the largest pores (leading to a decrease in ψ_a), in the microaggregates.

There were strong inverse linear relationships (Table 3) between the soil properties (especially for total OC and OC/SSA) and the *D* parameter. Such correlations suggest a decrease of apparent pore surface roughness with increasing OC content in the micropores. This is because lower *D* values indicate a greater proportion of drainable pores (Perfect et al., 2004), which might be the result of aggregation of soil particles by the organic component of the total C pool that acts as a cementing agent. The linear increase observed in the difference in the *D* parameter between the wetting and drying curves ($D_w - D_d$) with increasing total OC or OC/SSA signifies a greater deviation between the sizes of pore bodies and necks within the microaggregates due to the increase of OM-filled porosity. Therefore, the sensitivity of the parameters of the water retention model, *a* and *D*, to management practices can be explained in terms of OM-induced changes in bulk density, the diameter of the largest pores, and the pore size distribution and connectivity (Perfect et al., 2004; Ojeda et al., 2006). It is possible that OM-induced changes in the wetting angle may have also influenced hysteresis of the soil water characteristic; further research is needed to investigate this possibility.

Organic Matter Effect on the Hysteretic Characteristics of Water Retention

Consistent with the effects of management practices on OM content and distribution in microaggregates, there were pronounced differences in the soil water retention curves for the different management practices. The water content at any given tension was always greatest for the virgin prairie and lowest for the cultivated soil at the Fermilab site (Fig. 2). Retention curves for the tallgrass prairie restorations were intermediate between those for the virgin prairie and the cultivated soils, with no consistent differences in water retention with respect to length of time since establishment. In comparison, tillage and fertilization practices affected water retention much less than prairie restoration in terms of gravimetric water content. No-till was shown to be effective in enhancing water retention in soil microaggregates. The trends shown in Fig. 2 are primarily attributed to the large differences in soil OM level and distribution that resulted from the different management practices. This result agrees well with previous studies (e.g., Kumar et al., 1985; Aggelides and Londra, 2000; Ojeda et al., 2006), which showed that the application of organic wastes and sewage sludge increased soil water retention.

Restoration time, tillage, and fertilization significantly influenced the hysteresis of water retention by soil microaggregates (Fig. 3). The curves were plotted as the difference in water content between the main drying and wetting branches vs. water tension. Larger differences imply greater degrees of hysteresis. The results demonstrate that hysteresis of water retention generally decreased as the water tension increased. In terms of the trends of the differential curves plotted in Fig. 3A, the hysteresis of water retention was greatest for the virgin prairie and least for the cultivated soil, which was similar to the trends in OC content. For the differential curves in Fig. 3B, hysteresis was greater for the fertilized plots than for unfer-

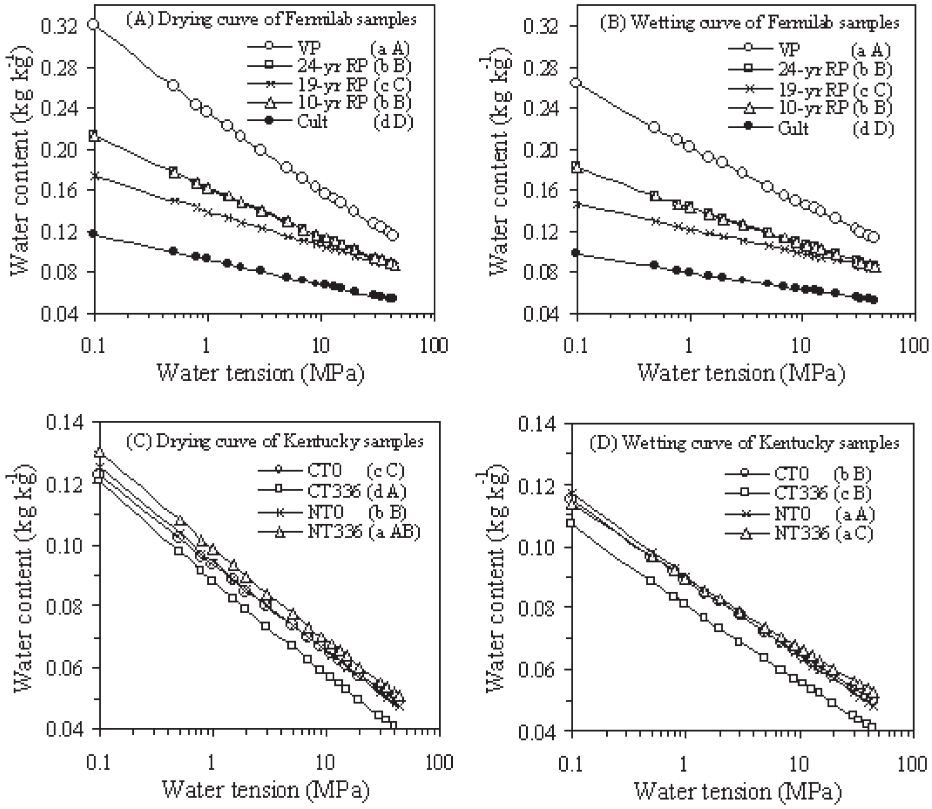

Fig. 2. Management practice effects on predicted water characteristics of soil microaggregates. Note that the scale of the *y* axis for Kentucky soils is different from that for Fermilab soils. In (A) and (B), VP = virgin prairie, RP = restored prairie, and Cult = cultivated land. In (C) and (D), CT = conventional tillage, NT = no-till, 0 and 336 are N-fertilization treatments (kg N ha^{-1}). Intercept and slope comparisons among treatments derived from significant analysis of covariance results followed by multiple Bonferroni-corrected Student's *t*-tests are given in parentheses after legend entries; the intercepts of treatments followed by the same lowercase letter and the slopes of treatments followed by the same uppercase letter were not significantly different at $P < 0.05$.

tilized plots, with NT336, which had the highest OC content, exhibiting the greatest hysteresis. Figure 3C summarizes the relationship between the total OC content in microaggregates and the magnitude of hysteresis of the water characteristics, represented by the difference in water content at $\psi = 1$ MPa. The slopes for Fermilab (Mollisols) and Kentucky (Alfisols) soils did not differ at $P = 0.05$ according to ANCOVA, although these soils are quite different in soil properties and formation processes. A regression analysis for the combined data shows a positive linear relationship between OC content and water hysteresis. Similar relationships (although not presented) resulted when hysteresis was quantified by the difference in water content at $\psi = 0.5$ MPa ($R^2 = 0.938$, $P < 0.001$) or $\psi = 2$ MPa ($R^2 = 0.926$, $P < 0.001$). Because a larger difference in water content between the drying and wetting curves ($\theta_{g,d} - \theta_{g,w}$) characterizes a broader size distribution of pores that dominantly contribute to total porosity, we infer from the linear relationship that OM must have increased the difference in pore size distribution of the microaggregates, and consequently changed the hysteretic behavior of water retention. In the microaggregates with high OM levels, OM may dominantly exist as particulates or amorphous materials that are physically protected in individual pores or surrounded by mineral clays. Our previous study using ultra-small-angle x-ray scattering (McCarthy et al., unpublished data, 2005) indicated that the virgin prairie soil had the greatest OM-filled porosity relative to the other soils (Table 1). This trend implies that pore-filling OM increases the hysteresis of water retention by mediating the pore size distribution in microaggregates. The increase would occur because OM-filled pores can reduce the connectivity and increase the tortuosity of water flow paths between pores. Water retained in small OM-filled pores is probably relatively immobile and consequently impedes the drainage of larger pores that are con-

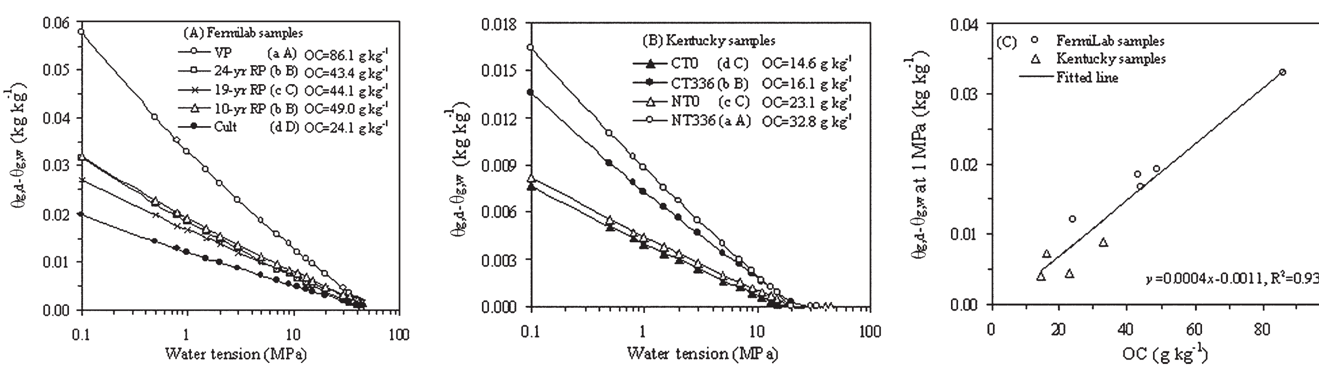

Fig. 3. (A and B) Difference in water content between the drying and wetting curves ($\theta_{g,d} - \theta_{g,w}$), and (C) the correlation between organic C (OC) content and $\theta_{g,d} - \theta_{g,w}$ at 1 MPa. In (A), VP = virgin prairie, RP = restored prairie, and Cult = cultivated. In (B), CT = conventional tillage, NT = no-till, 0 and 336 are N-fertilization treatments (kg N ha^{-1}). For (A) and (B), intercept and slope comparisons among treatments derived from significant analysis of covariance results followed by multiple Bonferroni-corrected Student's *t*-tests are given in parentheses after legend entries; the intercepts of treatments followed by the same lowercase letter and the slopes of treatments followed by the same uppercase letter were not significantly different at $P < 0.05$.

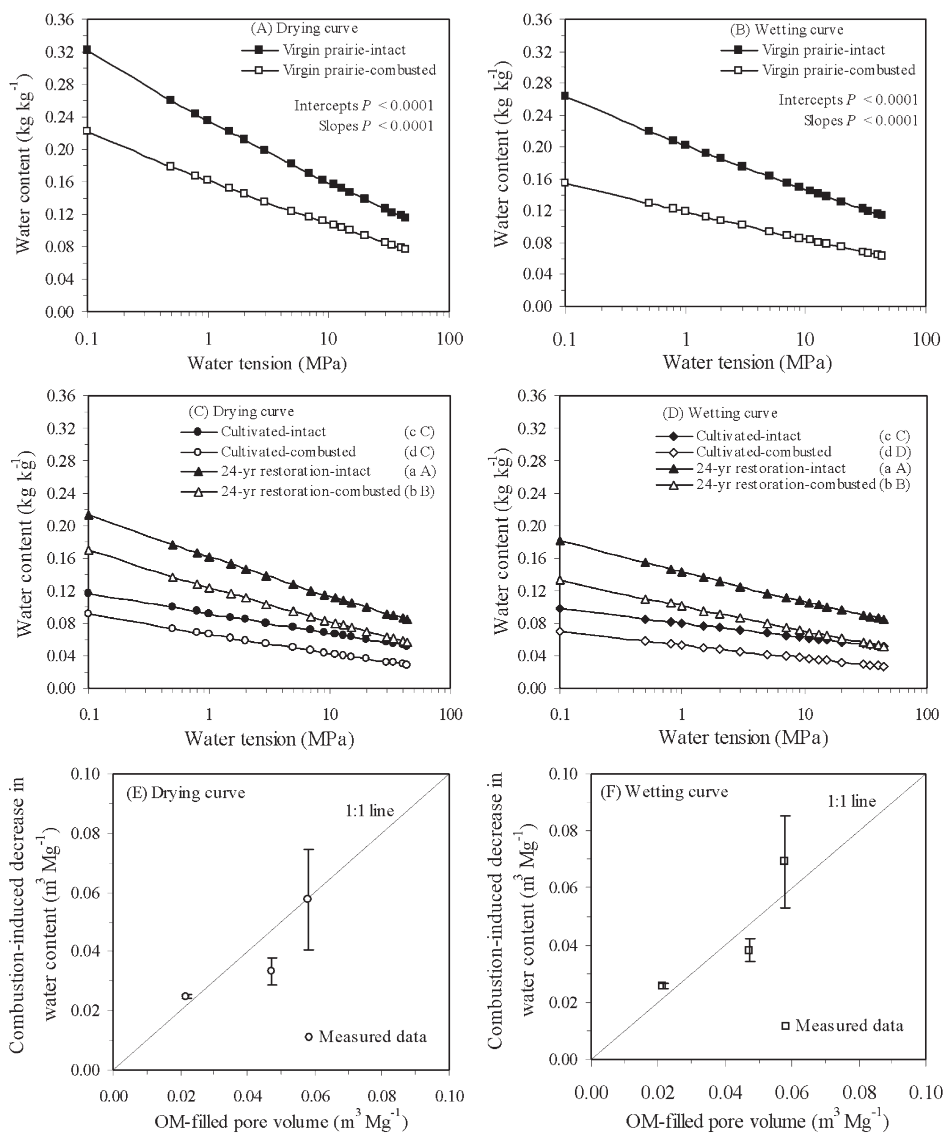

Fig. 4. (A–D) Organic matter (OM) removal effect on the drying and wetting curves of microaggregates of three choronsequence soils, and (E and F) the agreement between the OM-filled pore volume (measured using small-angle x-ray scattering technique [McCarthy et al., unpublished data, 2005]) and the decrease in water content resulting from OM removal (measured using water retention method). In (A) and (B), results of analysis of covariance (ANCOVA) comparisons of intercepts and slopes are indicated below the legend. For (C) and (D), intercept and slope comparisons among treatments derived from significant ANCOVA results followed by multiple Bonferroni-corrected Student's *t*-tests are given in parentheses after legend entries; the intercepts of treatments followed by the same lowercase letter and the slopes of treatments followed by the same uppercase letter were not significantly different at $P < 0.05$.The error bars in (E) and (F) indicate the standard deviations of combustion-induced water content change across a range of water tension from 0.1 to 44 MPa.

nected via the small OM-filled pore necks. The presence of high levels of OM in pores, and the resulting differences in air entrapment, shrinkage and swelling, and contact angle during wetting vs. drying, may also contribute to hysteresis (Araujo et al., 1995; Hillel, 1998, p. 771; Ustohal et al., 1998; Ojeda et al., 2006).

Organic Matter Removal Effects on the Hysteretic Characteristics of Water Retention

Differences existed in the drying and wetting curves between the intact and combusted (OM-removed) Fermilab microaggregates for three management treatments with a wide range in OC contents (Fig. 4A–4D). Organic matter removal by combustion reduced water retention in the microaggregates. The reduction tended to get smaller as the water tension increased, suggesting that more OM existed in larger than smaller pores from which water was drained. Figures 4E and 4F show that the reduction of water content, averaged across the pore size spectrum, which corresponds to the range of measured water tensions, increased with increasing levels of OM-filled pore volume in the microaggregates. The change in water volume identified by comparing the difference in the main drying or wetting curve between the intact and the combusted samples was generally consistent with the change in OM-filled pore volume measured on the intact samples using the ultra-small-angle x-ray scattering technique (McCarthy et al., unpublished data, 2005). Thus, the simple method of water retention measurement might be useful for characterization of the OM-filled pore volume in soil microaggregates.

The role of OM in influencing water retention is further verified by the difference in hysteretic characteristics between the intact and the combusted microaggregates. Figure 5 shows that OM removal by combustion promoted hysteresis in the water retention curves, i.e., a larger difference between the drying and wetting curves. Comparison of the results for the cultivated soil, 24-yr-old restoration, and virgin prairie indicate that this effect increased with increasing OM level. The increase in hysteresis due to OM removal implies that the change in pore structure was characterized by an increase in the breadth of the size distribution of pores within the soil microaggregates.

CONCLUSIONS

This study examined the influence of OM contained in soil microaggregates on the hysteretic characteristics of water retention by soil microaggregates with respect to different land use and tillage management practices. Organic matter content, especially the fraction of pore-filling OM, was positively related to the magnitude of hysteresis of water retention in the microaggregates. The accrual of OM in microaggregates associated with prairie restoration, no-till, and N fertilization was related to relatively large increases in the fraction of physically pro-

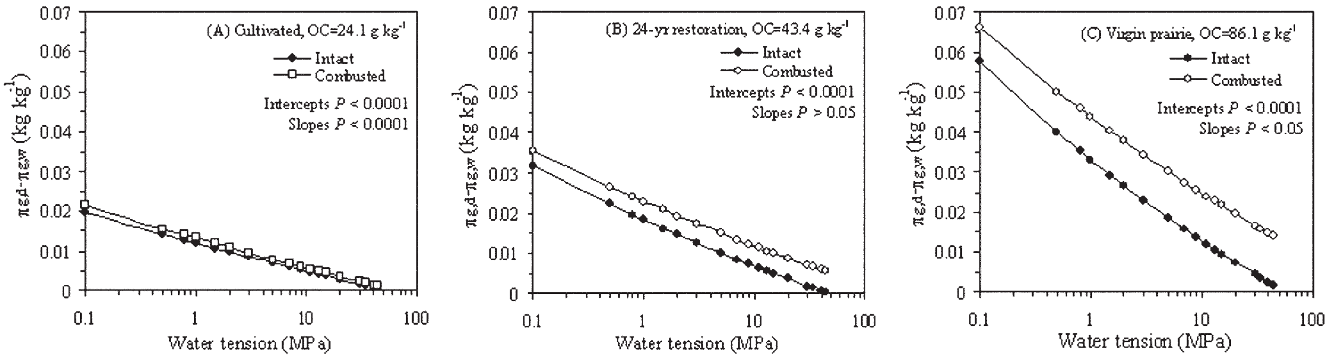

Fig. 5. Organic matter removal effect on the difference in water content between the drying and wetting curves ($\theta_{g,d} - \theta_{g,w}$) of three Fermilab chronosequence soil microaggregates. Results of analysis of covariance comparisons of intercepts and slopes are indicated below the legend. OC = organic C.

tected OM. The pore-filling OM can hold water tightly within its own nano- and micropores to lead to an overall increase in water retention capacity and decease in pore connectivity within soil microaggregates. Removal of OM by combustion at 350°C resulted in the emptying of OM-filled pores and broadening of the pore-size distribution. As a result, hysteresis of soil water retention (i.e., the difference in water content at the same tension between the drying and wetting curves) was promoted. The lower fractions of pore-filling OM in the tilled Kentucky (Alfisol) soil or even cultivated Fermilab (Mollisol) soil resulted in smaller hysteresis in their water retention curves relative to the soils subjected to other treatments (e.g., restoration and no-till), which had a higher fraction of OM-filled porosity. These results suggest that pore-filling OM plays a significant role in soil water retention, and, as a feedback effect, increased water saturation within the microaggregates might cause persistent accumulation of OM within soil pores by slowing down aerobic decomposition (Otsuki and Hanya, 1972). This study provides important mechanistic insights into the potential of optimized management practices for synergistically improving the retention of both water and OC in soils.

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