The Physical Basis of Carbon Sequestration in Soil Microaggregates

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Introduction

Concerns about global climate change and rising atmospheric CO_2 levels have motivated national and international efforts to develop a scientific basis for evaluating potential management strategies for enhancing carbon sequestration in the environment. The dynamics of soil aggregate formation and stability have profound implications on understanding and enhancing carbon sequestration in soil. Soil microaggregates (consisting of primary particles, clay microstructures, and organic matter [OM] bound up in aggregates of up to 250 μm) are particularly crucial to long-term sequestration because they protect C against decomposition, resulting in much longer residence times for C. However, the reasons why organic carbon in soil microaggregates has such long residence times are not well understood. The overall goal of this research is to determine the structural and chemical bases of soil microaggregate formation and stability.

C stabilization in microaggregates has been proposed to result from several processes [1], including (1) the inherent recalcitrance of the organic molecular structure, (2) interactions between OM and inorganic surfaces or other organic substances that decrease degradation rates, and (3) reduced physical accessibility. However, we do not currently understand which processes are most important or under what situations and settings the relative importance of any of the processes might be shifted. Our hypothesis is that management practices that reduce disturbance of the soil (such as prairie restoration) will exhibit the following features (compared to cultivated soils): (1) greater internal surface area in the microaggregate due to higher soil OM content and the convoluted conformation of OM compared to smooth mineral surfaces and (2) reduced accessibility of the internal porosity because pores become blocked, thus contributing to the slow turnover of soil OM in stable microaggregates.

Methods and Materials

To test these hypotheses, we examined the pore-scale structure of soil microaggregates by using small-angle x-ray scattering (SAXS). Soil microaggregates were isolated by flotation and wet sieving [2] from a tallgrass prairie restoration chronosequence at the National Environmental Research Park at Fermi National Accelerator Laboratory (Batavia, IL). We compared microaggregates from plots in the same soil series representing (1) a soil that has been in cultivation for over 100 years, (2) a plot that was converted from cultivation to prairie 20 years ago, and (3) a virgin prairie.

Results

Scattering curves were obtained by using the ultrasmall-angle x-ray scattering (USAXS) instrument at the University-National Laboratory-Industry Collaborative Access Team (UNI-CAT) beamline. The results (Fig. 1) were analyzed to evaluate the relative surface area of different size pores and the degree of roughness of the surfaces of the pores in microaggregates from the three cultivation histories.

The lower scattering intensity for the microaggregates from the cultivated field indicates that they have a much lower surface area than those from either prairie. The USAXS data also indicate that the virgin prairie has a slightly greater proportion of its surface area in the smaller-size pores (high Q) and less of its surface area in the larger-size pores (low Q) compared to the restored prairie.

Discussion

The shape of the scattering curves suggests that the morphology of the microaggregates is a randomly oriented surface fractal aggregate. A fractal object is one that is similar to itself across a range of scales. According to this model, the scattering is described by the following power law:

$$I(Q) \propto Q^{-(6-D_s)} \qquad (1)$$

where D_s = the surface fractal dimension and $2 \le D_s < 3$. Values of D_s are derived from the slopes of log-log plots of I versus Q (Fig. 1). The value D_s provides information on the roughness of the surface, with a value of 2 indicating a perfectly smooth surface and higher values indicating increasing surface roughness. The fractal approach has been used successfully to describe a number of porous structures [3–5], including the structure of Oxisol aggregates [6].

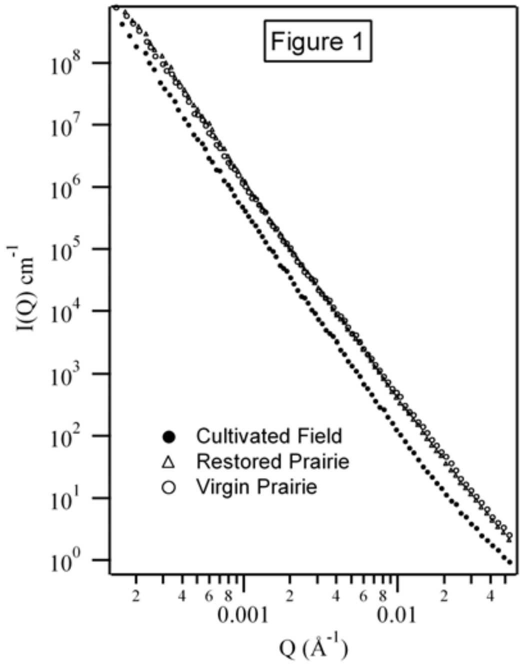

FIG. 1. USAXS scattering curve for soil microaggregates.

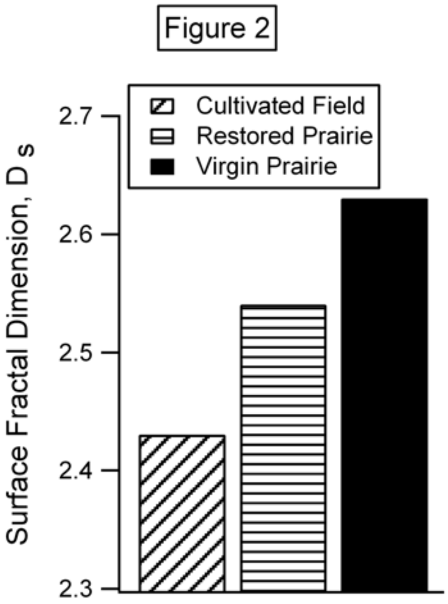

FIG. 2. Effect of management on D_S.

All of the microaggregate samples were surface fractals over a size range of 6 to 5000 nm (Fig. 1). The value of D_s increases with the age of the prairie and organic content of the soil (Fig. 2). This trend suggests that pores in microaggregates from the cultivated field are relatively smooth, which is consistent with their lower surface area. In contrast, the pore surfaces of microaggregates from the restored and virgin prairies are more convoluted, which is consistent with their greater total surface area (Fig. 1). This increased surface area is likely related to higher levels of convoluted, high-surface-area organic matter on the pore surfaces of these microaggregates. The virgin prairie has the roughest pore surfaces (highest D_S), and this appears to be associated with the increased surface area for the small-sized pores (Fig. 1).

Future studies will use contrast matching and anomalous scattering techniques to determine the accessibility of different size classes of solutes and colloids to internal microaggregate porosity [4, 7–10].

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