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Can intra-aggregate pore structures affect the aggregate's effectiveness in protecting carbon?

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ABSTRACT

Aggregates are known to provide physical protection to soil organic matter shielding it from rapid decomposition. Spatial arrangement and size distribution of intra-aggregate pores play an important role in this process. This study examined relationships between intra-aggregate pores measured using X-ray computed micro-tomography images and concentrations of total C in 4–6 mm macro-aggregates from two contrasting land use and management practices, namely, conventionally tilled and managed row crop agricultural system (CT) and native succession vegetation converted from tilled agricultural land in 1989 (NS). Previous analyses of these aggregates indicated that small ($<$15 μm) and large ($>$100 μm) pores prevail in NS aggregates while medium (30–90 μm) pores are more abundant in CT aggregates (Kravchenko et al., 2011; Wang et al., 2012). We hypothesized that these differences in pore size distributions affect the ability of macro-aggregates to protect C. The results of this study supported this hypothesis. Consistent with greater heterogeneity of pore distributions within NS aggregates we observed higher total C and greater intra-aggregate C variability in NS as compared with CT aggregates. Total C concentrations and intra-aggregate C standard deviations were negatively correlated with fractions of medium sized pores, indicating that presence of such pores was associated with lower but more homogeneously distributed total C. While total C was positively correlated with presence of small and large pores. The results suggest that because of their pore structure NS macro-aggregates provide more effective physical protection to C than CT aggregates.

1. Introduction

Macro-aggregates are known to provide physical protection to soil organic matter shielding it from rapid decomposition and thus are regarded among the key elements enabling soil C sequestration (Beare et al., 1994; Paustian et al., 1997; Bossuyt et al., 2002; von Lützow et al., 2006). Intra-aggregate physical protection is the leading driver of C sequestration occurring when land under intensive agricultural management is converted to conservational land use practices (Jastrow, 1996; Grandy and Robertson, 2007). In soils under conservational land use, e.g., grasslands or soils abandoned from agriculture, macro-aggregates tend to have higher C concentrations and are richer in newer C than other soil fractions (Jastrow, 1996; De Gryze et al., 2004). The newly added C often serves as a binding agent holding the macro-aggregates together. When intra-aggregate physical protection is eliminated by crushing macro-aggregates, the intra-aggregate C accumulated by conservational management is easily mineralized (Beare et al., 1994; Hassink, 1997). However, when macro-aggregates stay intact for prolonged time periods in undisturbed soils of conservational management, decomposition of organic binding agents is sufficiently slow to allow for formation of micro-aggregates where physical protection is enhanced by physicochemical and chemical protection processes (Six et al., 2000; Denef et al., 2001; Chenu and Plante, 2006).

One of the mechanisms of organic matter protection is heterogeneity of soil microenvironment which limits the access of decomposing microorganisms and their enzymes to organic material (Schmidt et al., 2011). Macro-aggregate formation increases such heterogeneity, and thus organic matter protection, by increasing complexity in spatial arrangement of soil matrix pores (Baldock and Skjemstad, 2000). Pores affect water and air fluxes, spatial distributions of soil nutrients, and movement of microorganisms through soil on scales ranging from a soil profile to a micro-aggregate (Or et al., 2007). For example, it has been shown that large pores of preferential flow paths contain younger soil organic C than their surroundings and serve as "hotspots" for biological activity (Bundt, 2001). Greater microbial activity and organic matter decomposition was observed in larger pores or were

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associated with greater numbers of large pores (Killham et al., 1993; Yoo et al., 2006; Ruamps et al., 2011). Soil nutrients were reported to accumulate around pores approximately 100–200 μm in diameter within soil aggregates (Jassogne, 2008). Pore arrangements may restrict microbial access to organic material and reduce microbial activity by limiting oxygen supply (Sexstone et al., 1985; Golchin et al., 1994; von Lützow et al., 2006).

Aggregate boundaries serve as dividers between smaller intra-aggregate pores inside aggregates and larger inter-aggregate pores surrounding them. Majority of air and water fluxes occur via inter-aggregate pores from which air, water, chemicals, and microorganisms can enter the aggregates. Comparisons of the intra-aggregate soil properties at different distances from aggregate boundaries supply ample evidence of the importance of pore sizes for intra-aggregate biogeochemical processes including those related to C. Within the aggregates, gradients are often observed in terms of a variety of soil properties reflecting the proximity to aggregate boundaries, that is, to inter-aggregate pores. Among the gradients that have been observed are gradients in oxygen levels (Sexstone et al., 1985), Ca, Mg, K, Na, Mn, K, Al, and Fe concentrations (Santos et al., 1997; Jasinska et al., 2006), and in composition of organic matter (Ellerbrock and Gerke, 2004; Urbanek et al., 2007). Differences have been found between external and internal aggregate layers in terms of microbial activities (Jasinska et al., 2006) and microbial community compositions (Blackwood et al., 2006). These gradients appear to be soil specific. For example, Chenu et al. (2001) found that microbial decomposition occurs throughout the whole aggregates of a sandy soil, while only near the surface of a clay soil aggregates. Especially diverse are results obtained for total C where some studies reported no intra-aggregate patterns (Ellerbrock and Gerke, 2004; Urbanek et al., 2007), while others found such gradients in some but not other soils (Santos et al., 1997; Jasinska et al., 2006). It is likely that not only proximity to the inter-aggregate pore space but also abundance, size, and connectivity of intra-aggregate pores play a substantial role in intra-aggregate C-related processes and resulting intra-aggregate patterns in spatial distributions of C.

When land is abandoned from an intensive agricultural use and is either converted into grassland or allowed to be taken by native vegetation, multiple factors contributing to C sequestration become activated. Among them are year-around presence of vegetation cover supplying fresh organic inputs different in quality from those of intensive agriculture, increased microbial and faunal activity, elimination of soil disturbance, and an increase in quantities and stabilities of soil aggregates. Recently it has been shown that such soils are not only different from conventionally managed agricultural soils in terms of aggregate size distributions or aggregate stability but also in terms of intra-aggregate pore characteristics. For example, Peth et al. (2008) reported prevalence of long continuous pores in a grassland aggregate while short thin interconnected pores were more abundant in a CT aggregate. Kravchenko et al. (2011) observed greater heterogeneity in intra-aggregate pore distributions in macro-aggregates from soil under native succession vegetation as compared to conventional agriculture. Wang et al. (2012) reported greater fractions of 30–60 μm crack-like pores in macro-aggregates from conventionally tilled soil while greater fractions of >90 μm pores of biological origin in aggregates from soil abandoned from agriculture for past 18 years. We hypothesize that in addition to the listed above factors contributing to C sequestration in soils converted to native vegetation the changes that take place in intra-aggregate pore structures constitute yet another factor that enables enhanced C sequestration to take place in such soils.

The goal of this study is to determine whether the intra-aggregate pore characteristics of macro-aggregates from a conservational land use system make such aggregates more effective in C protection as compared to those of conventional intensive agriculture. We examined soils from two highly contrasting land uses: a heavily disturbed soil in a conventionally plowed row crop agricultural system and an undisturbed soil under native vegetation. During past 18 years the first system was losing C (Senthilkumar et al., 2009) while the second system has been shown to rapidly accumulate it (Grandy and Robertson, 2007). The objectives of the study are to assess spatial patterns of C distribution within the aggregates from the two systems and to examine the relationships between intra-aggregate C and spatial distributions of intra-aggregate pores obtained via X-ray computed micro-tomography.

2. Materials and methods

2.1. Soil sampling

Soil samples were collected from Long Term Ecological Research (LTER) site at the W. Kellogg Biological Station in southwest Michigan. The soil is Kalamazoo loam (fine-loamy, mixed, mesic, Typic Hapludalf), developed on glacial outwash. The LTER experiment was established in 1988 (for details on site description, experimental design and research protocols see http://lter.kbs.msu.edu) (KBS, 2011). Prior to 1988 the entire experimental site was in conventionally plowed row crop agricultural management for at least past 100 years. The two most contrasting treatments in terms of soil management were used in this study, namely, conventional tillage (chisel-plowed) corn-soybean-wheat rotation with conventional chemical inputs (CT) and native succession grassland, abandoned from agricultural use after spring plowing in 1989 (NS).

Sampling was conducted in 2008 from two adjacent 1 ha plots, one plot per treatment. Within each plot three randomly selected sampling locations were identified and at each location a soil block approximately 15 × 15 × 15 cm in size was extracted by spade from the soil surface. Soil blocks were packed into closed-lid plastic containers and transported to the lab, where they were gently manually crushed to ensure breakage along the natural planes of weakness. Then crushed soil was air-dried and dry-sieved to obtain macro-aggregates 4–6.3 mm in size. In the rest of the manuscript we will refer to them simply as aggregates. Grandy and Robertson (2007) reported that based on wet-sieving results 2–8 mm aggregates constituted around 15% and 50% of the aggregates in CT and NS treatments, respectively. The aggregate size was chosen as a compromise between the need to have aggregates large enough to provide sufficient amount of soil material for multiple intra-aggregate measurements of soil C and the need for aggregates to be sufficiently small to enable fine resolution in X-ray computed micro-tomography scanning. Air-dried aggregates were stored in airtight containers at the room temperature until used for analyses. Six replicated aggregates from each treatment, i.e., two aggregates from each sampling site, were used in further analyses.

2.2. Image collection and analyses

The aggregate images were obtained at the Advanced Photon Source of Argonne National Laboratory (station BMD-13) using X-ray micro-tomography. Image resolution was equal to approximately 15 μm in x, y, and z directions. To obtain information on intra-aggregate pores, the images were segmented by classifying each image voxels as either a pore or a solid material. Segmentation was conducted using indicator kriging method (Oh and Lindquist, 1999; Wang et al., 2011). The pore characteristics that were studied are image-based porosity, that is the percent of pores visible at image resolution (>15 μm), and size distributions of such