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Spatial distributions of plant root carbon storage capacities within soil aggregates

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ABSTRACT

Soils are large carbon (C) reservoirs that mitigate global warming by removing greenhouse gases from the atmosphere and sequestering them as soil organic matter (SOM). SOC represents one of the major pools in the global C cycle. Therefore, even small changes in SOC stocks cause important CO_2 fluxes between terrestrial ecosystems and the atmosphere. The composition and distribution of plant root soluble C impacts the formation, stability and function of soil aggregates. Little is known about the spatial distribution and variable composition of these root-C compounds which are absorbed within individual soil aggregates. Both the rates or intensities of drying or wetting, and the differences or severity in water contents alter the transport of water, C and N through micro and mesofaunal habitats at both the micro and mesoscales. These changes alter gaseous compositions, C and N storage capacities and microbial communities among different regions within soil aggregates. Recent advances in X-ray microtomography enable the examination of intact pore networks within soil aggregates at resolutions as small as 3 microns.

In collaboration with the Advanced Photon Source near Chicago, we compared pore geometries of similar air-dried aggregates from the same soil type which were subjected to multiple drying/wetting (DW) cycles. DW cycling developed greater spatial correlation ranges that paralleled the sorption of ^{13}C away from respiring microorganisms resulting in significant shifts in the abundance of unique microbial ribotypes within exterior and interior regions of macroaggregates subjected to 0 and 5 DW cycles. Past research indicates that microbial activities within the soil aggregate matrix are spatially heterogeneous due to complex pore geometries within aggregates. Illumination of the “blackbox” interiors of soil aggregates by synchrotron microtomographic 2D and 3D imaging provide visual evidence of biophysical and biogeochemical regulated pathways controlling flow rates of soil solutions through intra-aggregate pore geometries. This presentation includes a discussion of natural and anthropogenic alterations of root-based C solution flow, sequestration and reduced respiration by soil aggregates containing biological, chemical and physical gradients.

BACKGROUND

Soil carbon (C) accumulations in soils originate directly from the adsorption of soluble plant root exudates and indirectly from soluble decomposition products of above and belowground plant parts and other soil organic matter. Surface layers of soil aggregates, which form the walls of most soil pores containing preferential flow, are among the first contacts with transported soluble C compounds. Preferential soil solution flow patterns, through soil volumes, supply most of the soluble organic C (SOC). As soluble C compounds intersect soil aggregate surfaces, gradients of soil C are formed within soil aggregates. Investigations of interior regions of soil aggregates have led to greater understandings of the complex intra-aggregate pore networks which sequester soil C, microbial communities, and ions (Park, et al., 2007). Additional information regarding the quantity, composition, and distribution of soil C provides a greater understanding of the complex interactions among the physical, chemical and biological mechanisms contributing to soil aggregation formation and function. The concept here is that more stable soil aggregates with more internal micro-pores will absorb and sequester more SOC beyond the reach of soil microbes and their associated C respiration enzymes.

Literature citations concerning which aggregate size class contains the greatest quantity of SOM and numbers or activities of soil microorganisms are inconclusive. Ladd *et al.* (1996) reported that clay, SOC, and management primarily control soil aggregate dynamics. Mendes *et al.* (1999) added seasonal variability and methods of fractionation as factors causing different conclusions. Peterson *et al.* (1997) and Ramakrishnan *et al.* (2000) reported that aggregate size class has very little correlation with microbial activities. The composition and quality of organic matter also impacts the microbial activity and community structure. Therefore, changes in the nature of organic compounds are likely to result in stratification of microbial activity within individual aggregates and contribute to accumulations of atmospheric greenhouse gases (Houghton *et al.*, 1999; Robertson *et al.*, 2000).

RESULTS

Twice as much carbon was contained by exterior/interior regions of peeled aggregates and by whole aggregates from NT soils than from CT soils (Smucker, et al., 2008). Nearly two-thirds of the C in aggregates from nontilled soils originated from the 40 years of continuous maize. Approximately one-half of the C in aggregates from conventionally tilled soils originated from the continuous maize crops. Sixty percent of maize-C (325 µg C/g soil per year) were sequestered by external soil layers of aggregates. Soil aggregate sequestrations of C were 575 Kg C/ha/y in non tilled soils than tilled soils. Carbon respiration rates of CT aggregate surfaces were 56% greater than their interior regions. Respiration rates of NT aggregate surfaces were 28% greater than their interiors (Smucker, et al., 2008). In laboratory studies which combined multiple additions of 250 ug or glucose (simulating root exudation) with wetting and drying cycles of soil aggregates resulted in the 40% greater soil retention of C with resultant reductions in the respiration of native soil C (Park, et al, 2007). These results suggest, continuous contributions of soluble root exudates to soil aggregates during simultaneous wetting and drying of the same aggregates, adjacent to roots, result in greater C sequestration in the rhizosphere.

Knowledge on the geometry of pore networks of intra-aggregate soil pore spaces are of great value for many soil environmental processes. Advances in non-invasive 3D imaging techniques such as synchrotron-radiation-based microtomography offer an excellent opportunity to study the interrelationship of the pore network geometry with physical processes at a spatial resolution of a few micrometers. Results of a quantitative 3D pore space geometry analysis of small scale, 2-5 microns across, within soil aggregates from contrasting soil management systems have shown expected differences in distributions of pore size, throat size, channel length and width as well as tortuosity and connectivity of the intra-aggregate pores with potential implications for soil functions have demonstrated the potential application of synchrotron-radiation-based microtomography to study pore network characteristics of soil aggregate samples from various regions and soil management systems. Visual comparison of different aggregates underlines the strong variation in pore space architectures suggesting also different functionality of intra-aggregate pore spaces in terms of physical, chemical and biological processes. From 3d image reconstructions using a selection of specific attenuation coefficient ranges (greyscale values) we have observed that material is coating old root channels and micro-aggregates. This clearly demonstrates the influence of soil structure on element distributions within soil aggregates caused by interacting chemical and physical processes.

Significantly more alfalfa C deposition by alfalfa roots accounted for nearly 70% of the total C stored in exterior layers of soil aggregates, 12.5 to 16 mm across, 20 months after sowing. Continuous deposition of C by alfalfa roots caused delta ^{13}C signatures to become more negative on surfaces of aggregates from both CT and NT soil managements, resulting in delta ^{13}C signatures of -26.5 vs. -24.5 ‰, remained on exterior soil layers of CT aggregates through the spring of the growing season of the alfalfa. These contrasting delta ^{13}C signatures suggest more alfalfa C respired from the NT aggregates than from the CT aggregates in the field, in a manner similar to the greater respiration rates of NT aggregates in laboratory incubation studies. Delta ^{13}C signatures of interior aggregate regions for both NT and CT management systems enabled us to estimate diffusion of C materials into soil aggregates a rates approximating 120 µm per week (Smucker, et al., 2008).

DISCUSSION AND CONCLUSIONS

Continuous supplies of root-like SOC to the soil solutions which bathe surfaces of soil aggregates, via macro-pore flow, provide multiple opportunities for the flux of SOC into and the sequestration of root C by soil aggregates having greater internal porosities. Soil aggregates containing nearly 20% more micro-porosities appear to be increased by frequent intervals of wetting and drying. Separate laboratory studies have demonstrated that additions of simulated maize root exudates during five wetting and drying cycles increased C sequestration, microbial biomass, microbial the aggregate strength.

Rhizodeposition of SOC onto soil aggregates can be considered one of the major contributions of agro-ecosystem management to soil C sequestration and soil structure stability. DW cycling expanded new storage regions within aggregates that both retained the newly added SOC and associated metabolites with reduced losses of native soil C by respiration. Increasing concentrations of applied $SO^{13}C$ accelerated diffusion rates into aggregate interiors modified soil respiration rates, and T-RFLP indicators of increased microbial ribotypes within all interior regions of macroaggregate. These data support the hypothesis that sustained SOC sources from root exudates can be deposited at surfaces of macro-aggregates and at surfaces of micro-aggregates accelerating the diffusion of C into aggregate interiors during multiple DW cycles.

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