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Forms and Functions of Meso and Micro-niches of Carbon within Soil Aggregates

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Abstract: Soil aggregates include sand/silt/clay, water, ion and organic matter contents combined with natural dry/wet (D/W) cycling alters both the formation and function of intra-aggregate pore continuity, connectivity, dead-end storage volumes, and tortuosity. Surface aggregates in the 0-5 cm depths of most soils experience from 34 to 57 D/W cycles that exceed differences in water contents >10%. Both the rates of drying or wetting, (intensity) and the D/W range of soil water contents (severity) alter the transport of water, C and N through micro and mesofaunal habitats among multiple size domains. This report identifies micro-niche locations of accumulating soil C within soil aggregate regions that may affect nematode residence sites and migration pathways. Recent advances in X-ray microtomography enable the examination of intact pore networks within soil aggregates at resolutions as small as 4 microns. Geostatistical and multi-fractal methods provide concise characteristics of pore spatial distributions within the aggregates and are useful for comparing these alterations among soils. Aggregates subjected to multiple D/W cycles developed greater spatial correlations that parallel increases in the ^{13}C sorption within aggregate interiors were compared with locations of soil microbial communities. Past research indicates 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 includes a discussion of natural and anthropogenic alterations of solution flow and carbon sequestration by soil aggregates containing biophysical gradients.

Key words: intra-aggregate pores, micro-tomographic images, carbon sequestration.

Review and Discussion

Recently, the "blackbox" of structural geometries controlling air and solution-filled pores within soil aggregates have become more visible (Peth, et al. 2008, Kravchenko, et al., 2009). These advances in X-ray microtomography provide new and exciting opportunities for examining internal pore structures of soil aggregates in 3D space at resolutions of several microns. Knowledge of observable pore diameters and connectivities will be useful in the modeling of solute sorption and flux rates as well as microbial and mesofaunal migrations through soil volumes.

Total soil organic carbon (SOC) has been shown to be positively related to C inputs and much of this C sequestration potential has been attributed to C stabilization within soil aggregates, both micro- and macro-aggregates (Six, et al. 2002). Since macro-aggregates constitute approximately 90% of the vast heterogeneity of the soil matrix of most medium and fine textured soils (Smucker and Park, 2006) greater knowledge of soil C sorption and movement within macro-aggregates are an essential component of soil C modeling. Exclusions of meso and micropore storage capacities, within soil aggregates, appear to be responsible for the relatively low predictions of potential carbon (C) sequestration by current soil carbon models. Park, et al. (2007) demonstrated continuous additions of root substrates to surfaces of aggregates, subjected to repeated D/W cycles, establish and maintain C gradients from exteriors to interior regions resulting in 4-fold increases in total C (Figure 1). During multiple D/W cycles soil dehydration causes multiple cracks and microfissures within soil volumes containing 2:1 expanding clays. Rehydration causes more pores to form within the volumes of soil aggregates. Therefore, the rate of D/W cycling between different percentages of soil water contents greatly influence connectivities of intra-aggregate pore geometries that sequesters 4-fold more carbon (Figure 1).

In a similar fashion, dendrograms of RsaI terminal restriction fragment length polymorphism (T-RFLP) profiles from the external and internal regions of individual soil aggregates, 4.0 to 6.3 mm across, contained significantly different microbial communities. Additionally, the external and internal layers of soil aggregates contained contrasting microbial colonies in the rhizospheres of alfalfa and maize (Blackwood, et al. 2005). Other T-RFLP electropherograms demonstrated significant shifts in the abundance of unique microbial ribotypes in exterior and interior regions of macroaggregates subjected to 0 and 5 D/W cycles (Park, et al., 2007). Current geostatistical and multi-fractal analytical methods are being used to identify concise characteristics of pore spatial distributions within the aggregates from different crop and soil management agroecosystems. Therefore we believe pore-based models of aggregate interiors must be developed before accurate microbial and C substrate solution flux rates into unsaturated soils can be identified. This knowledge is anticipated by the scientific community and will greatly contribute to environmental, microbiological and soil biophysical research.

Long-term field studies of the surface 10 cm of a 43-year continuous conservation tillage (ConT) treatment of a Wooster silt loam, doubled the C accumulation rates in macro-aggregates to 341 Kg C ha^{-1} y^{-1} (Table 1). Continuous C inputs during 43 years of ConT increased C in the outer 1/3 (exterior) regions of soil aggregates, 1 to 9.5 mm across which comprised 92% of the total soil, to rates of 325 mg C/g soil/y. These rates were 60% greater than the 200 mg C/g soil/y rates in the interior regions of aggregates reported by Smucker and Park (2006). In contrast, 104 years of conventional moldboard tillage (CMT) of macro-aggregates in continuous corn led to

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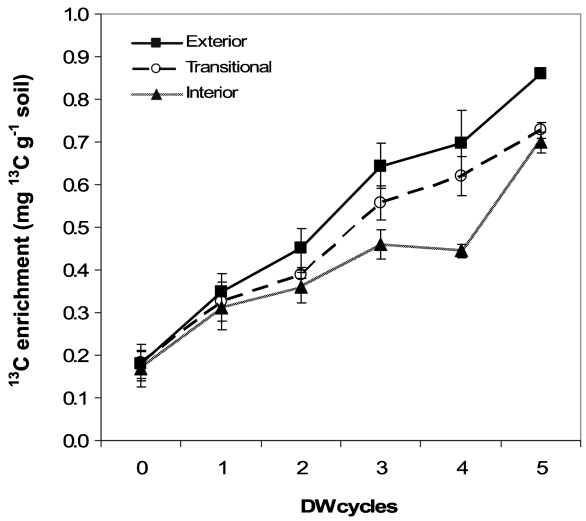

FIG. 1. D/W cycles increased concentration gradients from exterior to interior regions of aggregates and total retention of ^{13}C derived from glucose within aggregates following the completion of each D/W cycle. D/W cycles promoted a 4-fold increase of sequestered new soluble C by interior regions of macroaggregates 6.3 to 9.5 mm across. Error bars are the standard deviations of three replicates. (Taken from Soil Biol. & Biochem. J. 2007. 39:2758-2768).

losses of 234 Kg C ha^{-1} y^{-1}. Reduced inputs of C, during these 104 years, combined with tillage-enhancement of soil C respiration from broken macro-aggregates, (Grandy, et al., 2006) which comprised 89%, of the soil by weight, were losing an average of -164 mg C/g soil/y. Meanwhile, the C contents of their interior regions, which were 16% higher than their exteriors, retained C concentrations similar to the ConT treatments (Table 1).

One explanation for these large C gains by soil aggregates subjected to long-term ConT is described by the 2.5-fold greater accumulation and/or retention rates by macro-aggregate exterior regions residing in the rhizosphere C. Quantifying the delta ^{13}C signatures by C3

TABLE 1. Carbon accumulation (+) and loss (−) rates in soil macro-aggregates 1.0 to 9.3 mm across, from a Wooster silt loam subjected to long-term conservation tillage (ConT) and conventional moldboard tillage (CMT). Modified from Smucker and Park, 2006.

	Exteriors	Interiors	C accumulation
	mg C/g soil/y		rates Kg C/ha/y
#C gains into NT soil aggregates:	+325	+200	+341
(C gained, eg., (ConT – CMT in 43 y) E/I Gradient:	+60%		
*C losses from CMT soils aggregates:	−164	−195	−234
(C lost, eg., (^Forest – CMT in 100 y) E/I Gradient:	−16%		

All aggregates measured = 92% of total soil.
* All aggregates measured = 89% of total soil.
^ Soil C in similar aggregates from nearby permanent Forest soil.

exudates of alfalfa roots that diffused into exterior and interior regions of macro-aggregates 13.8 mm across can be used to measure new C accumulating in soil aggregates (Smucker and Park, 2006). Gill, et al. (2002) reported the capacity of soils to sequester C depends as much on the quantities of native C and the microbial communities within microniches, as the quantities of newly added C. This suggests a complex biogeochemistry of C sequestration of root exudate sorption along pore walls of microsites which may control metabolism of root exudate substrates by microbial communities.

Spectro-microscopy of Brookhaven synchrotron images of soil nano-pores filled with C suggest many of these nano- and micro-sites are niches which accumulate substantial quantities of soil C as calcium carbonates (Lehmann, et al., 2008). Frequent observations of the remains of roots, nematodes and other mesofauna, within micropores of Argonne National Laboratory synchrotron microtomographic image of soils (unpublished video on website: https://www.msu.edu/~smucker/images.htm) indicate these niches, which have accumulations and gradients of C and microbes may be attracting nematode and other mesofauna into the interior porosities of soil aggregates.

CONCLUSIONS

Visible and quantitative differences among intra-aggregate pore spaces display different functional relationships between solution flow patterns and microfaunal responses to newly added SOC compounds. When soil C contents are increasing, C concentrations at aggregate surfaces are 200 to 300% greater than interior regions of aggregates. Continuous contributions of small quantities of soluble organic C appear to protect original (natural) soil carbon and provide physical passage ways that facilitate biophysical and biogeochemical functions controlling flow rates of soil solutions through intra-aggregate pore geometries (Park, et al., 2007).

Therefore, the question whether currently published models accurately predict the maximum levels of C sequestration can be partially addressed when we understand the soil biogeochemical mechanisms of soil C protection. Once the geometries, connectivities, microniches and surface charges of associated pore walls are better defined and combined with the sorptive surfaces within pore microniches then soil C models will be able to more accurately predict higher levels of C sequestration.

LITERATURE CITED

Blackwood, C. B., Dell, C. J., Paul, E. A., and Smucker, A. J. M. 2005. Eubacterial community response to position within soil macroaggregates and soil management. Soil Biol Biochem J 37:28–50.

Grandy, A. S., and Robertson, G. P. 2006. Aggregation and organic matter protection following cultivation of an undisturbed soil profile. Soil Science Society of America Journal 70:1398–1406.

Kravchenko, A. N., Martin, M. A., Smucker, A. J. M., and Rivers, M. L. 2009. Theoretical and practical limitations in the

determination of multifractal spectra from pore/solid soil aggregate images. *Vadose Zone J.* 8:220–226.

Lehmann, J., Liang, B., Solomon, D., Lerotic, M., Luizao, F., Kinyangi, J., Schafer, T., Wirick, S., and Jacobsen, C. 2005. Near-edge X-ray absorption fine structure (NEXAFS) spectroscopy for mapping nano-scale distribution of organic carbon forms in soil: Application to black carbon particles. Global Biogeochem. Cycles 19:1013–1025.

Lehmann, J., Skjemstad, J. O., Sohi, S., Carter, J., Barson, M., Falloon, P., Coleman, K., Woodbury, P., and Krull, E. 2008. Australian climate-carbon cycle feedback reduced by soil black carbon. *Nature Geoscience* 1:832–835. (supplementary online information).

Peth, S., Horn, R., Beckmann, F., Donath, T., Fischer, J., and Smucker, A. J. M. 2008. Three-dimensional quantification of intra-aggregate pore-space features using synchrotron-radiation-based microtomography. Soil Sci Soc Am J 72:897–907.

Park, E. J., and Smucker, A. J. M. 2005. Soil polar tensile strength and surface erosivities of soil aggregates from conventional and no-till agroecosystems. Soil Sci Soc Amer J 69:1912–1921.

Park, E. J., Sul, W. J., and Smucker, A. J. M. 2007. Glucose additions to aggregates subjected to drying and wetting cycles promote carbon sequestration and aggregate stability. Soil Biol. and Biochem. J. 39: 2758–2768.

Six, J., Conant, R. T., Paul, E. A., and Paustian, K. 2002. Stabilization mechanisms of soil organic matter: Implications for C-saturation of soils. Plant Soil 241:155–176.

Smucker, A. J. M., and Park, E. J. 2006. Soil Biophysical Responses by Macroaggregates to Tillage of Two Soil Types. (Eds. Rainer Horn, Heiner Fleige, Stephan Peth, and Xinhua Peng). Adv. in GeoEcology 38:455–460. Catena Verlag Publishers 35447 Reiskirchen.