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Editorial

Ecosystems in flux: Molecular and stable isotope assessments of soil organic matter storage and dynamics

Soil organic carbon is the largest pool (1500 Pg C ($1\,\text{Pg} = 10^{15}\,\text{g}$)) in the terrestrial carbon cycle, and contains twice as much C as the atmosphere (780 Pg C) and nearly triple the amount of C in terrestrial biomass (550 Pg C) (Schlesinger, 1997; Amundson, 2001; Houghton, 2005). The soil organic carbon (SOC) pool is also a dynamic component of the C cycle that is closely linked to the atmospheric CO_2 pool via inputs from dead organic matter production ($\approx 60\,\text{Pg C yr}^{-1}$) and losses from decomposition ($\approx 60\,\text{Pg C yr}^{-1}$) (Schlesinger, 1997; Houghton, 2005). These fluxes are 10-fold greater than fossil fuel combustion ($\approx 6\,\text{Pg C yr}^{-1}$), so that even small changes in the magnitude of the SOC pool or the input/output rates associated with it could have profound consequences for the global C cycle, the concentration of CO_2 in the atmosphere, and the climate system (Lal et al., 1995).

Despite the obvious significance of SOC, our present concept of the global C cycle remains limited by uncertainties in the quantitative aspects of SOC storage and dynamics. On the one hand, historical reconstructions of land-use activities (agriculture and deforestation in particular) reveal that the global SOC pool has decreased by 55–78 Pg C since AD 1850, implying that soils have been a significant source of atmospheric CO_2 in recent history (Lal et al., 1995; Lal, 2004). On the other hand, indirect estimates based on geophysical constraints and inverse modeling of the atmosphere and oceans indicate that terrestrial ecosystems and soils must be presently accumulating C (Fan et al., 1998; Houghton, 2005). To reconcile these differences, we must enhance our understanding of the quantitative details and mechanisms of soil organic matter (SOM) storage and dynamics in relation to changes in land cover/land use, climate, and the gas composition of the atmosphere (Bellamy et al., 2005; Fung et al., 2005; Heath et al., 2005; Jastrow et al., 2005; Potter et al., 2006). This goal permeates nationally and globally identified scientific needs and is essential to be able to consider sustainable management of the Earth system (NRC, 2001b).

In addition to its role in the function of the Earth system at the global scale, SOM also plays a pivotal role in the provision of ecosystem services that are essential to the well-being of the human population (Daily et al., 1997; Millenium Ecosystem Assessment, 2005). These key ecosystem services include the maintenance of soil fertility, nutrient cycling, production of food and fiber, infiltration and storage of water, erosion and flood control, and the maintenance of biodiversity. August scientific bodies such as the National Academy of Sciences of the USA, International Union of Soil Sciences, US Carbon Cycle Program, the United Nations Millenium Ecosystem Assessment, and the Intergovernmental Panel on Climate Change all rate the mechanisms and processes that control SOM storage and dynamics among the most fundamental areas of science essential for an understanding of the Earth system. For example, of the eight Grand Challenges in environmental sciences identified by the US National Research Council that require enhanced scientific understanding and federal research funding, four of them (i.e. biogeochemical cycles, biological diversity and ecosystem functioning, climate variability, and land-use dynamics) have SOM dynamics as either an explicit or implicit central issue (NRC, 2001a). Additionally, the US NRC in their publication on basic research opportunities in the Earth science (NRC, 2001b) also places a particularly important emphasis on the need for greater understanding of the processes determining how soils control and respond to changes in the Earth system.

Over the last decade, a multidisciplinary collection of scientists have converged on this important issue, bringing fundamental knowledge in pedology, mineralogy, biogeochemistry, the biology of plants and microbes, and isotope chemistry to bear on this problem. To highlight recent advances resulting from these collaborations, we convened a symposium entitled ‘‘Ecosystems in Flux: Molecular and Stable Isotope Assessments of Soil Organic Matter Storage and Dynamics’’ held at the Fall 2004 American Geophysical Union (Biogeosciences Division) in San Francisco, California, USA. This session brought together scientists from many disciplines to discuss the interactions between soil structure, mineralogy, organic chemistry, and microbial community structure and activity, and how these factors determine the storage and turnover of organic C and nitrogen (N) in managed and natural ecosystems. In

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total, 42 presentations (28 posters and 14 talks) were given by scientists from Europe and the United States on topics including the chemical, physical and structural mechanisms of SOM stabilization among various ecosystems, the accessibility of C pools to soil microbes, the specific role of microbial communities and their enzyme systems in SOM dynamics, and the response of SOM pools to perturbations such as land uses, land cover changes, and rising atmospheric CO_2 concentration. This special issue of *Soil Biology and Biochemistry* represents some of the key contributions to that session.

This volume contains four contributions with the goal of directly or indirectly tracking the role of microbial activity on SOM dynamics through studies of enzyme activity, the isotopic composition of respired CO_2, and the isotopic composition of phospholipids and extractable microbial biomass. The paper by Kramer and Gleixner investigated the relative utilization of fresh particulate vs. old SOM by Gram-negative and Gram-positive bacteria in agricultural soils through combined ^{14}C and ^{13}C compound specific isotope analysis of phospholipids. Allison and Jastrow used physical fractionation procedures to investigate whether soil C is spatially isolated from degradative enzymes across a prairie restoration chronosequence, and found that enzyme production and C turnover occurred rapidly in particulate organic matter (POM) fractions, but slowly in mineral-dominated fractions where enzymes and their C substrates were immobilized on mineral surfaces. Dijkstra et al. presented a new technique for the isolation of microbial biomass for isotope analysis, and documented an enrichment in the natural abundances of ^{13}C and ^{15}N in microbial biomass relative to SOM across a broad range of soil types and vegetation. These results reflected the extent to which microbial products contributed to stabilized pools of SOM, and helped explain the ^{13}C and ^{15}N enrichment that is commonly observed along the SOM decay continuum. Crow et al. used density fractionation to separate light POM fractions from heavy, mineral-associated SOM fractions, and examined the accessibility of these pools to microbial inoculants by quantifying the amount and $\delta^{13}C$ value of CO_2 respired from those SOM density fractions.

Four additional papers illustrated the importance of land use and land cover in controlling SOM dynamics. In two of these manuscripts, Liao et al. elucidated the mechanisms responsible for changes in SOC and soil total N apportionment among aggregated and non-aggregated mineral-associated and POM following woody plant encroachment into grassland. To accomplish this, they analyzed the elemental and stable isotope ($\delta^{13}C$ and $\delta^{15}N$) abundances of specific size/density fractions along a chronosequence of C3 woody plant encroachment into C4 grassland. The paper by Krull et al. employed compound-specific $\delta^{2}H$ and $\delta^{13}C$ analyses of *n*-alkanes from SOM in a grassland–woodland system to examine interactions between carbon and water cycles, and to evaluate the "two-layer" soil water model in a semi-arid savanna system. Yamishita et al. analyzed the effect of land cover/land use (spruce forest, grassland, wheat and maize) on the distribution and turnover of SOM in size/density fractions. The mass and C content of both the free and occluded POM fractions were greater in the forest soil than in the grassland and arable soils, and ^{13}C kinetics indicated that the free POM fractions had the most rapid rates of turnover.

The effects of rising CO_2 concentrations on SOC allocation and subsequent SOM dynamics has garnered significant attention recently, and is the focus of the paper by Del Galdo et al. They quantified SOC stores and dynamics in relationship to soil aggregation and pool composition in a Californian chaparral ecosystem exposed for 6 years to a gradient of atmospheric CO_2. They found that increasing atmospheric CO_2 concentrations decreased soil C in chaparral, and that the microaggregate fraction was the most responsive to elevated concentrations of atmospheric CO_2.

Soil organic N dynamics are extremely important for forest, grassland, and agroecosystem productivity studies, but the state of knowledge of the mechanistic controls on N pools and the structural composition of stabilized pools is insufficient. Three manuscripts in this volume address these issues. Sollins et al. explored the common observation that C concentrations and C/N generally decrease with particle density. They applied detailed chemical, isotopic, molecular, and mineralogical analyses to a density-fractionated andic soil. Results were consistent with a general pattern of an increase in the extent of microbial processing with increasing organo-mineral particle density, and also with an "onion" layering model of SOM accumulation on mineral surfaces in which polar carboxyl and nitrogenous compounds sorb by ligand and cation exchange. The manuscript by Olk et al. examined yield decreases in several agricultural systems associated with repeated cropping under wet or submerged soil conditions, and attributed this decline in yield to the accumulation of phenolic lignin compounds that covalently bind nitrogenous compounds into recalcitrant forms. Recent advances in ^{15}N-NMR allowed them to identify agronomically significant quantities of lignin-bound N in rice cropping systems. Kölbl et al. applied ^{15}N-labelled mustard litter to an agricultural system to examine N-cycling processes in low yield vs. high yield portions of the landscape. The distribution of ^{15}N was followed in POM fractions and in fine mineral fractions. They found that the higher silt and clay contents of low yield areas promoted N stabilization in fine mineral fractions.

In total, the scientific contributions of these papers were many and varied, spanning a broad range of important SOM-related issues within climate change, land use, microbiology, soil chemistry, and soil structure. Furthermore, several of these papers present new and innovative technical advances in the use of isotopic and molecular techniques in soil science. These contributions will better enable the scientific community to understand and predict patterns and processes in the soil environment at scales ranging from the molecular to the global level. We hope these contributions will stimulate and influence further research into this fundamentally important area of Earth system science.

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