

Overview of the Symposium Proceedings, “Meaningful Pools in Determining Soil Carbon and Nitrogen Dynamics”

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ABSTRACT

Extraction of soil organic matter (SOM) fractions has been a long-standing approach to elucidating the pivotal roles of SOM in soil processes. Several types of extraction procedures are commonly used, and all provide partial information on SOM function. This report and accompanying papers summarize the information regarding SOM functions in real-world issues that has been gained through physical or chemical fractionations. Each procedure has its strengths and weaknesses; each is capable to some degree of distinguishing labile SOM fractions from nonlabile fractions for studying soil processes, such as the cycling of a specific soil nutrient or anthropogenic compound, and each is based on an agent for SOM stabilization. Physical fractionations capture the effects on SOM dynamics of the spatial arrangement of primary and secondary organomineral particles in soil, but they do not consider chemical agents for SOM stabilization. They appear better suited for C cycling than N cycling. Chemical fractionations cannot consider the spatial arrangement, but their purely organic fractions are suitable for advanced chemical characterization and can be used to elucidate molecular-level interactions between SOM and nutrients or other organic compounds. During all fractionations, the potential exists for sample alteration or mixing of material among fractions. We call for better coordination of research efforts by (i) developing integrated fractionation procedures that include physical, chemical, and/or biological components, and (ii) categorizing fractionations by their most suitable applications, defined by the nutrient, compound, or soil process in question, land use or crop type, crop management strategies, soil type, and possibly other factors. Selecting the most suitable fractionation procedure for a given research application would enable more precise approximation of the functional SOM pool.

SOIL ORGANIC MATTER plays pivotal roles in several processes of the soil ecosystem, including nutrient cycling, soil structure formation, C sequestration, water retention, detoxification of anthropogenic chemicals, and energy supply to soil microorganisms. These processes lie at the heart of leading agricultural and environmental issues. Our prediction and management of these processes has been limited, though, in part because we do not understand the underlying mechanisms of SOM activity. Despite considerable attention, SOM remains a mysterious soil component.

Mechanistic investigations of SOM are often based on the premise that SOM is composed of a continuum of materials, whose cycling rates vary from weeks to millennia (Jenkinson, 1981). This broad continuum can be conceptually divided into discrete kinetic pools, and

researchers strive to characterize those pools that contribute to their research issues. Most agricultural and environmental issues develop over timescales ranging from months to decades, which calls for the isolation and study of relatively young SOM pools. A daunting research challenge, though, has been to extract from soil meaningful SOM fractions: those which correspond to the conceptual pools and whose cycling rates are both measurable and relevant to the issue in question.

An ideal fractionation of SOM provides for the exhaustive extraction from all soils of unaltered material that is free of contaminants (Stevenson, 1994). All these conditions may never be achieved simultaneously. A useful, if not ideal, extraction procedure isolates meaningful fractions that are significant proportions of total SOM and are responsive in quantity and chemical nature to land management within the appropriate timescale. Such fractions can be used to elucidate (i) the effects of land use on SOM pools that are cycling at relevant rates, and (ii) the altered contributions of these SOM pools to soil processes and the research issue.

The extraction of SOM fractions that differ in cycling rate can be based on any of several modes for SOM stabilization in soil. These modes are of physical, chemical, or biological nature, including recalcitrant SOM chemical structures, microbially mediated condensations, binding to mineral surfaces, binding to polyvalent cations, protection within aggregates, inaccessibility in small micropores, and inhibited microbial activity (Sollins et al., 1996). During more than two centuries of research, SOM fractions have been extracted by many different procedures. Most studies used only one type of extraction procedure. Chemical extractions were dominant until recent decades, when physical extractions have become increasingly popular and more elaborate analyses for microbial characteristics have been developed. Comprehensive reviews are available for extractions involving particulate organic matter and the light fraction (Gregorich and Janzen, 1996; Wander, 2004), particle size fractions (Christensen, 1992), aggregate classes (Six et al., 2004), and chemical extractants (Hayes, 1985; Stevenson, 1994).

The modes of SOM stabilization have proven to vary in significance by the situation, depending on soil type, land use, and other factors. No SOM extraction procedure has proven to be the most suitable in all cases. Researchers have tended to cluster into groups centered on preferred fractionations. Unfortunately, collaboration and dialog among the different groups have been lacking. Chemical extractions are used for advanced chemical characterization of SOM and in studies of aquatic systems and decomposition of organic materials, but they have not been linked to physical extractions that

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Abbreviations: SOM, soil organic matter.

are commonly used in field studies to isolate discrete SOM fractions. Many field researchers have not considered chemical modes for stabilization. The biological activity of physical or chemical fractions has only recently received some attention. These collaboration gaps inhibit the synthesis of knowledge that is gained from different fractionation types.

One approach to begin synthesizing our fragmented SOM knowledge is to identify the most suitable extraction procedure for a specific research situation, that is the specific land use, soil type, and nutrient or compound in question. This approach acknowledges that no extraction procedure is the most suitable choice for all situations and instead proposes to identify for that situation the SOM fraction that best represents the functional SOM pool—the SOM material that is most involved in the issue at hand. The functional SOM pool will cycle within the same timeframe as the issue in question, it will respond in quantity and chemical nature to the issue, and its dynamics will affect the performance of the soil ecosystem. Given the diversity of stabilization modes, the functional SOM pool may include different SOM materials in different situations.

At the 2004 joint annual meeting in Seattle, WA, of the Canadian Society of Soil Science and the Soil Science Society of America, the special symposium “Meaningful pools in determining soil C and N dynamics” was held to discuss the most commonly used procedures for SOM fractionation. The accompanying papers comprise a partial proceedings of the symposium. They summarize knowledge regarding real world issues that has been gained by some of the fractionation procedures, and they identify strengths and weaknesses of each procedure. A brief overview of some fractionations and related literature is presented in this report, as grouped by physical and chemical fractionations, followed by some recommendations for future action.

PHYSICAL FRACTIONATIONS

Physical fractionation methods separate soil constituents on the basis of size and/or density. These methods are predicated on the premise that the associations of organic matter with soil minerals and their three-dimensional architecture are responsible for the function and dynamics of SOM. For example, the macroscale arrangement of uncomplexed organic matter, sand, silt and clay mineral particles combined with organic compounds, and inorganic cementing agents influences the diffusion, transmission, and storage of water (Prove et al., 1990) and gases (Sexstone et al., 1985); adsorption and desorption of cations and anions (Linguist et al., 1997), the size and structure of microbial communities (Blackwood and Paul, 2003), and the turnover and mean residence of SOM (Saggar et al., 1996, 1999; Jenkinson et al., 1987).

Physical fractionation also recognizes the importance of the microscale location of SOM. The degree to which SOM is in contact with mineral surfaces (i.e., via cohesion and adsorption bonding forces (Chenu et al., 2002) and whether it is located in a conglomeration of particles that act as a physical barrier to microbes will influence

its chemical makeup and turnover (Sollins et al., 1996; Baldock and Skjemstad, 2000). A fundamental research question is, “Do these binding forces and the accessibility of organic matter in these different fractions influence the turnover at time frames relevant to management practices?” The consensus opinion is that they do (Chenu et al., 2002; Christensen, 2001; Gregorich et al., 2006, this issue; Six et al., 2004).

Physically Uncomplexed Organic Matter

Physically uncomplexed organic matter is not bound to or associated with soil mineral particles. It mostly comprises relatively unaltered plant material and has a wide C to N ratio. Its quantity, while a substantial proportion of SOM, usually changes more quickly than does SOM in response to land management (Gregorich and Janzen, 1996). Factors that affect its quantity and chemical and biological characteristics include the amount, composition, and accessibility of plant residues entering the soil and soil environmental conditions. Gregorich et al. (2006, this issue) reviewed its application to several research issues.

What Have We Learned from Physically Uncomplexed Organic Matter?

Uncomplexed organic matter is labile and hence could be considered a readily available source of energy and nutrients. Generally this concept may hold true for energy, as the C in physically uncomplexed organic matter has been shown to be a sensitive indicator and predictor of C mineralization and total soil organic C (Paul et al., 2004; Campbell et al., 2001; Biederbeck et al., 1994; Janzen et al., 1992). Uncomplexed organic matter may be a source of specific nutrients in particular soils or ecosystems, but this is not true across all soils. Most studies of N mineralization did not find strong relationships between N content of uncomplexed organic matter and soil N mineralization, suggesting that the N in uncomplexed organic matter does not represent labile soil organic N. Possible reasons are summarized by Gregorich et al. (2006, this issue).

Limitations of the Method

Organic material is fragmented and comminuted by sample preparation, especially during drying, rewetting, grinding, sieving, and freezing. The amount of energy used to disperse the soil (e.g., sonication) affects the quantity of uncomplexed organic matter recovered by sieving methods (i.e., particulate organic matter). Small differences in the solution density may substantially affect the quantities of the density fractions (Richter et al., 1975).

Primary Particles

Separation of primary organomineral complexes (i.e., clay-, silt- and sand-sized particles) involves complete dispersion in an aqueous solution (usually water) by ultrasonic vibration or shaking with glass beads or agate marbles. Coarser fractions, such as sand, are separated by sieving, and finer fractions (such as silt and clay)

are separated by sedimentation, which is based on Stokes' law.

The separation and analysis of particle size fractions has been used to evaluate the dynamics of SOM and nutrients, including their source of origin, turnover, and mean residence times (Balesdent et al., 1998). Christensen (1992) reviewed the use of particle size fractionations in studying the dynamics of anthropogenic compounds. This fractionation has been used to assess effects of cultivation (Tiessen and Stewart, 1983) and land use (Guggenberger et al., 1995) on the quantity and biochemical composition of SOM.

What Have We Learned from Particle Size Fractionations?

In the majority of temperate soils, clay-sized particles are the most enriched in SOM and sand-sized particles are least enriched. Analysis by ^{13}C nuclear magnetic resonance spectroscopy has shown that the chemical composition of SOM differs significantly among clay-, silt-, and sand-sized classes (Guggenberger et al., 1995). Clay-sized particles are usually enriched in microbial products but depleted in plant residue components, whereas silt-size particles are enriched in plant-derived aromatics and the sand-size fraction is enriched in plant polymers (Christensen, 2001).

Studies have shown an apparent discontinuity between particle size and organic matter stability. For example, Anderson and Paul (1984) found the oldest ^{14}C ages in the fine silt and coarse clay fractions. Christensen (1992), in a review of several studies, observed that organic matter of the fine silt and coarse clay fractions tended on average to be more stable than organic matter of the other size fractions.

Limitations of the Method

Problems encountered during particle size fractionation include complete removal of water and air from aggregate surfaces and cavities, complete disruption of aggregates and flocules, maintenance of dispersion during fractionation, and changes in organomineral complexes arising from ultrasonic treatment and solution effects of dense liquids.

In each size fraction, especially the coarser fractions, organic matter may exist in varying degrees of association with the mineral components (Skjemstad et al., 1988). Deviations in the size (i.e., not spherically shaped) and density violate some of the assumptions in Stokes' sedimentation law and can result in co-extraction of particles of varying nature (Christensen, 1996). For example, Turchenek and Oades (1979) observed both clay and SOM particles within the same size class of particles.

Interpretation of data derived from particle-size fractionation is at times difficult because the fractionation procedure may cause transfer among particle size fractions. McGill et al. (1975) found that organic material in the finest clay fraction contained a substantial proportion of recently immobilized N, which they suggested had originated from cytoplasmic constituents that had been released during sonication. Extensive cell

rupture during sonication would obscure the natural distribution of immobilized N among fractions resulting from immobilization-mineralization reactions (Ladd et al., 1977).

Aggregates

Secondary organomineral complexes (i.e., aggregates) are separated by sieving in either air or water. Because aggregates are assemblages of mineral-associated and uncomplexed organic matter together with microorganisms and fine roots, their chemical and biological properties are much more complex than any of the individual constituents. Aggregates are typically classified into micro- and macroaggregates (size separation at 250 μm), each of which may have distinct organic binding agents. Tisdall and Oades (1982) classified the binding agents as transient, temporary, or persistent, and they used the perspective of aggregate hierarchy to explain how microaggregates are formed by polysaccharide-based glues produced by roots and microbes and by calcium bridges. These relatively stable microaggregates were thought in turn to be bound into macroaggregates by a network of roots and hyphae. Aggregate formation plays an important role in biological, chemical, and physical processes of the soil (Hartge and Stewart, 1995).

What Have We Learned from Aggregate Fractionations?

Aggregates and the process of aggregate formation have been studied to explain long-term stabilization of SOM and to assess the effects on soil structure of soil fauna and microorganisms, roots, inorganic binding agents, and environmental variables (Six et al., 2004). The amount and size distribution of aggregates and their properties respond relatively quickly to agricultural management, including crop type, rotation, and tillage practices (Tisdall and Oades, 1982). For example, a significant increase in water-stable aggregates can occur within 2 to 3 yr following conversion of conventionally tilled soil to no-tillage management (Arshad et al., 1999; Angers et al., 1993).

Limitations of the Method

The fractionation of soil by aggregate size and/or stability has been criticized because, it is argued, the fractionation procedures may affect the biological properties (i.e., organic C and N and soil respiration) of the fractions isolated (Ashman et al., 2003). Methods for fractionating aggregates have not been standardized, and variables such as moisture content before fractionation (Dickson et al., 1991), the form and magnitude of mechanical energy input, initial aggregate size, sieve loading, and sieve oscillation rate can all affect the quantity and size range distribution of aggregates recovered (Kemper and Koch, 1966). This lack of standardization complicates the interpretation of the role of aggregates in SOM dynamics. Similar to physically uncomplexed organic matter, the degree of soil aggregation has had mixed significance for soil N mineralization (Feller and

Beare, 1997; Christensen, 1992), in contrast to the much clearer effects of aggregation on soil C mineralization.

Integrated Physical Fractionations

Each of the three major types of physical fractionations—aggregates, primary particles, and uncomplexed organic matter—distinguishes one component of the physical architecture in soil (Christensen, 2001). They have been applied to many of the same issues, yet they vary subtly in their appropriateness for research issues or soil types. For example, fractionation of soil into clay- and silt-sized primary particles is well suited for molecular-level investigations into binding of organic matter to specific types of mineral surfaces, which can provide useful information on adsorption phenomena and effects of intrinsic soil properties on turnover of C, N, and anthropogenic compounds. Fractionations for physically uncomplexed organic matter and aggregates are also used to study C and N turnover, and they are well suited for determining seasonal dynamics under field conditions, as they can consider (i) the three-dimensional soil architecture, whose ephemeral nature is altered by field practices, and (ii) labile, C-rich fractions that continually change with the ongoing balance between C input and C degradation.

Few studies have fully integrated all three approaches for physical fractionation. Many more studies have combined portions of at least two approaches. They usually start at the highest level of complexity (aggregation) and fractionate further for recovery of the primary components—particle sizes and/or uncomplexed organic matter. Such methods are usually used to evaluate the formation and stabilization of aggregates and the properties of SOM within the aggregates. Only a few studies will be described here to give a brief overview of important findings.

Turchenek and Oades (1979) dispersed soils into seven size ranges and then fractionated each size range into at least four density fractions. Organic matter was concentrated in low-density fractions in all size ranges. The light fractions of the sand-sized range had wide C/N ratios characteristic of plant debris, while those of the fine silt and coarse clay ranges appeared to be humic material derived from microbial cell debris.

Oades and Waters (1991) used a gradient of disruption intensity and a combination of size and densitometric fractionations to conclude that aggregate hierarchy exists in soils where organic materials are the dominant stabilizing agents in larger aggregates. But in oxide-rich soils where the oxides dominated as stabilizing agents, an aggregate hierarchy based on organic materials did not form.

Puget et al. (1996) combined size and density fractionations to find a relatively large proportion of uncomplexed organic matter within stable macroaggregates. Using a similar approach, Six et al. (1998, 1999, 2000) developed a conceptual model that linked a proportion of the C lost through tillage to increased turnover of macroaggregates. Significant amounts of labile SOM within macroaggregates were also demonstrated by crushing various sized aggregates, presumably to mostly primary particles (e.g., Elliott, 1986; Gregorich et al., 1989).

Shang and Tiessen (2000) isolated different density fractions within sand- and silt-size fractions and used the natural abundance of ^{13}C to determine C turnover in each subfraction. Highly variable turnover of C in the density fractions across and within size fractions indicated that mean residence time was not a singular property of soil C but rather a composite of a spectrum of mean residence times of different C fractions. Hence, stabilization and destabilization of SOM can follow different pathways and involve different fractions; there may be no unique pools having specific stability.

CHEMICAL FRACTIONATIONS

Chemical fractionations distinguish SOM fractions based on their respective solubilities in various extractants, sometimes before and after selected pretreatments of the soil. Extractants have included organic solvents and aqueous solutions of acids and bases (Hayes, 2006, this issue). Chemical fractionations consider the type of chemical binding between SOM and mineral soil particles and the chemical binding within SOM, but they do not consider the three-dimensional arrangement of organomineral complexes. The intent is often to obtain a purely organic sample, which facilitates chemical characterization by spectroscopic techniques. Some studies distinguished labile SOM fractions from recalcitrant fractions, while other studies strived to maximize the amount of extracted material. Accompanying papers by Farenhorst (2006), Hayes (2006), Oik (2006), and Simpson (2006) provide examples of the range of agricultural and environmental issues that have been addressed by chemical fractionations.

Of the many chemicals used to extract SOM, inorganic bases and acids have been most common. The following sections summarize information gained through these two approaches.

Acid Extractions

Hydrochloric acid has been by far the most common acid extractant. Sulfuric acid has also been used for extraction of sugars, and HF has been used for extraction of pure SOM and of clay-bound organic matter (Stevenson, 1994).

What Have We Learned from Acid Extractions?

For C forms, HCl hydrolysis has been shown to remove younger materials from soil, leaving a relatively resistant SOM fraction as reviewed by Paul et al. (2006) in these proceedings. For N forms, HCl hydrolysis has been the conventional procedure for extraction of amino acids to determine N forms in SOM (Stevenson, 1994, 1996; González-Prieto and Carballas, 1988). The amount of extracted amino acid-N was previously viewed as a measure of available organic N (Stevenson, 1994).

Limitations of the Method

Paul et al. (2006, this issue) summarize the disadvantages of HCl hydrolysis in distinguishing C forms by

their lability. Acid hydrolysis typically recovers only about half of all organic N for determination of organic N forms (Stevenson, 1994). As reviewed by Stevenson (1982), acid hydrolysis has proven to have little practical value for determining levels of available soil N or for predicting crop yields. Mulvaney and Khan (2001) reported methodological errors in this method and questioned its sensitivity to field treatments.

Base Extractions

The most commonly used base for extracting SOM has been NaOH (Swift, 1996), and most of the following results were achieved with NaOH. Some extractions were also done with sodium pyrophosphate after adjustment to varying pH values in the neutral and basic ranges.

What Have We Learned from Base Extractions?

To develop a molecular-level understanding of SOM functions, considerable effort has been directed toward identifying the chemical structure of SOM. The evolution of beliefs regarding the chemical structure of SOM was described by Stevenson (1994), Hayes and Malcolm (2001), and Hayes (2006, this issue). Despite use of numerous analytical approaches (Hayes et al., 1989), a single chemical structure of SOM has not yet been identified for soils. This failure, along with ecological concepts, has fostered the thought that SOM might not have a regular chemical structure. An irregular pattern of component molecules and chemical bonds might explain the resistance of SOM to degradation—which is catalyzed by substrate-specific microbial enzymes—hence resulting in the generally slow turnover of SOM (MacCarthy, 2001; Burdon, 2001; Hayes and Clapp, 2001).

Many environmental issues investigated by SOM researchers concern the sorption and transport of anthropogenic chemicals, including pesticides and other organic xenobiotics, metals, radionuclides, and other industrial products. Reports by Farenhorst (2006) and Simpson (2006) in these proceedings illustrate the application of base extractions to contaminant behavior at two of the three spatial scales described by Simpson (2006): landscape-level, macroscopic, and molecular-level. In these two reports, base extractions were used to describe partitioning coefficients and pesticide distributions across landscapes and to elucidate sorption mechanisms at the molecular scale. Applications of base extractions to additional environmental issues were reported in several conference proceedings, including those of the International Humic Substances Society (e.g., Swift and Spark, 2001; Martin-Neto et al., 2004), the Humic Substances Seminar (e.g., Davies et al., 1998; Ghabbour and Davies, 2004), and others (Christman and Gjessing, 1983; Hayes and Wilson, 1997). These issues included SOM functions in aquatic ecosystems and organic systems (composts, urban wastewaters, animal manures, and sludges/biosolids), and commercial use of humic fractions in agriculture, medicine, and pollution control.

Base extractions have been used to study the chemical forms of organic nutrients, including C and N (Steven-

son, 1994; Preston, 1996; Kögel-Knabner, 1997), but this work has often not been placed within a dynamic field context. In these proceedings, Olk (2006) reported on the role of Ca binding in SOM stabilization and nutrient cycling. A role of Fe oxides in SOM sequestration was indicated through chemical dissolution of Fe oxides (Kiem and Kögel-Knabner, 2002; Eusterhues et al., 2003). In these proceedings, Hayes (2006) reports that a urea washing following base extraction might better distinguish the unextractable humin, which is thought to consist mostly of relatively old, stabilized C and whose aliphatic nature makes it highly interactive with some anthropogenic compounds (Rice, 2001).

Limitations of the Method

Base extractions—and all chemical extractions—do not consider the spatial distribution of SOM in soil. Consequently, they do not distinguish physically inaccessible material (inside aggregates or micropores) from fully accessible material, or soil-bound material from uncomplexed material, and therefore they cannot capture many of the insights gained through physical fractionations. During base extraction, material may be mixed among SOM fractions to unknown degrees, and it may also undergo chemical alterations such as autoxidation. This danger can be substantially reduced by maintaining an O₂-free atmosphere (Choudhri and Stevenson, 1957). A frequent concern is that chemical extractions cause random cleavage of SOM into subunits, followed by random repolymerization into new molecules—and possibly new SOM fractions—that are irrelevant to field conditions.

A BRIEF VIEW TOWARD THE FUTURE

A Call for Better Coordination

Soil organic matter may well be a continuum of related material, not a series of discrete pools (Paul et al., 2006, this issue; Shang and Tiessen, 2000). Therefore, a laboratory fractionation can at best partition this continuum into subunits that differ from each other more than they are similar in their chemical compositions and cycling rates. The guiding principle to these proceedings was that no single fractionation procedure provides the best partitioning for all situations. The accompanying studies have reinforced this concept by illustrating strengths and weaknesses of each procedure. Each procedure provided fundamental insights into the cycling or stabilization of a nutrient or anthropogenic compound in one situation or another. Each has enabled distinction of older SOM from younger SOM to some degree. Yet all of the procedures have the potential for sample alteration during extraction. Some fractions were shown to consist of subfractions.

In fact, no procedure appears capable of distinguishing SOM fractions based on all possible agents for SOM stabilization, which vary in significance among soils and among compounds. For example, C and N are considered as closely linked in soil processes, yet physically uncomplexed SOM and labile aggregate fractions are more meaningful for C cycling than for N cycling.

To improve on this array of useful yet imperfect fractionations, one path of coordinated action would use multiple fractionation procedures, whether integrated into one grand procedure or instead run in parallel on separate subsamples. The approach described by Paul et al. (2006) in these proceedings contains both a chemical extraction and a biological assay. Integrating and combining multiple fractionation procedures, especially both physical and chemical fractionations, would encompass a range of stabilization agents not previously coupled.

A second path of coordinated action, grouping the fractionations by their most suitable applications, would enable more precise approximation of the functional SOM pool(s) for any situation. To do this, however, would require a coordination of efforts among researchers who currently do not interact regularly with each other.

Some Ideas for Future Research with Soil Organic Matter Fractions

As we progress in characterizing extracted fractions, the emphasis should be on the dynamics and kinetics of these fractions, not merely within multiyear time frames but also within seasonal time frames that would capture the dynamics of labile SOM in response to short-term soil processes. Stable isotopes have been used for this purpose and should continue to be used; use of radioactive isotopes will probably diminish as other labels (e.g., biomarkers) become more widely used. Greater information on dynamics and kinetics would facilitate the development of SOM pools that can be directly used in simulation models and that are based on properties of extracted SOM fractions, similar to the approach of Paul et al. (2006) in these proceedings. Although SOM dynamics may well reflect the interaction of multiple factors (Paul et al., 2006), close linkage of the chemical and kinetic properties for SOM fractions might nevertheless allow better prediction of the stabilization of organic inputs in soil.

Carbon sequestration will remain a focus for soil research for the foreseeable future. Can chemical and/or biological fractionations be integrated with physical fractionations to provide a more holistic understanding of C sequestration, whether in the humin, aggregate-related fractions, or on clay surfaces? A broader fractionation will better describe the complete effects of C sequestration on the soil ecosystem: C sequestration requires simultaneous sequestration of N and other plant-essential nutrients into less available forms, it increases the potential sequestration of anthropogenic compounds, it improves aggregation and other physical properties of the soil, and it increases the potential food supply for microorganisms.

Investigations of SOM contributions to soil physical properties have focused on aggregation. Other soil physical properties warrant more attention. For example, the growing size of farm machinery ensures continuing problems with soil compaction. Can increased quantity or quality of SOM fractions be managed to mitigate compaction? Would labile or stable SOM fractions provide more lasting benefit? Also, it is not clear whether

water retention is associated more with labile SOM fractions or with recalcitrant fractions, and which extraction procedure would best isolate the pertinent fractions. If climatic projections of increased temperatures and variable precipitation patterns come true, water storage in soil will become more critical for rainfed agriculture. A process-level understanding of water retention would enable better evaluation of management options such as no-tillage that are thought to increase soil water-holding capacity.

CONCLUSIONS

Vast bodies of research have used any of several SOM fractionation procedures to address the role of SOM in real-world issues. Each of the fractionation methods has provided useful information for specific conditions, but all have procedural limitations and none has been shown to be the most suitable choice for all situations. We call for greater interaction among SOM researchers to (i) develop integrated fractionations that account for multiple modes of SOM stabilization and (ii) categorize the existing procedures by their most suitable applications.

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