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Soil organic carbon is not just for soil scientists: measurement recommendations for diverse practitioners

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Abstract

Soil organic carbon (SOC) regulates terrestrial ecosystem functioning, provides diverse energy sources for soil microorganisms, governs soil structure, and regulates the availability of organically-bound nutrients. Investigators in increasingly diverse disciplines recognize how quantifying SOC attributes can provide insight about ecological states and processes. Today, multiple research networks collect and provide SOC data, and robust, new technologies are available for managing, sharing, and analyzing large data sets. We advocate that the scientific community capitalizes on these developments to augment SOC datasets via standardized protocols. We describe why such efforts are important and the breadth of disciplines for which it will be helpful, and outline a tiered approach for standardized sampling of SOC and ancillary variables that ranges from simple to more complex. We target scientists ranging from those with little to no background in soil science to those with more soil-related expertise, and offer examples of the ways in which the resulting data can be organized, shared, and discoverable.

Keywords: standardized soil methods; soil climate feedbacks; global C cycle

1. Introduction

Soil organic carbon (SOC) plays a critical role in terrestrial ecosystem functioning as the dominant energy source for microorganisms and as a fundamental control on soil structure and ecosystem productivity. Whether solid or dissolved, SOC is derived from aboveground and belowground plant materials, and soil organisms and the secondary products they synthesize (Lal et al. 2001; Schlesinger and Bernhardt 2013). Soil organic C regulates critical ecosystem services such as nutrient provisioning, water-holding capacity and soil drainage, soil stability, and greenhouse gas emissions that can mitigate or accelerate climate change (Davidson and Janssens 2006; Jackson et al. 2017). Containing more than three times as much C as the atmosphere (Lal 2004) and perhaps up to 3000 Pg (Scharlemann et al. 2014), Earth's reservoir of SOC has undergone depletion due to land cover changes and unsustainable land management in the Anthropocene (Paustian et al. 1997; Amundson et al. 2015; Sanderman et al. 2017; Harden et al. 2017). The potential to reverse these trends via management practices is currently debated (Minasny et al 2017; Amundson & Biardeau 2018), but evidence suggests that increased SOC storage in agricultural lands alone has the potential to detectably reduce the atmospheric CO_2 burden (Griscom et al. 2017; Mayer et al. 2018). Collectively, these observations and concerns underscore the importance of advancing our ability to identify the environmental conditions linked to SOC input, losses, and retention (Smith et al. 2019) and, ultimately, to understand the mechanisms driving patterns of SOC distributions within and among ecosystems.

Recent works highlight two phenomena that, if fully leveraged, offer a means for significantly advancing understanding of SOC dynamics. First, a growing number of practitioners across diverse disciplines are recognizing the importance of SOC attributes as indicators of ecological states or ecosystem processes not obviously linked to SOC (Lange et al. 2015; Doetterl et al. 2016; Hirmas et al. 2018; Fan et al. 2019). In addition to disciplines that are more traditionally aligned with SOC data like ecosystem ecology and soil science, scientists from the diverse realms of hydrology, pedology, geochemistry, and community ecology are developing a new or renewed appreciation of the importance of quantifying SOC attributes to better understand their physical, chemical and biological systems of interest. Second, multiple research and observatory networks that target SOC as a variable of interest have emerged over recent decades (Harden et al. 2017; Malhotra et al. 2019; Weintraub et al. 2019; see more details in Section 4). This has been paired with the development of technologies needed to manage, share, and analyze the resulting large data sets. Here, we call for increased efforts to capitalize on these developments. Specifically, we outline a tiered approach to best practices for standardized SOC sampling, aimed at (1) expanding the geographic and depth extent of SOC sampling and (2) maximizing the utility of the resulting data for diverse disciplines. Via these means, we hope to improve global understanding of SOC pools and processes.

First, in Section 2, we briefly describe why, in spite of a myriad of extant SOC studies, more data quantifying SOC concentrations, pool sizes, and dynamics in managed and natural systems are needed for understanding Earth's C cycle and associated climate feedbacks. In Section 3, we provide examples of how multiple scientific disciplines can benefit from such efforts, ranging from those in which SOC is clearly relevant, to those with more subtle, yet important linkages to SOC. We then emphasize in Section 4 how existing research networks offer long-term collections of SOC data, and highlight data compilation and harmonization efforts that allow us to synthesize and analyze these large, living datasets. These networks and datasets permit diverse scientific communities to develop and test previously unarticulated or otherwise untestable hypotheses, including by parameterizing and validating models.

In Section 5, we outline a tiered measurement approach, ranging from simple (Tier 1) to more complex (Tier 3), for standardized sampling of SOC in diverse systems depending on investigator goals and available resources. We specifically contend that the efforts of individual scientists from an increasingly diverse set of disciplines will better advance understanding of SOC dynamics across environmental gradients if methods are standardized, and if results of these studies are more integrated with network science initiatives. We further highlight the most important ancillary variables that enhance SOC data use within diverse scientific pursuits. We highlight the critical nature of quantifying SOC concentrations and stocks (Tier 1) as well as selected measures of soil biological, physical, and chemical attributes that can help us understand mechanisms of SOC formation, retention, and loss at a site (Tiers 2 and 3). These tiers of sampling complexity (Figure 1) are targeted at scientists across disciplines, ranging from those with little to no background in soil science to those with more soil-related expertise, all of whom may be interested in assessing linkages between their primary data target(s) and SOC attributes while also contributing to the broad effort to grow SOC databases. It is our hope that investigators interested in quantifying SOC and related variables in their system(s) of choice can agree on the most valuable metrics to maximize the utility of the resulting data to others. Finally, in Section 6, we offer prescriptive examples of ways in which these data can be organized and made discoverable to maximize their utility for diverse scientific communities.

2. Expanding the global reach and depth of standardized SOC data will improve projections of the global C cycle

Existing SOC data have advanced our knowledge of soil feedbacks to the global C cycle and climate system in innumerable ways. Particularly exciting are recent advances that harmonize diverse datasets (Wieder et al. 2020) to promote use of SOC data collected across space and time. For example, large-scale SOC databases have advanced our understanding of environmental controls over SOC stabilization (Rasmussen et al. 2018), SOC responses to land management (Nave et al. 2018), and the ecosystems in which uncertainty in SOC stocks is especially high (Jackson et al. 2017). Abundant data on SOC stock sizes and timescales of SOC formation and loss can be found in the literature (e.g., Jobbagy and Jackson 2000; Cotrufo et al. 2015; Hicks Pries et al. 2017), helping investigators to parameterize and evaluate large-scale representations of the global C cycle in models (Luo et al. 2016; Collier et al. 2018; Zhang et al. 2020). In spite of these advances, two categories of problems limit our ability to gain a predictive understanding of SOC feedbacks to the global C cycle. First, uncertainty related to the vulnerability of this large terrestrial C pool remains high (Todd-Brown et al. 2014; Wieder et al. 2019). Furthermore, a lack of standardized approaches to collecting SOC and key, related data has resulted in many datasets having limited or no utility for those hoping to develop large-scale analyses.

Addressing uncertainty in SOC projections requires additional SOC measurements from diverse ecosystems (Malhotra et al. 2019), collected in a standardized manner. Soil organic C pools are poorly characterized in multiple ecosystems and depths. For example, SOC stocks in northern ecosystems and wetlands are very large, but exhibit tremendous spatial heterogeneity and thus challenge our ability to estimate their contributions to global SOC stocks (Hengl et al. 2017; Hugelius et al. 2013; Jackson et al. 2017; Malhotra et al. 2019). Soil sampling efforts in non-temperate regions (e.g., northern latitudes, the tropics, northern Africa) and central Asia have lagged behind those in other areas (Batjes et al. 2020). Worldwide, limited deep soil sampling – which most investigators consider to be depths greater than 30 cm (Richter and Billings 2015) – due to accessibility challenges (Richter and Markewitz 1995; Jobbagy and Jackson 2000) limits our understanding of deep, lateral SOC heterogeneity. These gaps in coverage of SOC data limit our ability to project SOC responses to a changing environment (van Wesemael et al. 2011; Smith et al. 2019), and to understand any broad-scale trends in SOC responses to changing environmental conditions revealed by data harmonization efforts. Filling these gaps cannot reliably occur without standardized data collection and presentation. For example, reports of SOC concentration without corresponding soil mass or volume information prohibit investigators from computing SOC stock estimates. We thus argue that the pressing demand for accurate projections of soil feedbacks to climate and land use prompts a need for augmenting standardized datasets describing SOC concentrations, pool sizes, and links to biotic and abiotic variability in a range of managed and natural systems across the globe.

3. Diverse scientific disciplines benefit from augmenting SOC datasets

The importance of SOC data to some disciplines is self-evident. For example, soil microbiologists and chemists rely on SOC data for fundamental information on availability of resources for microbes and chemical reactivity of soil, respectively. Similarly, ecosystem ecologists, biogeochemists, and ecosystem process modelers rely on SOC datasets to infer past and contemporary C fluxes and ecosystem status, and to project future terrestrial feedbacks to climate (Doetterl et al. 2016; Hicks Pries et al. 2017; Wieder et al. 2017). Soil organic C measurements are also part of a constellation of datasets necessary for understanding nutrient availability (Vicca et al. 2018) and, more broadly, soil "health" (Doran 1996), a concept that broadly represents the productivity potential of a soil for food, fiber, and water quality (see https://www.soilhealthinstitute.org). With recent advances in our biogeochemical understanding of interrelated ecosystem dynamics, the characterization of SOC concentrations and stocks throughout soil profiles has proven invaluable to additional, diverse environmental science disciplines (Table 1).

The science of pedology is perhaps the discipline most obviously relevant to SOC. Visual assessments of SOC abundance, using field-observed soil color and texture as guides, serve as one feature in a constellation of observations that help pedologists discern and identify the horizons within a given soil profile (Buol et al. 1989). Less obvious is the important role of SOC data in understanding how ecological communities and populations function. Community ecologists are increasingly recognizing the strong, positive relationship between SOC and plant diversity (Chen et al. 2018; Yang et al. 2019), and studies of flora and fauna populations also benefit from understanding SOC abundance. For example, the abundance of soil-dwelling invertebrates is strongly driven by SOC contents across natural and agro-ecosystems (Wang et al., 2016; Zhao et al. 2017). Studies of soil microbial populations and communities are also invaluable for understanding the fundamental mechanisms governing how soils can feed back to climate at a large scale. For example, individual and mixed populations of bacteria and fungi as well as field and lab studies of soil microbial communities (Frey et al. 2013; Cotrufo et al. 2015; Kallenbach et al. 2015; Kallenbach et al. 2016; Min et al. 2016; Kallenbach et al. 2019; Bradford et al. 2013) reveal that microbes modify the fraction of C allocated to biomass growth, CO_2 release, and extracellular compounds that may persist as SOC as environmental conditions change. This mechanism is likely responsible, in part, for the varying competitive abilities of microbial populations under varying environmental conditions (Langenheder et al. 2006).

Recent work also highlights how SOC data can serve as a critical feature of understanding how soil structure governs ecosystem functioning. Indeed, changes to SOC abundance can prompt a switch between alternate stable states in soil structure (Robinson et al. 2019) as soil solids and voids shift in shape and connectivity with SOC additions or losses (Arnold et al. 2015). Hirmas et al. (2018) demonstrated that soil effective porosity, a hydraulic parameter that drives soil water movement through profiles, can change on decadal timescales – far more rapidly than has been thought to date. The rapidity with which this soil structural attribute appears to change suggests that is influenced by biotic processes, and alterations in SOC content may be an important driver of this soil hydro-physical characteristic (Hirmas et al. 2018). The dynamic two-way relationship between soil water status and SOC stocks and losses continues to underpin our understanding of environmental controls on SOC dynamics (Ghezzehei et al. 2019). The linkage between SOC and soil structure necessarily means that SOC is an important feature governing hydraulic flow paths through and across landscapes, and thus SOC is directly linked to the emerging discipline of hydropedology which explores the interactions of hydrological and pedological processes in the unsaturated zone (Lin 2012), as well as soil physics itself. As such, reactive transport modelers also benefit from knowledge of SOC abundances in diverse environmental settings. At the pedon, hillslope, watershed, and continental scales, varying soil structural attributes can modify root C inputs and rates of microbial mineralization of SOC, resulting in divergent rates of soil weathering (Sullivan et al. 2019) and water and energy fluxes (Fan et al. 2019) that provide important feedbacks to climate.

4. Research networks and data compilations are powerful means of generating and leveraging data

Though SOC data are deemed useful for many disciplines (Vicca et al. 2018), datasets describing changes in SOC pools over decadal and centennial timescales are relatively rare (Richter et al. 2007). These datasets reveal how the power to detect change depends on sampling intensity in time and space, and on parameter variability at discrete depths (Mobley et al. 2019). Networks often struggle to balance standardized data collection across diverse environments with the unstandardized approaches often exhibited by hypothesis-driven research (Richter et al. 2018). Despite these challenges, research networks provide contextual data to help us understand and model SOC drivers and feedbacks (Baatz et al. 2018), and offer varying degrees of standardized approaches that permit comparisons across wide gradients and over time.

Several major research networks recognize the importance of SOC to diverse, transdisciplinary environmental processes and make measurements of SOC concentrations (Richter et al. 2018; Weintraub et al. 2019). These networks include the Long-Term Ecological Research network (LTER; lternet.edu) and the International LTER (lternet.edu/international), the Critical Zone Collaborative Network (CZCN; criticalzone.org) and additional CZ Exploratory Network sites (czen.org), and the National Ecological Observatory Network (NEON; neonscience.org). These networks focus on testing of site-specific hypotheses (LTER, CZCN) and/or monitoring (NEON, LTER). The Long-Term Agroecosystem Research Network (LTAR; Kleinman et al. 2018) highlights monitoring and hypothesis testing in agricultural systems as ecosystems across the U.S. Long-term soil experiments (LTSEs; Richter et al. 2007; Janzen 2009) and networks of chronosequence sites serve as invaluable repositories of SOC data, with sampling at multiple depths over long time periods or across space as described in Smith et al. (2019). Many LTSEs have been integrated into a network to help publicize their work (https://iscn.fluxdata.org/network/partner-networks/ltse/) but operate independently; as such they represent a diversity of approaches to documenting SOC changes over time. It is challenging to maintain well-documented, comparable LTSE sampling and analytical approaches over many decades (Richter et al. 2007). However, LTSEs offer a suite of opportunities to nurture insights about SOC dynamics over timescales often longer than the human lifespan. Further, networks of experimental sites, such as the Detrital Input and Removal Treatments (DIRT; https://dirtnet.wordpress.com/) and the Nutrient Network (NutNet; https://nutnet.org/) are collecting data over decades that can help elucidate mechanisms driving SOC losses and gains following a perturbation.

While researchers participating in networks such as those described above are generating large volumes of data, other researchers are working on harmonization and synthesis of data across sites and experiments. The International Soil Reference and Information Centre (ISRIC, https://www.isric.org), the International Soil Radiocarbon Database (ISRaD, https://soilradiocarbon.org), and the International Soil Carbon Network (ISCN, http://iscn.fluxdata.org) are examples of entities leading efforts to compile soil databases. The Soils Data Harmonization (SoDaH, https://lter.github.io/som-website/index.html) is compiling SOC data from research networks into one accessible database. A list of soil databases and their attributes are discussed in detail in a recent review (Malhotra et al. 2019). Briefly, the following are examples of best uses of the aforementioned networks. ISRIC has the largest global database (containing 150,000 + soil cores) and is best suited to questions of global variation in carbon stocks (Batjes et al. 2020). ISCN, ISRaD and SoDaH, on the other hand, also describe soil C stocks, but may be more useful for mechanistic questions as they contain information on other soil attributes such as pH, radiocarbon signatures and soil fractions, among other features; SoDaH also includes time series data. (Lawrence et al. 2020, Malhotra et al. 2019, Wieder et al. 2020). The International Soil Modeling Consortium (ISMC, https://soil-modeling.org) hosts diverse soil models, many of which require SOC as input data. This landscape of emerging "big soil data" highlights that there is room for both organized research networks to contribute large, standardized datasets, and for individual researchers to contribute more targeted datasets from specific sites and experiments. In concert, these data advance our ability to understand and model the dynamics of SOC (Harden et al. 2017; Malhotra et al. 2019), and by extension global climate.

5. Sampling opportunities

Measurements of SOC will be more powerful collectively if the community uses standardized approaches and provides data for key, associated variables whenever possible. Multiple publications describe the myriad approaches to sampling soil for SOC measurements. Most recently, a handbook described many C-related measurement protocols for climate-related studies (Halbritter et al. 2019). Below, we refer to a select few publications. Our main aims are to provide a starting point for practitioners who may not have a background in soil science, but who are interested in generating SOC data for their site(s) of interest. We offer a compilation of well-accepted approaches for beginning and more advanced SOC practitioners to promote method convergence, reflecting the understanding that standardized protocols promote ease of data usage. We divide recommended sampling strategies into a hierarchy of sampling and analytical complexity, ranging from basic to more advanced. For each sampling tier, we briefly outline the categories of questions that the resulting data can help to address.

5.1. TIER 1: The simplest sampling scheme

The simplest recommendation for generating soil C data requires an accurate measurement of SOC concentration and bulk density at each depth (Al-Shammary et al. 2018) or soil mass per depth (Wendt and Hauser 2013). Note that we focus specifically on SOC, and not soil organic matter, which can only be estimated and is difficult to reproduce (Bhattacharyya et al. 2015). Collecting Tier 1 data (soil C stocks) is particularly useful for filling the spatial gaps in SOC stock estimates (see section 2.0; Batjes et al. 2020) that preclude more accurate quantification of Earth's SOC reservoir. It is also critical for model evaluation and validation, because any modern soil C model will produce estimates of total soil C stocks as a primary output. Measurements of soil C stocks made across sites can serve as needed tests of how accurately models represent the combined impact of site factors (e.g., climate factors, soil physical properties, and plant litter inputs) on SOC contents. If the investigator plans to expand their analyses to embrace Tiers 2 and 3, collecting Tier 1 measurements is also required.

To accomplish this first tier of data collection, the site must be accurately described with latitude and longitude, landscape position (i.e., slope position or curvature, slope angle or percent, and aspect), vegetation cover and type. If possible, land use history should also be recorded as well as the soil's taxonomic grouping (see Section 5.2). Accurate sampling location details and online soil mapping tools permit later addition of the taxonomic grouping. Soils must be sampled in a way that bulk density (see below) may be measured or later calculated for each depth increment analyzed. This means sampling with an intact corer of known volume rather than with a trowel, shovel, or punch tube. In addition, care must be taken not to compress soil horizons (distinct layers within the soil profile, distinguished from each other via chemical, physical, visual, and/or biological features), which results in an overestimation of bulk density. Standard protocols for field soil sampling are outlined in Standard Soil Methods for Long-Term Ecological Research (Robertson et al. 1999).

Organic (O) horizons must be collected independently from the mineral soil, and accurate records of the surface area collected and O horizon depth should be made in the field that can be linked later to their air-dry mass. Mineral soils can be collected by absolute depth (i.e., 0-10 cm, 10-20 cm, etc.) or by horizon identity (i.e., O horizon, A horizon, Bt horizon; see Brady 1990 for descriptions). If collected by absolute depth, 10-cm increments are often used. Sampling by absolute depth is easier in many systems, but may result in some soil horizons expressed in multiple samples, and some thinner horizons being missed entirely. Sampling by horizon avoids these problems but requires more pedological knowledge and results in sampling depths that are not easily comparable across sampling sites. The practitioner must assess their particular situation and sample accordingly. The depth to which soils are sampled depends on the researcher's interest, but typically varies from relatively shallow in systems where profiles extend mere cm above bedrock to 1-2 m above bedrock. In systems where the soil profile extends many meters (e.g., Nepstad et al. 1994), samples can be collected using auger extensions. Because of the relative paucity of deep soil sampling, deeper samples are especially highly valued.

An estimate of the mass of soil per volume (i.e., bulk density) or depth interval (i.e., equivalent soil mass) is critical for converting SOC concentration measurements to spatial estimates of C stocks. Even small differences in bulk density estimates can result in widely varying estimates of SOC stocks (Throop et al. 2012; Walter et al. 2016; Smeaton et al. 2020). As a result, care must be taken to not compact soils when sampling for bulk density. Methods are outlined in detail by Page-Dumroese et al. (1999), Walter et al. (2016), and Al-Shammary et al. (2018). In soils with few rocks or rock fragments, cylinders of known volume can be pushed into soil, and the collected soil is dried, weighed, and bulk density reported as g_{soil} cm^{-3}. Inaccuracies can result from soil compaction which can be remedied with the use of a larger cylinder. Small cylinders may also exclude roots, and inaccuracies can arise if a corer must be moved to avoid rocks. In soils with larger rock fragments or roots, a small pit can be excavated, soils collected and weighed (dry mass), and the pit volume estimated using water, sand, or Styrofoam balls. Note that rock volume must also be measured to accurately assess the site's SOC stocks. Even where rocks are rare, deep samples are difficult to collect using intact cores, and thus bulk density measurements must be obtained using additional, alternative methods such as the clod-saran method (Lal and Kimble 2001). This approach requires that the soils have characteristics that result in natural clods. The limitations of the coring and clod methods are outlined in Lal and Kimble (2001).

The equivalent soil mass approach has been proposed as another means by which to determine SOC stocks, particularly in soils prone to changes in compaction over time (e.g., following grazing, amendments, or tillage; Ellert et al. 2002; Wuest 2009; Wendt and Hauser 2013). This method involves sampling soils within defined depth intervals (e.g., 10 cm increments) throughout a soil profile. Each sample is weighed (dry mass), and SOC is measured on an air-dried subsample. The resulting SOC concentrations are fitted with soil mass using a spline curve, generating estimates of SOC on an areal basis to a known depth (e.g., Mg C ha^{-1}). Free software is available to simplify the procedure (SRS1 Software LLC, http://www.srs1software.com).

After sampling, measurements of SOC require air-drying of the sample followed by sieving with a 2 mm mesh to remove material > 2 mm (note that some soils require sieving prior to air-drying if drying hardens them and prevents sieving). The <2 mm fraction is then oven-dried for analysis (often at 60 ºC for more than 48 h though some investigators advocate for lower temperature to prevent any changes in C concentration), pulverized to a fine powder, and combusted in a CHN elemental analyzer. Note that soils with circum-neutral pH or greater should be acid treated prior to analysis to ensure that no inorganic C pools (carbonates) are included in the C values reported. Even if pH is not measured (see Section 5.2), online soil mapping can tell an investigator whether carbonates are a concern. Details of the various methods and their assumptions and drawbacks are provided in multiple papers (Midwood and Boutton 1998; Harris et al. 2001; Walthert et al. 2010; Ramnarine et al. 2011; Bao et al. 2018).

We note that for many soils it is possible to obtain total soil nitrogen (N) concentrations from the same samples run for SOC using the dry combustion approach on the CHN elemental analyzer. These N concentrations, especially when used to generate depth distributions of soil C:N, offer one way of inferring the propensity of soil organic matter to be retained by a soil profile or to undergo additional microbial processing, with associated losses of SOC via mineralization to CO_2 (Sollins et al. 2006; Kramer et al. 2017). Thus, when feasible, it is advantageous to collect these data along with SOC.

Spatial heterogeneity in soil properties at scales ranging from the mm to km presents a challenge for characterizing mean soil properties and detecting changes over time and across space (Webster and Oliver 2007; Mobley et al. 2019). Soil sampling strategies thus must account for spatial variation in soil attributes. We recommend using a random or stratified random sampling approach when the goal is to characterize the mean properties of a site. This necessitates collecting many soil cores. Variance tends to increase with area, so the number of samples should scale with the size of the site (Boone et al. 1999; Robertson et al. 1999). However, variance does not always scale linearly with area, making it difficult to prescribe the number of samples needed to estimate the mean with precision. For example, past and present land use can alter the magnitude and dominant scale of spatial variability of soil properties (Robertson et al. 1993; Bennett et al. 2005; Fraterrigo et al. 2005; Mobley et al. 2019). Whenever possible, variance should be directly measured for a site (i.e., by sampling without compositing) and used to determine the number of samples needed for estimating the mean and variance within a specified confidence interval. Similarly, empirical or model-based estimates of statistical variance (e.g., standard deviation) of SOC change can inform sampling designs aimed at detecting temporal changes in SOC at specified levels (Spencer et al. 2011). Quantifying variance in soil properties is also important in a modeling context. Relative measures of variance that account for mean-variance scaling (e.g., the coefficient of variation or standard deviation of log-transformed values; Fraterrigo and Rusak 2008) can indicate the level of uncertainty in soil parameter estimates and thus their potential to contribute to uncertainty in model results (Raczka et al. 2018). If the spatial structure of soil properties is of explicit interest, other sampling strategies may be more efficient than random or stratified random sampling. For example, a cyclic sampling design with a repeating series of sampling points spaced different distances apart is effective for characterizing spatial autocorrelation at various scales (Fraterrigo et al. 2005).

5.2 TIER 2: Additional variables most closely linked to SOC measurements

Tier 2 measurements are useful for diagnosing the mechanisms driving a mismatch between modeled and measured C stocks and, more broadly, developing an understanding of an ecosystem's C investments belowground and the biological, chemical and physical environment in which SOC resides. Four features stand out as having explanatory power for characterizing an ecosystem's propensity to gain and lose SOC: root biomass, soil pH, particle size distribution, and soil taxonomy. Root biomass can be difficult to determine because of high variance even within one ecosystem type (Cairns et al. 1997). However, an estimate of root biomass can aid in models that seek to elucidate patterns of soil C sequestration mechanisms. For a simple estimate of root biomass, fine roots can be isolated from soil cores during the sieving (2 mm) process. Roots are generally hand-picked from sieves with tweezers, gently washed, air- or oven dried at low temperature to a constant mass and weighed (Viera and Rodríguez-Soalleiro 2019). Large woody roots are often estimated from allometric equations derived from aboveground plant biomass (e.g., Plugge et al. 2016; He et al. 2018), but allometric equations must be vegetation-specific, and ideally should be site-specific.

Soil pH is one of the single most informative measures of soil chemical properties (Sparks et al. 1996), and has been termed a "master variable" because of its control on properties such as metal speciation, nutrient availability, microbial community composition, and rates of soil organic matter decay (e.g., Fierer and Jackson 2006; Min et al. 2014). Stabilization mechanisms of SOC vary with pH, varying from organo-metal complexation in acidic conditions (pH 4-6) to organo-mineral association and non-hydrolyzing cation interactions in neutral to basic conditions (pH 6-8) (Rasmussen et al. 2018). Soil pH is a measure of acidity, specifically the H+ ion concentration in a soil-liquid mixture and can be measured quickly and inexpensively in the field or laboratory, with handheld portable pH meters providing reliable and accurate results. The recommended approach is to measure pH in a 0.01 M $CaCl_2$ solution (McLean 1982). Soil:solution ratios vary throughout the literature (Minasny et al. 2011), but we suggest a 1:2 air-dry soil sample:solution ratio and mixing the solution well with a glass stir rod prior to measurement with an electrode, with results expressed as pH_{Ca}. Measuring pH in a 1:1 soil:H_2O slurry is the method most commonly used in the field because of the availability of water, and it too is considered robust, though typically results in pH values slightly higher than those obtained via $CaCl_2$.

Though recent efforts advocate for selecting multiple, mechanistically-informed variables to help predict SOC content (Rasmussen et al. 2018), particle size distribution remains an important tool for understanding soil C dynamics. It is a measure of the distribution of different particle sizes in the fraction < 2000 μm (Dane et al. 2002), and (among other features) directly controls soil moisture availability and water movement through the soil. Soil moisture availability moderates macro- and microbiological activity with direct implications for the decay of soil organic matter (Ghezzehei et al. 2019). Particle size distribution also provides a measure of the potential reactive surface area for organo-mineral interactions, with specific surface area and charge increasing with decreasing particle size (Dwivedi et al. 2019). Measuring particle size distribution involves the physical and chemical dispersion of soil particles and then isolating particles of different sizes. The most common way to present particle size distribution data is the partitioning of particles into three size classes: sand (2000 - 53 μm), silt (53 - 2 μm), and clay (< 2 μm). Two common methods of particle size analysis are the pipette and hydrometer methods, and both are outlined in detail in Kroetsch and Wang (2008) as well as in many other soil manuals (e.g., Robertson et al. 1999).

We also highlight soil taxonomic classification as a key feature to characterize, because it improves understanding of a site's SOC dynamics. For example, because clay-sized particles can retain water and offer protection of SOC from microbial attack (Poeplau et al. 2015), a soil pedon description that reveals the presence of an argillic (i.e., clay-rich) horizon suggests that water and SOC in that horizon may experience longer residence times relative to surrounding horizons, and hints that the soil profile has been in place long enough to experience lessivage (the downward movement of clay-sized particles in suspension through a soil profile; Calabrese et al. 2018). A soil's taxonomic classification is based on its horizons' diverse properties, and places soils into specified groups using unique nomenclature intended to reveal a soil's typical moisture, temperature, color, texture, structure, and chemical and mineral properties (Brady 1990). Soil taxonomic classifications are often mapped, providing spatially explicit context for the ecosystem in which a soil is collected. Much like one would never publish an ecological paper without providing the taxonomic classification of the species being studied, the formal taxonomic classification of a sampled soil should be included as part of data reporting (Schimel and Chadwick 2013). One of the issues with reporting soil taxonomic classification is the lack of experience of non-soil scientists with soil taxonomic systems, and the diversity of soil taxonomic systems among countries. Two of the most prevalent taxonomic systems are the United States Department of Agriculture Soil Taxonomy (Soil Survey Staff 1999) and the International Union of Soil Scientists World Reference Base (IUSS-WRB; Food and Agriculture Organization of the United Nations 2018). The degree of detail in soil taxonomy maps varies across regions and countries, but many online sources of soil taxonomic information are available. The UN provides a useful overview of soil taxonomy at the FAO Soil Portal (http://www.fao.org/soils-portal/en/). Relatively high resolution data for the conterminous U.S. are available in an easily accessible web/mobile device-based application through SoilWeb (https://casoilresource.lawr.ucdavis.edu/gmap), an IUSS-WRB app for Android and Apple provides location-based soil taxonomic information (http://www.fao.org/soils-portal/soil-survey/soil-classification/world-reference-base/en/), and the International Soil Reference and Information Centre has an app version of its SoilGrids maps. The Soil Explorer app for Apple devices (https://apps.apple.com/us/app/soil-explorer/id996159565) provides location-based information about soil taxonomy, as well as soil and landscape properties for various US states, and global, high resolution maps of soil distributions.

5.3 TIER 3: More advanced corollary data collections relevant to SOC

Tier 3 measurements are particularly useful for predicting a soil profile's capacity to release or retain relatively persistent SOC. This Tier calls for quantifying SOC within distinct soil fractions, microbial biomass C and fungal:bacteria ratios, soil mineral assemblage, aggregate size and stability, and soil organic matter chemical composition. These measurements are often features of studies that evaluate underlying processes in models, including decomposition rates of different C pools, microbial processes, and physico-chemical stabilization of organic matter (Cambardella and Elliott 1992; Jastrow 1996; Sulman et al., 2018).

Identifying different fractions of SOC that have different dominant cycling mechanisms can increase knowledge of soil stabilization and destabilization processes and connect C cycle processes with microbial activity and functions. Specifically, SOC within distinct soil fractions is linked to different degrees of availability to soil microbes (van Gestel et al. 1996; Lupwavi et al. 2001; Tiemann et al. 2015; Upton et al. 2019; Lavallee et al. 2020). Thus, by fractionating soil and quantifying the SOC within each fraction, the investigator can gain a sense of the relative vulnerability of SOC to microbially-mediated loss in that soil. There are multiple ways to fractionate soil; most attempt to isolate pools possessing distinct characteristics such as SOC persistence, nutrient concentrations, and even distinct microbial communities. Many fractionation schemes have been proposed (e.g., Six et al. 2000; Marzaioli et al. 2010; Heckman et al. 2018) that use either physical fractionation or selective dissolution to identify meaningful pools of SOC and to infer SOC stabilization mechanisms. Unfortunately, the large number of soil fractionation schemes that have been proposed as means of testing different hypotheses about SOC stabilization mechanisms has made it difficult to conduct broad surveys across studies (different fractionation methods, and their drawbacks, are discussed in von Lützow et al. (2007), Moni et al. (2012), Poeplau et al. (2018), and Sohi et al. (2001)).

One of the most widely accepted methods is the isolation of light and heavy fractions of SOC, an approach that separates pools of C based on the degree of association with minerals (Strickland and Sollins 1987; Bremer et al. 1994; Sollins et al. 2006; Sollins et al. 2009). Emerging process-based soil C models divide C pools similarly, with the light fraction generally mapping to relatively unprotected C (i.e., C that is accessible to soil microbial decomposers) and the heavy fraction mapping to more physico-chemically protected C that typically exhibits greater persistence (Sulman et al. 2014; Wieder et al. 2014). This heavy fraction is linked to microbial necromass (Liang et al. 2019) and soluble compounds derived from both plants and microbes that are then sorbed and retained on mineral surfaces (Six et al. 2006; Grandy et al. 2007; Grandy and Neff 2008; Sulman et al. 2014; Kohl et al. 2017). These fractionation measurements are therefore highly useful constraints on model processes related to the fates of diverse sources of SOC and are fairly simple to implement. Indeed, a recent study explicitly discusses the importance of soil organic matter fractionation approaches for addressing global-scale environmental change (Lavallee et al. 2020). Such approaches are methodologically fairly simple. For example, though examining multiple density pools of SOC is useful for detailed studies of SOC distribution (e.g., Lajtha et al. 2014; Yeasmin et al. 2017; Crow and Sierra 2018), a one-step separation of light, or free, particulate SOC from heavier, mineral-associated C is simple enough to be routine. This method demonstrably isolates chemically distinct SOC pools differing in stabilization mechanisms, response to management, and persistence (von Lützow et al. 2007; Schrumpf et al. 2013; Williams et al. 2018). Across a wide range of soils, exposing samples to sodium iodide possessing a density of between 1.3 to 1.7 g cm^{-3} is effective for this separation of light from heavy material (Strickland and Sollins 1987; Jastrow 1996; Compton and Boone 2000; McLauchlan et al. 2004; Billings 2006). Sometimes this approach is applied in conjunction with the particle size fractionation approach (section 5.2). Importantly, different methods of separating SOC into fractions often result in congruent conclusions about microbial accessibility to SOC within each fraction (Billings 2006; McLauchlan et al. 2006)

Soil microbes regulate the release as well as the accumulation of soil C (Cotrufo et al. 2013) and, therefore, microbial biomass carbon (MBC) is also a recommended Tier 3 measurement. Microbes release soil C by decomposing organic matter or metabolizing exudates from living roots. The megadiversity of soil microbes is partially maintained by variation in the types of organic matter they metabolize. Generally, bacteria and archaea are considered to undergo relatively rapid growth while metabolizing relatively simpler compounds, while fungi appear to grow more slowly, metabolizing complex organic polymers (Shade et al. 2012; Malik et al. 2020). Knowing the fungi:bacteria ratio of soil thus can help inform predictions of soil C fluxes (Malik et al. 2016). Perhaps counterintuitively, microbes also can contribute to soil C accumulation by producing metabolites and necromass that are stabilized on minerals in the heavy C fraction. Microbial exudates along with root exudates bind together soil particles into micro and macroaggregates (Bronick and Lal 2005). Fungal necromass and exudates persist in soil (Certano et al. 2018), and therefore soils with high fungal biomass are correlated with high soil C content (Bailey et al. 2002). Measuring soil microbial biomass C or fungi:bacteria ratios are lab-intensive methods, but we recommend them as Tier 3 measurements to increase our understanding and the predictability of microbially mediated soil C fluxes. Total microbial biomass is typically measured using a fumigation-extraction method (Brooks et al. 1985) or by substrate-induced respiration (Anderson and Domsch 1978). The fungi:bacteria ratio is commonly determined using phospholipid fatty acid analysis (White et al. 1979; but see Buyer and Sasser (2012) for a high throughput approach) or quantitative PCR (Fierer et al. 2005). Multiple methods are compared in Kaiser et al. (1992).

Clay mineral composition, including phyllosilicate minerals and metal oxyhydroxides, is also recommended as a Tier 3 measurement. Physical protection of SOC is directly related to chemical and physical properties of the mineral matrix and their various interactions with SOC (Heckman et al., 2013). Clay mineral composition is highly correlated with SOC content at broad scales (Poeplau et al. 2015), a feature incorporated into SOC modelling efforts (Sulman et al. 2014). However, other studies have suggested that specific clay minerals might be more explanatory of SOC stabilization (Percival et al. 2000; Sanderman et al. 2014; Yeasmin et al. 2017; Rasmussen et al. 2018b), and that the type of mineral present in a given environment may determine the availability of mineral-associated organic matter to biological degradation (Mikutta et al. 2007). In particular, the influence of short-range order (SRO) Fe- and Al- oxides and (oxy)hydroxides (largely ferrihydrite and nano-crystalline goethite, allophane, imogolite, proto-imogolite, and amorphous gibbsite) on the total amount, resilience and molecular structure of soil organic matter has been observed in many studies (Torn et al. 1997; Masiello et al. 2004; Rasmussen et al. 2005; Hernández et al. 2012; Hall and Silver 2015; Coward et al. 2017; Rasmussen et al. 2018). Therefore, the measurement of SRO metal oxides is recommended as a 3rd tier tool to interpret patterns of SOC abundance and persistence across experiments and geographic locations. The diverse extraction methods available can result in different information gained; Hall and Silver (2015) describe different extractions and their benefits.

Aggregation of organic matter and mineral particles provides another mechanism of SOC stabilization (Oades & Waters 1991; Six et al. 2000). Soil aggregates are held together by soil organic matter, roots, fungal hyphae, and some cations (e.g., Ca^{2+}) and are a sensitive indicator of the functioning of soils, including their bulk density and potential to store SOC and water (Tisdall and Oades 1982; Grandy and Robertson 2007). While aggregate distributions are not an adequate replacement for understanding *in situ* pore architecture, O_2, or water in soils (Keiluweit et al. 2017; Smith et al. 2017), aggregation can be used as an integrative index of the response of soil properties and functions to disturbance (Grandy and Robertson 2006; Wagai et al. 2009a). Quantifying the size distributions of water-stable soil aggregates requires weighing of dried aggregates retained on sieves of known mesh size after being subjected to submersion in water. Detailed instructions are available in multiple sources, but explanatory annotations are particularly useful in Nimmo and Perkins (2002) and USDA NRCS (2014).

The final recommendation as a Tier 3 measurement is an assessment of SOC molecular composition. The composition of soil organic matter (SOM), comprised of SOC and myriad other organic compounds that exist as particulate matter or chemically bound to the surfaces of soil minerals, can be revealed via a range of advanced, non-destructive, and relatively rapid analytical techniques. Some of the available approaches (ex. ^{13}C Nuclear Magnetic Resonance (^{13}C NMR) spectroscopy (Kaiser and Guggenberger 2000; Kaiser and Guggenberger 2001)) have historically been shown to be useful to determine composition of SOM but are time and resource intensive, and have some major limitations that make them less useful in specific soil types (Swift 1996; Baldock et al. 2004). However, recently there has been growing use of Fourier Transformed Infrared Spectroscopy to detect and characterize organic functional groups in soil (Cheng et al. 2006; Keiluweit et al. 2010; Lee et al. 2010), microbial surfaces (Jiang et al. 2004), and micro- to mm-scaled aggregates (Lehmann et al. 2007; Leue et al. 2010). Further, mid-infrared spectral libraries can reveal soil properties often linked to SOC preservation, even offering a means of predicting soil bulk density (Dangal et al. 2019). These approaches are particularly useful for characterizing the chemical composition of organic substrates in vegetation, bulk soils, and density fractions. (Ellerbrock et al. 2005; Kaiser and Ellerbrock 2005). Using Diffuse Reflectance Fourier Transformed Infrared (DRIFT), one can characterize the chemical composition of organic compounds and identify C functional groups that play different roles in the interactions among organic and inorganic compounds (Ellerbrock et al. 1999; Kaiser and Ellerbrock 2005; Leue et al. 2010), including the role of cation bridging (C=O) or ligand exchange reactions (C=O and OH) in SOM stabilization (Tombacz et al. 2004; Kleber et al.

2007;). Further, this approach is useful for identifying the source and extent of decay of OM associated with reactive minerals in soil (Kaiser et al. 2014; Ryals et al. 2014; Hall et al. 2018).

6. Sharing data in its most useful, discoverable forms

Publishing research data benefits the scientific and greater communities by fostering reproducibility (Poisot et al. 2013; Marwick et al. 2018); providing resources for meta-analyses and parameterizing, validating, and advancing modelling efforts; and facilitating big-picture questions and analyses that would otherwise be impossible (Hampton et al. 2013). Given a growing appreciation of the importance of SOC as an influence on processes studied by diverse disciplines, there is increasing demand for publicly available SOC data.

6.1 Data structure and documentation

We encourage those providing SOC and related data to the broader community to adhere to the following standards, which improve data findability, accessibility, interoperability, and reusability (FAIR; Wilkinson et al. 2016). Investigators should always provide the original dataset (Ellis and Leek 2018), preferably in open file formats (e.g., delimited, plain text rather than *.xlsx format; White et al. 2013). Adhering to “tidy” guidelines such as those described by Wickham (2014) and Verde Arregoitia et al. (2018) will contribute to a more efficient, reproducible workflow for the investigators. As described in section 5.1, providing sufficient details for envisioning the site’s location and ecosystem type can help the user understand the data (White et al. 2013). Methods of sample collection and processing and thorough descriptions of the organization and characteristics of the data are also critical to facilitate data reuse.

6.2 Environmental data repositories and soil databases

Investigators can now submit data to any of a large number of established data repositories spanning a wide array of topical areas. The robust number of options can pose a challenge to identifying the best place to share data. A registry such as www.re3data.org is a helpful resource for locating a domain-relevant repository with appropriate features for archiving data (for example, the Environmental Data Initiative is often used by soil scientists; https://environmentaldatainitiative.org/). The citable nature of datasets in such repositories offers investigators the flexibility of associating authorship with the dataset distinct from that of the scholarly works with which datasets are associated (Poisot et al. 2013), and generally promotes higher citation rates for those works (Li et al. 2018).

Many organizations, universities, research programs, and other platforms provide data storage and access for projects associated with their institution or initiative. In addition, many journals have collaborations with repositories (e.g., Soil Science Society of America Journal is a member of the Dryad Digital Repository), and many science societies (e.g., American Geophysical Union, Ecological Society of America) are proactive about publishing research data and can often provide guidance concerning appropriate repositories. Many research networks (e.g., LTER, CZO (now CZ), NEON; see Section 4) facilitate the storage, curation, and accessing of relevant datasets. Once stored in a repository and associated with a digital object identifier (DOI), a soil dataset can be ingested by existing soil databases and further improve data discoverability (e.g., ISRIC, ISCN). These large soil databases compile disparate datasets into one format so that data users may ask research questions on broad spatial scales. Most recently, manuscripts describing the contemporary landscape of publicly available SOC databases (Malhotra et al. 2019) and the status of cross-organization communication about SOC (Harden et al. 2017) highlight where SOC datasets can be deposited for reuse. The SOC Data Rescue and Harmonization Repository (https://github.com/ISCN/SOC-DRaHR) facilitates access to SOC data via script sharing. The SOils DAta Harmonization (SoDaH) and Synthesis effort (https://lter.github.io/som-website) provides a means for contributing SOC data to a database comprised of LTER, CZO, and NEON SOC datasets, and a web application (and tutorial for its use) that allows exploration of the compiled data. Combined, these initiatives demonstrate the rapid development of a multitude of databases where SOC data can be found, shared, and reused.

7. Conclusions

Soil organic C data and the ancillary datasets we describe above have much to contribute to our understanding of the mechanisms governing Earth's SOC reservoir size and thus to our ability to improve climate model accuracy. However, SOC and related data are increasingly viewed as important for enhancing the understanding of processes in diverse disciplines, many of which are not traditionally considered closely linked to soil science. Because SOC simultaneously represents biotic production of reduced C compounds, serves as a resource for living biota, and comprises a critical structural feature of soils, its influence on diverse disciplines is far-reaching. Thus, from population, community, and ecosystem ecology to hydropedology and soil physics, SOC data have been instrumental in helping scientific communities understand processes at scales ranging from the nanometer to the biosphere. As a result of the tremendous diversity of disciplines in which SOC data have proven useful, practitioners from many non-soil-related realms frequently express interest in quantifying SOC in their system of interest. We applaud such efforts, and emphasize the need for standardizing collection protocols. We also highlight how the development of multiple national and international research networks and online repositories for SOC data make it possible to generate and share these data.

By defining a tiered sampling approach, we provide a springboard for those who recognize the value of using SOC as a metric for addressing their question of interest. We offer this approach as a framework for discerning the level of complexity an investigator may develop, and a starting point for understanding sampling and analysis methods. The world's community of scholars able and motivated to generate robust SOC datasets is broadening, and capitalizing on this growth using standardized approaches, the rapid growth of network science, and the burgeoning availability of analytical capacity and durable data repositories can benefit us all.

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Table 1. Examples of the utility of SOC data (concentration, content, or depth distribution of those attributes) for understanding mechanisms driving environmental dynamics at scales ranging from the biosphere down to the population. Order roughly represents relevant spatial scale of studies in ascending order.

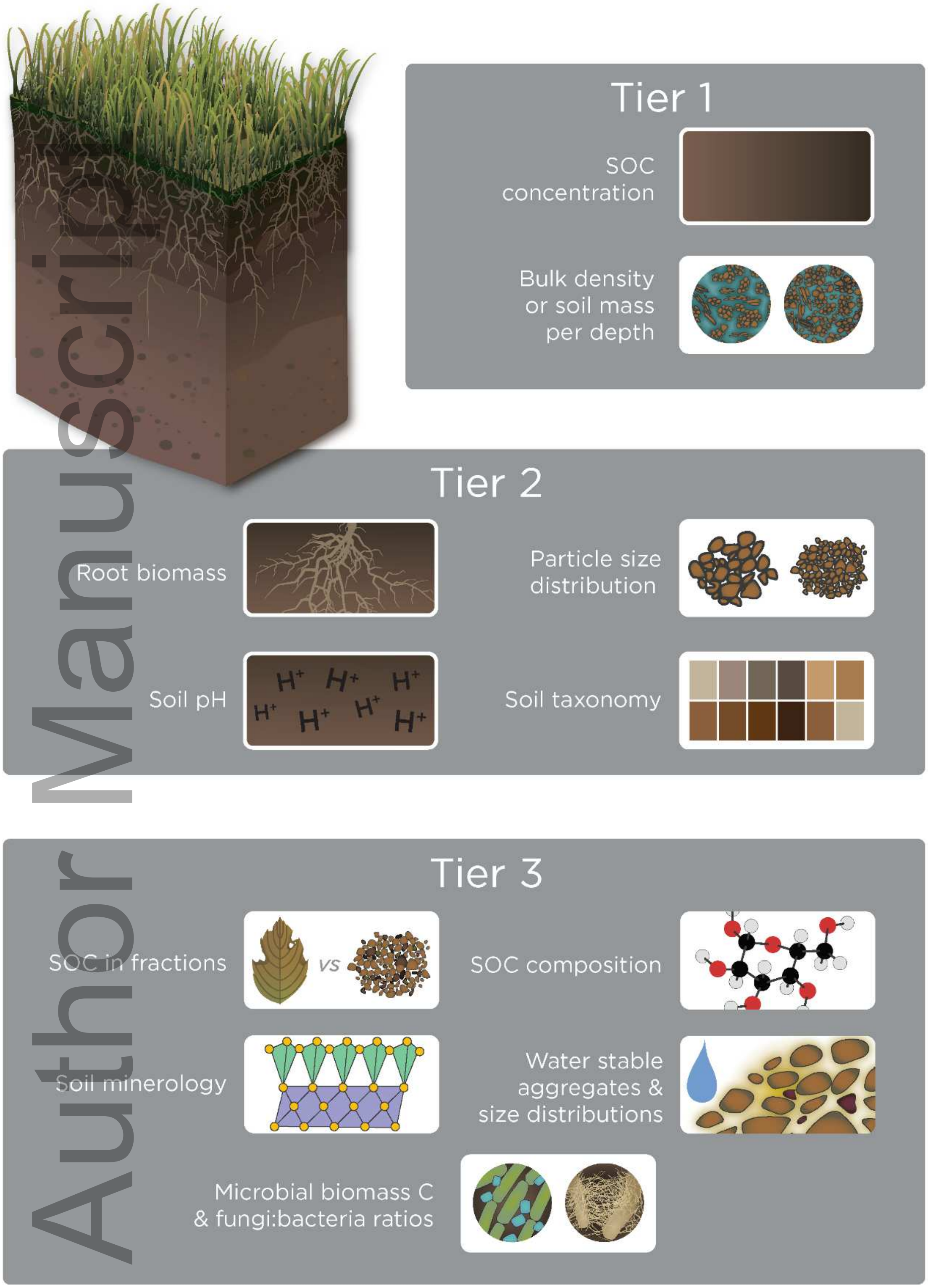
Utility	**Scale**	**Example reference(s)**	**Implications**
SOC reflects the difference between ecosystem C gains and losses, and thus of a system's role in Earth's climate	Biosphere, ecosystem	Kasting JF, Siefert JL. 2002. Life and the evolution of Earth's atmosphere. Science 296:100-106. Kump LR. 2008. The rise of atmospheric oxygen. Nature 451:277-278.	Fixed C retained in a system serves as a contemporary demonstration of the CO_2 consumption and oxygen production so critical to the rise of atmospheric oxygen in Earth's past.
SOC availability and rates of mineralization modify weathering	Pedon to watershed	Sullivan PL, Stops MW, Macpherson GL, Li L, Hirmas DR, Dodds WK. 2019. How landscape heterogeneity governs stream water concentration-discharge behavior in carbonate terrains (Konza Prairie, USA). Chemical Geology 10.1016/j.chemgeo.2018.12.002.	Enhanced deep soil CO_2, whether from roots or microbial mineralization of SOC, enhances deep soil weathering and by extension soil formation
SOC availability influences arrangement of soil solids and voids	Plot to landscape	Robinson DA, Hopmans JW, Filipovic V, van der Ploeg M, Lebron I, Jones SB, Reinsch S, Jarvis N, Tuller M. 2019. Global environmental changes impact soil hydraulic functions through biophysical feedbacks. Global Change Biology 25: 1985-1904.	Changing biotic influences on soil structure through SOC dynamics alters soil hydraulic functioning
SOC reflects degree to which a system relies on OM recycling instead of mineral weathering for	Ecosystem	Brantley SL, Goldhaber MB, Ragnarsdottir KV. 2007. Crossing disciplines and scales to understand the Critical Zone. Elements 3:307-314.	The capacity of a system to extract nutrients from decaying organic matter can be inversely related to that system's need to

nutrient release		Brantley SL, Megonigal JP, Scatena FN et al. 2011. Twelve testable hypotheses on the geobiology of weathering. Geobiology 9:140-165.	induce mineral dissolution and associated soil weathering patterns.
SOC over time at multiple depths constrains estimates of potential C sequestration by the forest sector	Ecosystem	Nave, L. E., G. M. Domke, K. L. Hofmeister, U. Mishra, C. H. Perry, B. F. Walters, and C. W. Swanston. 2018. Reforestation can sequester two petagrams of carbon in US topsoils in a century. Proceedings of the National Academy of Sciences 115:2776-2781.	Carbon sequestration in reforesting topsoils offsets a small percentage of greenhouse gas emissions but accounts for >10% of the C sequestration needed to stabilize the forest C sink beyond the mid-21st century.
SOC over time at multiple depths reveals how SOC can be lost due to nutrient demands of an ecosystem	Ecosystem	Richter DD, Markewitz D, Trumbore SE, Wells CG. 1999. Rapid accumulation and turnover of soil carbon in a re-establishing forest. Nature 400:56-58.	Surface horizons tend to accumulate C as ecosystems regenerate, but these effects are mitigated or even reversed in deeper horizons due to root nutrient uptake and subsequent OM decay as microbes meet their resource demand.
SOC depth distributions across landscapes can reveal patterns of lateral movement of material	Ecosystem	Doetterl S, Berhe, AA, Nadeu E, Wang Z, Sommer M, Fiener P. 2016. Erosion, deposition and soil carbon: A review of process-level controls, experimental tools and models to address C cycling in dynamic landscapes. Earth-Science Reviews 154:102-122.	Erosion rates, dependent in part on soil type and geomophology, influence the distribution of SOC across a landscape, the spatial distribution of its diverse forms, and its propensity for retention vs. loss.
SOC over time illuminates the time-varying influence of temperature regime on SOC stocks	Ecosystem	Melillo JM, Frey SD, DeAngelis KM, Werner WJ, Bernard MJ, Bowles FP, Pold G, Knorr MA, Grandy AS. 2017. Long-term pattern and magnitude of soil carbon feedback to the climate system in a warming world. Science 358:101-105.	Global-scale, anthropogenic perturbations can influence SOC reservoir size via temporally variable, microbially-mediated mechanisms

SOC demonstrates effects of N deposition on a system's capacity to generate and retain organic matter	Ecosystem	Entwistle EM, Zak DR, Argiroff WA. 2018. Anthropogenic N deposition increases soil C storage by reducing the relative abundance of lignolytic fungi. Ecological Monographs 88:225-244.	Global-scale, anthropogenic perturbations influence the SOC reservoir size via suppression of key members of the soil microbial community
SOC data calibrates a model demonstrating linkages between SOC dynamics and those of N and P	Ecosystem	Muhammed SE, Coleman K, Wu L, Bell V A, Davies JAC, Carnell EJ, Tomlinson SJ, Dore AJ, Dragosits U, Naden PS, Glendining MJ, Whitmore AP, Tipping E. Impact of two centuries of intensive agriculture on soil carbon, nitrogen, and phosphorus cycling in the UK. Science of the Total Environment doi:10.1016/j.scitotenv.2018.03.378	Long-term SOC measurements in arable and grassland systems provide a means of understanding the long-term linkages among the C, N, and P cycles in soils.
SOC data provide a key metric for understanding a soil's ability to support critical ecosystem functions	Ecosystem	Janzen HH. 2006. The soil carbon dilemma: Shall we hoard it or use it? Soil Biology and Biochemistry 38:419-424.	SOC is viewed as a metric of soil capacity to provide nutrients, but to do so requires loss of that same reservoir via microbial transformations.
SOC is positively linked to plant diversity	Community	Chen S, Wang W, Xu W, et al. 2018. Plant diversity enhances productivity and soil carbon storage. PNAS doi/10.1073/pnas.1700298114.	SOC measurements can help us understand how plant communities drive SOC-mediated ecosystem services
SOC is positively linked to plant diversity even when soil microbial activity is enhanced	Community	Lange M, Eisenhauer N, Sierra CA, et al. 2015. Plant diversity increases soil microbial activity and soil carbon storage. Nature Communications doi: 10.1038/ncomms7707.	SOC measurements can help us understand the intersection of plant and soil microbial communities, and how those interactions govern SOC-mediated ecosystem services
SOC scales with plant functional diversity	Community	Fornara DA, Tilman D. 2008. Plant functional composition influences rates of soil carbon and nitrogen accumulation. J Ecology 96:314-322.	SOC accumulation rates, not just stock sizes, can be positively influenced by complementary combinations of plant

			functional groups
SOC reveals differences in regeneration time of diverse ecosystem attributes	Community	Martin PA, Newton AD, Bullock JM. 2013. Carbon pools recover more quickly than plant biodiversity in tropical secondary forests. Proceedings of the Royal Society B 280:20132236.	The timescale of recovery to antecedent conditions can differ for SOC stocks and biodiversity in some systems
SOC availability relative to nutrients influences microbial C allocation and stoichiometric plasticity	Population	Min K, Lehmeier CA, Ballantyne IV F, Billings SA. 2016. Carbon availability modifies temperature responses of heterotrophic microbial respiration, carbon uptake affinity, and stable carbon isotope discrimination. Frontiers in Microbiology doi: 10.3389/fmicb.2016.02083.	C availability in soils governs how microbes influence its possible fates of mineralization to CO2 vs. biomass growth
SOC availability promotes the success of some microbial populations over others	Population	Langenheder S, Lindstrom ES, Tranvik LJ. 2006. Struction and function of bacterial communities emerging from different sources under identical conditions. Applied Environmental Microbiology 72:212-220.	Availability of organic matter and abiotic environmental conditions govern who can prosper in the environment, ultimately driving microbially-mediated ecosystem functions

Figure 1. Summary descriptions of soil features and properties to quantify or characterize, to gain an understanding of soil organic C (SOC) pool sizes and mechanisms of its formation, retention, and losses. Features are arranged into three tiers representing a gradient of complexity, from the simplest (Tier 1) to those requiring greater investigator investment (Tiers 2 and 3). For all Tiers, site-level data such as latitude and longitude, landscape position, and vegetation cover and type should be collected to contextualize SOC data.


Tier 1
SOC concentration
Bulk density or soil mass per depth
Tier 2
Root biomass
Particle size distribution
Soil pH
H+
Soil taxonomy
Tier 3
SOC in fractions
vs
SOC composition
Soil minerology
Water stable aggregates & size distributions
Microbial biomass C & fungi:bacteria ratios