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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 capitalize on these developments to augment SOC data sets 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.

Key words: *global C cycle; soil–climate feedbacks; standardized soil methods.*

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 3,000 Pg (Scharlemann et al. 2014), Earth's

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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, Harden et al. 2017, Sanderman et al. 2017). The potential to reverse these trends via management practices is currently debated (Minasny et al. 2017, Amundson and 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 *Research Networks and Data Compilations are Powerful Means of Generating and Leveraging Data*). 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 *Expanding the Global Reach and Depth of Standardized SOC Data Will Improve Projections of the Global C Cycle*, 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 *Diverse Scientific Disciplines Benefit from Augmenting SOC Datasets*, 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 *Research Networks and Data Compilations are Powerful Means of Generating and Leveraging Data* 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 data sets. These networks and data sets permit diverse scientific communities to develop and test previously unarticulated or otherwise untestable hypotheses, including by parameterizing and validating models.

In *Sampling Opportunities*, 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 (Fig. 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 *Sharing Data in Its Most Useful, Discoverable Forms*, we offer prescriptive examples of ways in which these data can be organized and made discoverable to maximize their utility for diverse scientific communities.

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 data sets (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*a*), SOC responses to land management (Nave et al. 2018), and the ecosystems in which uncertainty in SOC stocks is

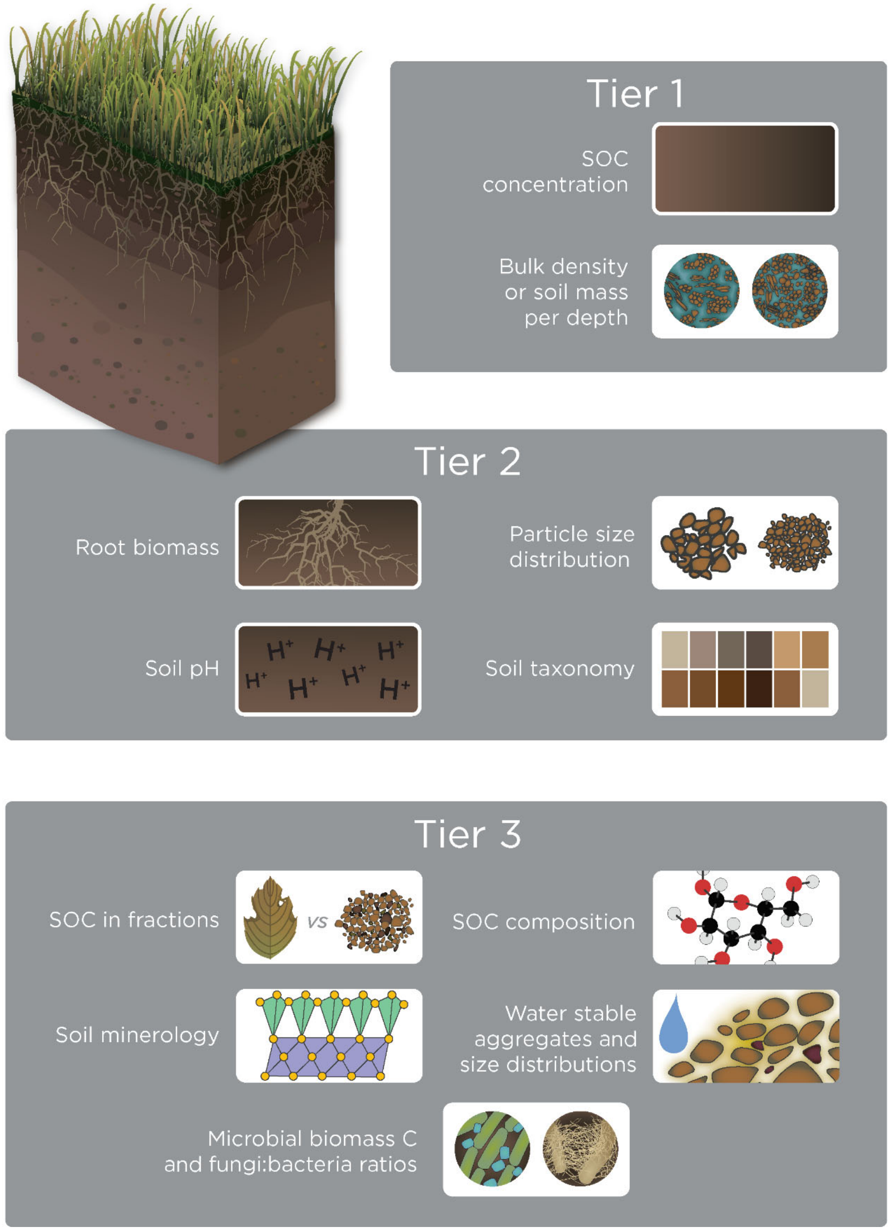

FIG. 1. Summary descriptions of soil features and properties to quantify or characterize to gain an understanding of soil organic C (SOC) pool sizes and mechanisms of its formation, retention, and losses. Features are arranged into three tiers representing a gradient of complexity, from the simplest (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.

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 (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 data sets 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 (Hugelius et al. 2013, Hengl et al. 2017, 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 Markewitz 1995), 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 broadscale 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 data sets describing SOC concentrations, pool sizes, and links to biotic and abiotic variability in a range of managed and natural systems across the globe.

Diverse Scientific Disciplines Benefit from Augmenting SOC Data sets

The importance of SOC data to some disciplines is self-evident. For example, soil microbiologists and soil 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 data sets 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. 2018). Soil organic C measurements are also part of a constellation of data sets necessary for understanding nutrient availability (Vicca et al. 2018) and, more broadly, soil “health” (Doran et al. 1996), a concept that broadly represents the productivity potential of a soil for food, fiber, and water quality (see Soil Health Institute in Table 1). 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 2).

Table 1. Organizations, networks, and databases for soil organic C (SOC) data.

Organization	URL
Soil Health Institute	https://www.soilhealthinstitute.org
Long-Term Ecological Research network (LTER)	https://lternet.edu
International LTER	https://lternet.edu/international
Critical Zone Collaborative Network (CZCN)	https://criticalzone.org
CZ Exploratory Network	https://www.czen.org
National Ecological Observatory Network (NEON)	https://www.neonscience.org
International Soil Carbon Network (ISCN)	https://iscn.fluxdata.org/network/partner-networks/ltse/
International Soil Reference and Information Centre (ISRIC)	https://www.isric.org
International Soil Radiocarbon Database (ISRaD)	https://soilradiocarbon.org
International Soil Carbon Network (ISCN)	http://iscn.fluxdata.org
Soils Data Harmonization (SoDaH)	https://lter.github.io/som-website
International Soil Modeling Consortium (ISMC)	https://soil-modeling.org

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 (Bradford et al. 2013, Frey et al. 2013, Cotrufo et al. 2015, Kallenbach et al. 2015, 2016, 2019, Min et al. 2016) 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).

TABLE 2. Examples of the utility of soil organic carbon (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 descending 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 and Siefert (2002), Kump (2008)	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 et al. (2019)	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 et al. (2019)	Changing biotic influences on soil structure through SOC dynamics alter soil hydraulic functioning.
SOC reflects degree to which a system relies on organic matter recycling instead of mineral weathering for nutrient release.	ecosystem	Brantley et al. (2007, 2011)	The capacity of a system to extract nutrients from decaying organic matter can be inversely related to that system's need to 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 et al. (2018)	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 et al. (1999)	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 organic matter decay as microbes meet their resource demand.
SOC depth distributions across landscapes can reveal patterns of lateral movement of material.	ecosystem	Doetterl et al. (2016)	Erosion rates, dependent in part on soil type and geomorphology, 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 et al. (2017)	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 et al. (2018)	Global-scale, anthropogenic perturbations influence the SOC reservoir size via suppression of key members of the soil microbial community.
SOC data calibrate a model demonstrating linkages between SOC dynamics and those of N and P.	ecosystem	M*uhammed* et al. (2018)	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 (2006)	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 et al. (2018)	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 et al. (2015)	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 and Tilman (2008)	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 et al. (2013)	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 et al. (2016)	C availability in soils governs how microbes influence its possible fates of mineralization to CO_2 vs. biomass growth.
SOC availability promotes the success of some microbial populations over others.	population	Langenheder et al. (2006)	Availability of organic matter and abiotic environmental conditions govern who can prosper in the environment, ultimately driving microbially mediated ecosystem functions.

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 it 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.

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), data sets describing changes in SOC pools over decadal and centennial timescales are relatively rare (Richter et al. 2007). These data sets 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) and the International LTER, the Critical Zone Collaborative Network (CZCN) and additional CZ Exploratory Network sites, and the National Ecological Observatory Network (NEON; Table 1). 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 United States. 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 (International Soil Carbon Network, ISCN; Table 1) 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) and the Nutrient Network (NutNet) 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), the International Soil Radiocarbon Database (ISRaD), and the International Soil Carbon Network (ISCN) are examples of entities leading efforts to compile soil databases. The Soils Data Harmonization (SoDaH) 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. (Malhotra et al. 2019, Lawrence et al. 2020, Wieder et al. 2020). The International Soil Modeling Consortium (ISMC) 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 data sets, and for individual researchers to contribute more targeted data sets 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.

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.

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 *Expanding the Global Reach and Depth of Standardized SOC Data Will Improve Projections of the Global C Cycle*; 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 be recorded as well as the soil's taxonomic grouping (see *TIER 2: Additional variables most closely linked to SOC measurements*). 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 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 separate sampling of 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 centimeters above bedrock to 1–2 m. In systems where the soil profile extends many meters (Nepstad et al. 1994; Richter and Markewitz 1995), 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 and weighed, and bulk density reported as grams of soil per cubic centimeter. Inaccuracies can result from soil compaction, which may 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). Free software is available to simplify the procedure (SRS1 Software; *available online*).[19]

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°C 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 circumneutral 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 *TIER 2: Additional variables most closely linked to SOC measurements*), 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 millimeters to kilometers presents a challenge for characterizing mean soil properties and detecting changes over time and across space (Webster and Oliver 2001, 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).

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

[19]http://www.srs1software.com

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 handpicked 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 (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 (Thomas 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 (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*a*). 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 mol/L $CaCl_2$ 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*a*), 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 <2,000 μm (Gee and Or 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 (2,000–53 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 (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 (*available online*).[20] Relatively high resolution data for the conterminous United States are available in an easily accessible web/mobile device-based application through SoilWeb (*available online*),[21] an IUSS-WRB app for Android and Apple provides location-based soil taxonomic

[20]http://www.fao.org/soils-portal/en/

[21]https://casoilresource.lawr.ucdavis.edu/gmap

information (*available online*),[22] and the International Soil Reference and Information Centre has an app version of its SoilGrids maps. The Soil Explorer app for Apple devices provides location-based information about soil taxonomy, as well as soil and landscape properties for various U.S. states, and global, high resolution maps of soil distributions (*available online*).[23]

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 physicochemical stabilization of organic matter (Cambardella and Elliott 1992, Jastrow 1996, Sulman et al. 2014).

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 (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 Sohi et al. 2001, von Lützow et al. 2007, Moni et al. 2012, and Poeplau et al. 2018).

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, 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 physicochemically 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 (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 and 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, Billings 2006, McLauchlan et al. 2006). Sometimes this approach is applied in conjunction with the particle size fractionation approach (*TIER 2: Additional variables most closely linked to SOC measurements*). 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 promoting decay of organic matter and mineralizing released C, 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

[22] http://www.fao.org/soils-portal/soil-survey/soil-classification/world-reference-base/en/
[23] https://apps.apple.com/us/app/soil-explorer/id996159565

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, high fungal biomass is 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 modeling 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. 2018*b*), 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 nanocrystalline 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*a*). Therefore, the measurement of SRO metal oxides is recommended as a third-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 and 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. 2009). 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, 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, nondestructive, and relatively rapid analytical techniques. Some of the available approaches (e.g., ^{13}C nuclear magnetic resonance [^{13}C NMR] spectroscopy [Kaiser and Guggenberger 2000, 2001]) have historically been shown to be useful to determine soil organic matter composition 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 micrometer- to millimeter-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 or ligand exchange reactions in soil organic matter stabilization (Tombacz et al. 2004, Kleber et al. 2007). Further, this approach is useful for identifying the source and extent of decay of organic matter associated with reactive minerals in soil (Kaiser et al. 2014, Ryals et al. 2014, Hall et al. 2018).

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 modeling 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.

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 data set (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 *TIER 1: The simplest sampling scheme*, 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.

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 the Registry of Research Data Repositories 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; *available online*).[24,25] The citable nature of data sets in such repositories offers investigators the flexibility of associating authorship with the data set distinct from that of the scholarly works with which data sets 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 CZCN), NEON; see *Research Networks and Data Compilations are Powerful Means of Generating and Leveraging Data*) facilitate the storage, curation, and accessing of relevant data sets. Once stored in a repository and associated with a digital object identifier (DOI), a soil data set can be ingested by existing soil databases and further improve data discoverability (e.g., ISRIC, ISCN). These large soil databases compile disparate data sets 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 data sets can be deposited for reuse. The SOC Data Rescue and Harmonization Repository facilitates access to SOC data via script sharing (*available online*).[26] The SOils DAta Harmonization (SoDaH) and Synthesis effort provides a means for contributing SOC data to a database comprised of LTER, CZO, and NEON SOC data sets, and a web application (and tutorial for its use) that allows exploration of the compiled data (*available online*).[27] Combined, these initiatives demonstrate the rapid development of a multitude of databases where SOC data can be found, shared, and reused.

Conclusions

Soil organic C data and the ancillary data sets 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

[24] www.re3data.org
[25] https://environmentaldatainitiative.org/
[26] https://github.com/ISCN/SOC-DRaHR
[27] https://lter.github.io/som-website

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 data sets 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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Literature Cited

Al-Shammary, A. A. G., A. Z. Kouzani, A. Kaynak, S. Y. Khoo, M. Norton, and W. Gates. 2018. Soil bulk density estimation methods: a review. Pedosphere 28:581–596.

Amundson, R., A. A. Berhe, J. W. Hopmans, C. Olson, A. E. Sztein, and D. L. Sparks. 2015. Soil and human security in the 21st century. Science 348:1261071.

Amundson, R., and L. Biardeau. 2018. Opinion: Soil carbon sequestration is an elusive climate mitigation tool. Proceedings of the National Academy of Sciences USA 115:11652–11656.

Anderson, J. P. E., and K. H. Domsch. 1978. A physiological method for the quantitative measurement of microbial biomass in soils. Soil Biology and Biochemistry 10:215–221.

Arnold, C., T. A. Ghezzehei, and A. A. Berhe. 2015. Decomposition of distinct organic matter pools is regulated by moisture status in structured wetland soils. Soil Biology and Biochemistry 81:28–37.

Baatz, R., et al. 2018. Steering operational synergies in terrestrial observation networks: Opportunity for advancing Earth system dynamics modelling. Earth System Dynamics 9:593–609.

Bailey, V. L., J. L. Smith, and H. Bolton. 2002. Fungal-to-bacterial ratios in soils investigated for enhanced C sequestration. Soil Biology and Biochemistry 34:997–1007.

Baldock, J. A., C. A. Masiello, Y. Gelinas, and J. I. Hedges. 2004. Cycling and composition of organic matter in terrestrial and marine ecosystems. Marine Chemistry 92:39–64.

Bao, R., A. P. McNichol, J. D. Hemingway, M. C. Lardie Gaylor, and T. I. Eglinton. 2018. Influence of different acid treatments on the radiocarbon content spectrum of sedimentary organic matter determined by RPO/accelerator mass spectrometry. Radiocarbon 61:395–413.

Batjes, N. H., E. Ribeiro, and A. van Oostrum. 2020. Standardized soil profile data to support global mapping and modelling (WoSIS snapshot 2019). Earth System Science Data 12:299–320.

Bennett, E. M., S. R. Carpenter, and M. K. Clayton. 2005. Soil phosphorus variability: scale-dependence in an urbanizing agricultural landscape. Landscape Ecology 20:389–400.

Bhattacharyya, T., et al. 2015. Walkley-Black recovery factor to reassess soil organic matter: Indo-Gangetic Plains and Black Soil Region of India case studies. Communications in Soil Science and Plant Analysis 46:2628–2648.

Billings, S. A. 2006. Soil organic matter dynamics and land use change at a grassland/forest ecotone. Soil Biology and Biochemistry 38:2934–2943.

Boone, R. D., D. F. Grigal, P. Sollins, R. J. Ahrens, and D. E. Armstrong. 1999. Soil sampling, preparation, archiving, and quality control. Pages 462 *in* G. Robertson, D. C. Coleman, C. S. Bledsoe, and P. Sollins, editors. Standard soil methods for long-term ecological research. Oxford University Press, New York, New York, USA.

Bradford, M. A., A. D. Keiser, C. A. Davies, C. A. Mersmann, and M. S. Strickland. 2013. Empirical evidence that soil carbon formation from plant inputs is positively related to microbial growth. Biogeochemistry 113:271–281.

Brady, N. C. 1990. The nature and properties of soils. MacMillan Press, New York, New York, USA.

Brantley, S. L., et al. 2011. Twelve testable hypotheses on the geobiology of weathering. Geobiology 9:140–165.

Brantley, S. L., M. B. Goldhaber, and K. V. Ragnarsdottir. 2007. Crossing disciplines and scales to understand the Critical Zone. Elements 3:307–314.

Bremer, E., H. H. Janzen, and A. M. Johnston. 1994. Sensitivity of total, light fraction and mineralizable organic matter to management. Canadian Journal of Soil Science 74:131–138.

Bronick, C. J., and R. Lal. 2005. Soil structure and management: a review. Geoderma 124:3–22.

Brooks, P. C., A. Landman, G. Pruden, and D. S. Jenkinson. 1985. Chloroform fumigation and the release of soil nitrogen:

a rapid direct extraction method to measure microbial biomass nitrogen in soil. Soil Biology and Biochemistry 17:837–842.

Buol, S. W., F. D. Hole, and R. J. McCracken. 1989. Soil genesis and classification. Iowa State University Press, Ames, Iowa, USA.

Buyer, J. S., and M. Sasser. 2012. High throughput phospholipid fatty acid analysis of soils. Applied Soil Ecology 61:127–130.

Cairns, M. A., S. Brown, and G. A. Baumgardner. 1997. Root biomass allocation in the world's upland forests. Oecologia 111:1–11.

Calabrese, S., D. D. Richter, and A. Porporato. 2018. The formation of clay-enriched horizons by lessivage. Geophysical Research Letters 45:7588–7595.

Cambardella, C. A., and E. T. Elliott. 1992. Particulate soil organic-matter changes across a grassland cultivation sequence. Soil Science Society of America Journal 56:777–783.

Certano, A. K., C. W. Fernandez, K. A. Heckman, and P. G. Kennedy. 2018. The afterlife effects of fungal morphology: contrasting decomposition rates between diffuse and rhizomorphic necromass. Soil Biology and Biochemistry 126:76–81.

Chen, S., et al. 2018. Plant diversity enhances productivity and soil carbon storage. Proceedings of the National Academy of Sciences USA 115:4027–4032.

Cheng, C., J. Lehmann, J. Thies, S. Burton, and M. Engelhard. 2006. Oxidation of black carbon by biotic and abiotic processes. Organic Geochemistry 37:1477–1488.

Collier, N., F. M. Hoffman, D. M. Lawrence, G. Keppel-Aleks, C. D. Koven, W. J. Riley, M. Mu, and J. T. Randerson. 2018. The International Land Model Benchmarking (ILAMB) System: Design, theory, and implementation. Journal of Advances in Modeling Earth Systems 10:2731–2754.

Compton, J. E., and R. D. Boone. 2000. Long-term impacts of agriculture on soil carbon and nitrogen in New England forests. Ecology 81:2314–2330.

Cotrufo, M. F., J. L. Soong, A. J. Horton, E. E. Campbell, M. L. Haddix, D. H. Wall, and W. J. Parton. 2015. Formation of soil organic matter via biochemical and physical pathways of litter mass loss. Nature Geoscience 8:776–779.

Cotrufo, M. F., M. D. Wallenstein, C. Boot, K. Denef, and E. Paul. 2013. The Microbial Efficiency-Matrix Stabilization (MEMS) framework integrates plant litter decomposition with soil organic matter stabilization: Do labile plant inputs form stable soil organic matter? Global Change Biology 19:988–995.

Coward, E. K., A. T. Thompson, and A. F. Plante. 2017. Iron-mediated mineralogical control of organic matter accumulation in tropical soils. Geoderma 306:206–216.

Crow, S. E., and C. A. Sierra. 2018. Dynamic, intermediate soil carbon pools may drive future responsiveness to environmental change. Journal of Environmental Quality 47:607–616.

Dangal, S. R., J. Sanderman, S. Wills, and L. Ramirez-Lopez. 2019. Accurate and precise prediction of soil properties from a large mid-infrared spectral library. Soil Systems 3:11.

Davidson, E. A., and I. A. Janssens. 2006. Temperature sensitivity of soil carbon decomposition and feedbacks to climate change. Nature 440:165–173.

Doetterl, S., A. A. Berhe, E. Nadeu, Z. Wang, M. Sommer, and P. Fiener. 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.

Doran, J. W., M. Sarrantonio, and M. A. Liebig. 1996. Soil health and sustainability. Advances in Agronomy 56:1–54.

Dwivedi, D., J. Tang, N. Bouskill, K. Georgiou, S. S. Chacon, and W. J. Riley. 2019. Abiotic and biotic controls on soil organo–mineral interactions: developing model structures to analyze why soil organic matter persists. Reviews in Mineralogy and Geochemistry 85:329–348.

Ellerbrock, R. H., H. H. Gerke, J. Bachmann, and M.-O. Goebel. 2005. Composition of organic matter fractions for explaining wettability of three forest soils. Soil Science Society of America Journal 69:57–66.

Ellerbrock, R. H., A. Höhn, and H. H. Gerke. 1999. Characterization of soil organic matter from a sandy soil in relation to management practice using FT-IR spectroscopy. Plant and Soil 213:55–61.

Ellert, B. H., H. H. Janzen, and T. Entz. 2002. Assessment of a method to measure temporal change in soil carbon storage. Soil Science Society of America Journal 66:1687–1695.

Ellis, S. E., and J. T. Leek. 2018. How to share data for collaboration. American Statistician 72:53–57.

Entwistle, E. M., D. R. Zak, and W. A. Argiroff. 2018. Anthropogenic N deposition increases soil C storage by reducing the relative abundance of lignolytic fungi. Ecological Monographs 88:225–244.

Fan, Y., et al. 2019. Hillslope hydrology in global change research and Earth system modeling. Water Resources Research 55:1737–1772. https://doi.org/10.1029/2018WR023903

Fierer, N., and R. B. Jackson. 2006. The diversity and biogeography of soil bacterial communities. Proceedings of the National Academy of Sciences USA 103:626–631.

Fierer, N., J. A. Jackson, R. Vilgalys, and R. B. Jackson. 2005. Assessment of soil microbial community structure by use of taxon-specific quantitative PCR assays. Applied Environmental Microbiology 71:4117–4120.

Food and Agriculture Organization of the United Nations. 2018. World reference base for soil resources 2014: International soil classification system for naming soils and creating legends for soil maps—update 2015. Food and Agriculture Organization, Rome, Italy.

Fornara, D. A., and D. Tilman. 2008. Plant functional composition influences rates of soil carbon and nitrogen accumulation. Journal of Ecology 96:314–322.

Fraterrigo, J. M., and J. A. Rusak. 2008. Disturbance-driven changes in the variability of ecological patterns and processes. Ecology Letters 11:756–770.

Fraterrigo, J. M., M. G. Turner, S. M. Pearson, and P. Dixon. 2005. Effects of past land use on spatial heterogeneity of soil nutrients in southern Appalachian forests. Ecological Monographs 75:215–230.

Frey, S. D., J. Lee, J. M. Melillo, and J. Six. 2013. The temperature response of soil microbial efficiency and its feedback to climate. Nature Climate Change 3:395–398.

Gee, G. W., and D. Or. 2002. Particle-size analysis. Pages 255–293 *in* J. H. Dane and G. C. Topp, editors. Methods of soil analysis: Part 4 physical methods. Book Series No. 5. Soil Science Society of America, Madison, Wisconsin, USA.

Ghezzehei, T. A., B. Sulman, C. L. Arnold, N. A. Bogie, and A. A. Berhe. 2019. On the role of soil water retention characteristic on aerobic microbial respiration. Biogeosciences 16:1187–1209.

Grandy, A. S., and J. C. Neff. 2008. Molecular soil C dynamics downstream: the biochemical decomposition sequence and its effects on soil organic matter structure and function. Science of the Total Environment 404:297–307.

Grandy, A. S., J. C. Neff, and M. N. Weintraub. 2007. Carbon structure and enzyme activities in alpine and forest ecosystems. Soil Biology and Biochemistry 39:2701–2711.

Grandy, A. S., and G. P. Robertson. 2006. Cultivation of a temperate-region soil at maximum carbon equilibrium immediately accelerates aggregate turnover and CO_2 and N_2O emissions. Global Change Biology 12:1507–1520.

Grandy, A. S., and G. P. Robertson. 2007. Land-use intensity effects on soil organic carbon accumulation rates and mechanisms. Ecosystems 10:59–74.

Griscom, B. W., J. Adams, P. W. Ellis, R. A. Houghton, G. Lomax, D. A. Miteva, W. H. Schlesinger, D. Shoch, J. V. Siikamäki, and P. Smith. 2017. Natural climate solutions. Proceedings of the National Academy of Sciences USA 114:11645–11650.

Halbritter, A. H., et al. 2019. The handbook for standardized field and laboratory measurements in terrestrial climate change experiments and observational studies (ClimEx). Methods in Ecology and Evolution 11:22–37. https://doi.org/10.1111/2041-210X.13331

Hall, S. J., A. A. Berhe, and A. Thompson. 2018. Order from disorder: do soil organic matter composition and turnover co-vary with iron phase crystallinity? Biogeochemistry 140:93–110.

Hall, S. H., and W. L. Silver. 2015. Synergisms among reactive minerals and reducing conditions explain spatial patterns of soil carbon in humid tropical forest soils. Biogeochemistry 125:149–165.

Hampton, S. E., C. A. Strasser, J. J. Tewksbury, W. K. Gram, A. E. Budden, A. L. Batcheller, C. S. Duke, and J. H. Porter. 2013. Big data and the future of ecology. Frontiers in Ecology and the Environment 11:156–162.

Harden, J. W., et al. 2017. Networking our science to characterize the state, vulnerabilities, and management opportunities of soil organic matter. Global Change Biology 24:e705–e715. https://doi.org/10.1111/gcb.13896

Harris, D., W. R. Horwath, and C. van Kessel. 2001. Acid fumigation of soils to remove carbonates prior to total organic carbon or carbon-13 isotopic analysis. Soil Science Society of America Journal 65:1853–1856.

He, H., C. Zhang, X. Zhao, F. Fousseni, J. Wang, H. Dai, S. Yang, and Q. Zuo. 2018. Allometric biomass equations for 12 tree species in coniferous and broadleaved mixed forests, Northeastern China. PLoS ONE 13:e0186226.

Heckman, K., A. S. Grandy, X. Gao, M. Keiluweit, K. Wickings, K. Carpenter, J. Chorover, and C. Rasmussen. 2013. Sorptive fractionation of organic matter and formation of organo-hydroxy-aluminum complexes during litter biodegradation in the presence of gibbsite. Geochimica et Cosmochimica Acta 121:667–683.

Heckman, K., C. R. Lawrence, and J. W. Harden. 2018. A sequential selective dissolution method to quantify storage and stability of organic carbon associated with Al and Fe hydroxide phases. Geoderma 312:24–35.

Hengl, T., et al. 2017. SoiGrids250m: Global gridded soil information based on machine learning. PLoS ONE. https://doi.org/10.1371/journal.pone.0169748

Hernández, Z., G. Almendros, P. Carral, A. Álvarez, H. Knicker, and J. P. Pérez-Trujillo. 2012. Influence of non-crystalline minerals in the total amount, resilience and molecular composition of the organic matter in volcanic ash soils (Tenerife Island, Spain). European Journal of Soil Science 63:603–615.

Hicks Pries, C. E., C. Castanha, R. C. Porras, and M. S. Torn. 2017. The whole-soil carbon flux in response to warming. Science 355:1420–1423.

Hirmas, D. R., D. Gimenez, A. Nemes, R. Kerry, N. A. Brunsell, and C. J. Wilson. 2018. Climate-induced changes in continental-scale soil macroporosity may intensify water cycle. Nature 561:100–103.

Hugelius, G., C. Tarnocai, G. Broll, J. G. Canadell, P. Kuhry, and D. K. Swanson. 2013. The northern circumpolar soil carbon database: spatially distributed datasets of soil coverage and soil carbon storage in the northern permafrost regions. Earth System Science Data 5:3–13.

Jackson, R. B., K. Lajtha, S. E. Crow, G. Hugelius, M. G. Kramer, and G. Piñeiro. 2017. The ecology of soil carbon: Pools, vulnerabilities, and biotic and abiotic controls. Annual Review of Ecology, Evolution, and Systematics 48:419–445.

Janzen, H. H. 2006. The soil carbon dilemma: Shall we hoard it or use it? Soil Biology and Biochemistry 38:419–424.

Janzen, H. H. 2009. Long-term ecological sites: musings on the future, as seen (dimly) from the past. Global Change Biology 15:2770–2778.

Jastrow, J. D. 1996. Soil aggregate formation and the accrual of particulate and mineral-associated organic matter. Soil Biology and Biochemistry 28:665–676.

Jiang, W., A. Saxena, B. Song, B. B. Ward, T. J. Beveridge, and S. C. Myneni. 2004. Elucidation of functional groups on gram-positive and gram-negative bacterial surfaces using infrared spectroscopy. Langmuir 20:11433–11442.

Jobbagy, E. G., and R. B. Jackson. 2000. The vertical distribution of soil organic carbon and its relation to climate and vegetation. Ecological Applications 10:423–436.

Kaiser, M., and R. H. Ellerbrock. 2005. Functional characterization of soil organic matter fractions different in solubility originating from a long-term field experiment. Geoderma 127:196–206.

Kaiser, K., and G. Guggenberger. 2000. The role of DOM sorption to mineral surfaces in the preservation of organic matter in soils. Organic Geochemistry 31:711–725.

Kaiser, K., and G. Guggenberger. 2001. Sorption-desorption of dissolved organic matter in forest soils. Eleventh Annual V. M. Goldshmidt Conference, University of Bayreuth, Bayreuth, Germany.

Kaiser, M., M. Kleber, T. Ghezzehei, D. Myrold, and A. A. Berhe. 2014. Calcium carbonate and charcoal applications promote storage and stabilization of organic matter associated with silt-sized aggregates. Soil Science Society America Journal 78:1624–1631.

Kaiser, E., T. Mueller, R. Joergensen, H. Insam, and O. Heinemeyer. 1992. Evaluation of methods to estimate the soil microbial biomass and the relationship with soil texture and organic matter. Soil Biology and Biochemistry 24:675–683.

Kallenbach, C. M., S. D. Frey, and A. S. Grandy. 2016. Direct evidence for microbial-derived soil organic matter formation and its ecophysiological controls. Nature Communications 7:13630.

Kallenbach, C. M., A. S. Grandy, S. D. Frey, and A. F. Diefendorf. 2015. Microbial physiology and necromass regulate agricultural soil carbon accumulation. Soil Biology and Biochemistry 9:279–290.

Kallenbach, C. M., M. D. Wallenstein, M. E. Schipanski, and A. S. Grandy. 2019. Managing agroecosystems for optimal soil microbial carbon use efficiency. Frontiers in Microbiology 10:1146.

Kasting, J. F., and J. L. Siefert. 2002. Life and the evolution of Earth's atmosphere. Science 296:100–106.

Keiluweit, M., K. Gee, A. Denney, and S. Fendorf. 2017. Anoxic microsites in upland soils dominantly controlled by clay content. Soil Biology and Biochemistry 118:42–50.

Keiluweit, M., P. Nico, M. Johnson, and M. Kleber. 2010. Dynamic molecular structure of plant biomass-derived black carbon (biochar). Environmental Science and Technology 44:1247–1253.

Kleber, M., P. Sollins, and R. Sutton. 2007. A conceptual model of organo-mineral interactions in soils: self-assembly of organic molecular fragments into zonal structures on mineral surfaces. Biogeochemistry 85:9–24.

Kleinman, P. J. A., et al. 2018. Advancing the sustainability of U.S. agriculture through long-term research. Journal of Environmental Quality 47:1412–1425.

Kohl, L., M. Philben, K. A. Edwards, F. A. Podrebarac, J. Warren, and S. E. Ziegler. 2017. The origin of soil organic matter controls its composition and bioreactivity across a mesic boreal forest latitudinal gradient. Global Change Biology 24: e458–e473.

Kramer, M. G., K. Lajtha, and A. K. Aufdenkampe. 2017. Depth trends of soil organic matter C: N and 15N natural abundance controlled by association with minerals. Biogeochemistry 136:237–248.

Kroetsch, D., and C. Wang. 2008. Particle size distribution. Pages 713–725 *in* M. R. Carter and E. G. Gregorich, editors. Soil sampling and methods of analysis. Second edition. CRC Press, Boca Raton, Florida, USA.

Kump, L. R. 2008. The rise of atmospheric oxygen. Nature 451:277–278.

Lajtha, K., K. Townsend, M. Kramer, C. Swanston, R. Bowden, and K. Nadelhoffer. 2014. Changes to particulate versus mineral-associated soil carbon after 50 years of litter manipulation in forest and prairie experimental ecosystems. Biogeochemistry 119:341–360.

Lal, R. 2004. Soil carbon sequestration impacts on global climate change and food security. Science 304:1623–1627.

Lal, R., and J. M. Kimble. 2001. Importance of soil bulk density and methods of its importance. Pages 31–44 *in* R. Lal, J. M. Kimble, R. F. Follett, and B. A. Stewart, editors. Assessment methods for soil carbon. Lewis Publishers, New York, New York, USA.

Lal, R., J. M. Kimble, R. F. Follett, and B. A. Stewart. 2001. Assessment methods for soil carbon. Advances in soil science series. Lewis Publishers, Madison, Wisconsin, USA.

Lange, M., et al. 2015. Plant diversity increases soil microbial activity and soil carbon storage. Nature Communications 6:6707.

Langenheder, S., E. S. Lindstrom, and L. J. Tranvik. 2006. Structure and function of bacterial communities emerging from different sources under identical conditions. Applied Environmental Microbiology 72:212–220.

Lavallee, J. M., J. L. Soong, and M. F. Cotrufo. 2020. Conceptualizing soil organic matter into particulate and mineral-associated forms to address global change in the 21st century. Global Change Biology. https://doi.org/10.1111/gcb14859

Lawrence, C. R., et al. 2020. An open-source database for the synthesis of soil radiocarbon data: International Soil Radiocarbon Database (ISRaD) version 1.0. Earth System Science Data 12:61–76.

Lee, J. W., M. Kidder, B. R. Evans, S. Paik, A. C. Buchanan III, C. T. Garten, and R. C. Brown. 2010. Characterization of biochars produced from cornstovers for soil amendment. Environmental Science and Technology 44:7970–7974.

Lehmann, J., J. Kinyangi, and D. Solomon. 2007. Organic matter stabilization in soil microaggregates: implications from spatial heterogeneity of organic carbon contents and carbon forms. Biogeochemistry 85:45–57.

Leue, M., R. H. Ellerbrock, and H. H. Gerke. 2010. DRIFT mapping of organic matter composition at intact soil aggregate surfaces. Vadose Zone Journal 9:317–324.

Li, K., J. Rollins, and E. Yan. 2018. Web of Science use in published research and review papers 1997–2017: a selective, dynamic, cross-domain, content-based analysis. Scientometrics 115:1. https://doi-org.ezproxy1.lib.asu.edu/10.1007/s11192-017-2622-5

Liang, C., W. Amelung, J. Lehmann, and M. Kastner. 2019. Quantitative assessment of microbial necromass contribution to soil organic matter. Global Change Biology 25:3578–3590.

Lin, H. 2012. Hydropedology. Academic Press, Cambridge, Massachusetts, USA.

Luo, Y. Q., et al. 2016. Toward more realistic projections of soil carbon dynamics by Earth system models. Global Biogeochemical Cycles 30:40–56.

Lupwavi, M. A., M. A. Arshad, W. A. Rice, and G. W. Clayton. 2001. Bacterial diversity in water-stable aggregates of soils under conventional and zero tillage management. Applied Soil Ecology 16:251–261.

Malhotra, A., et al. 2019. The landscape of soil carbon data: Emerging questions, synergies and databases. Progress in Physical Geography: Earth and Environment 43:707–719.

Malik, A. A., S. Chowdhury, V. Schlager, A. Oliver, J. Puissant, P. G. M. Vazquez, N. Jehmlich, M. von Bergen, R. I. Griffiths, and G. Gleixner. 2016. Soil fungi:bacteria ratios are linked to altered carbon cycling. Frontiers in Microbiology 7:1247.

Malik, A. A., J. B. H. Martiny, E. L. Brodie, A. C. Martiny, K. K. Treseder, and S. D. Allison. 2020. Defining trait-based microbial strategies with consequences for soil carbon cycling under climate change. ISME Journal 14:1–9.

Martin, P. A., A. D. Newton, and J. M. Bullock. 2013. Carbon pools recover more quickly than plant biodiversity in tropical secondary forests. Proceedings of the Royal Society B 280:20132236.

Marwick, B., C. Boettiger, and L. Mullen. 2018. Packaging data analytical work reproducibly using R (and friends). American Statistician 72:80–88.

Marzaioli, F., C. Lubritto, I. D. Galdo, A. D'Onofrio, M. F. Cotrufo, and F. Terrasi. 2010. Comparison of different soil organic matter fractionation methodologies: evidences from ultrasensitive ^{14}C measurements. Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms 268:1062–1066.

Masiello, C. A., O. A. Chadwick, J. R. Southon, M. S. Torn, and J. W. Harden. 2004. Weathering controls on mechanisms of carbon storage in grassland soils. Global Biogeochemical Cycles 18:GB4023.

Mayer, A., Z. Hausfather, A. D. Jones, and W. L. Silver. 2018. The potential of agricultural land management to contribute to lower global surface temperatures. Sciences Advances 4: eaaq0932.

McLauchlan, K. K., S. E. Hobbie, and W. M. Post. 2006. Conversion from agriculture to grassland builds soil organic matter on decadal timescales. Ecological Applications 16:143–153.

McLean, E. O. 1982. Soil pH and lime requirement. Pages 199–224 *in* A. L. Page, R. H. Miller, and D. R. Keney, editors. Methods of soil analysis part 2: Chemical and microbiological properties. Second edition. ASA-SSSA, Madison, Wisconsin, USA.

Melillo, J. M., S. D. Frey, K. M. DeAngelis, W. J. Werner, M. J. Bernard, F. P. Bowles, G. Pold, M. A. Knorr, and A. S. Grandy. 2017. Long-term pattern and magnitude of soil carbon feedback to the climate system in a warming world. Science 358:101–105.

Midwood, A. J., and T. W. Boutton. 1998. Soil carbonate decomposition by acid has little effect on $\delta^{13}C$ of organic matter. Soil Biology and Biochemistry 30:1301–1307.

Mikutta, R., C. Mikutta, K. Kalbitz, T. Scheel, K. Kaiser, and R. Jahn. 2007. Microbial mineralization of organic matter bound to minerals via different binding mechanisms. Geochimica et Cosmochimica Acta 71:2569–2590.

Min, K., C. A. Lehmeier, F. Ballantyne IV, and S. A. Billings. 2016. Carbon availability modifies temperature responses of heterotrophic microbial respiration, carbon uptake affinity, and stable carbon isotope discrimination. Frontiers in Microbiology 25:1793–1807. https://doi.org/10.3389/fmicb.2016.02083

Min, K., C. A. Lehmeier, F. Ballantyne, A. Tatarko, and S. A. Billings. 2014. Differential effects of pH on temperature sensitivity of organic carbon and nitrogen decay. Soil Biology and Biochemistry 76:193–200.

Minasny, B., et al. 2017. Soil carbon 4 per mille. Geoderma 292:59–86.

Minasny, B., A. B. McBratney, D. M. Brough, and D. Jacquier. 2011. Models relating soil pH measurements in water and calcium chloride that incorporate electrolyte concentration. European Journal of Soil Science 62:728–732.

Mobley, M. L., Y. Yang, R. D. Yanai, K. A. Nelson, A. R. Bacon, P. R. Heine, and D. D. Richter. 2019. How to estimate statistically detectable trends in a time series: a study of soil carbon and nutrient concentrations at the Calhoun LTSE. Soil Science Society America Journal 83:S133–S140.

Moni, C., D. Derrien, P.-J. Hatton, B. Zeller, and M. Kleber. 2012. Density fractions versus size separates: does physical fractionation isolate functional soil compartments? Biogeosciences 9:5181–5197.

Muhammed, S. E., et al. 2018. Impact of two centuries of intensive agriculture on soil carbon, nitrogen, and phosphorus cycling in the UK. Science of the Total Environment 634:1486–1504. https://doi.org/10.1016/j.scitotenv.2018.03.378

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 USA 115:2776–2781.

Nepstad, D. C., C. R. de Carvalho, E. A. Davidson, P. H. Jipp, P. A. Lefebvre, G. H. Negreiros, E. D. da Silva, T. A. Stone, S. E. Trumbore, and S. Vieira. 1994. The role of deep roots in the hydrological and carbon cycles of Amazonian forests and pastures. Nature 372:666–669.

Nimmo, J. R., and K. S. Perkins. 2002. Aggregate stability and size distribution. Pages 317–328 *in* J. H. Dane and G. C. Topp, editors. Methods of soil analysis, Part 4—Physical methods. Soil Science Society of America, Madison, Wisconsin, USA.

Oades, J. M., and A. G. Waters. 1991. Aggregate hierarchy in soils. Soil Research 29:815–828.

Page-Dumroese, D. S., M. F. Jurgensen, and G. D. Mroz. 1999. Comparison of methods for determining bulk densities of rocky forest soils. Soil Science Society of America Journal 63:379–383.

Paustian, K., H. P. Collins, and E. A. Paul. 1997. Management controls on soil carbon. Pages 15–49 *in* E. A. Paul, K. Paustian, E. T. Elliot, and C. V. Cole, editors. Soil organic matter in temperate agroecosystems. CRC Press, Boca Raton, Florida, USA.

Percival, H. J., R. L. Parfitt, and N. A. Scott. 2000. Factors controlling soil carbon levels in New Zealand grasses: Is clay content important? Soil Society Science America Journal 64:1623–1630.

Plugge, D., D. Kübler, P. R. Neupane, K. Olschofsky, and L. Prill. 2016. Measurement, reporting, and verifications systems in forest assessment. Pages 839–882 *in* L. Pancel and M. Köhl, editors. Tropical forestry handbook. Springer Berlin Heidelberg, Berlin, Heidelberg, Germany.

Poeplau, C., et al. 2018. Isolating organic carbon fractions with varying turnover rates in temperate agricultural soils—A comprehensive method comparison. Soil Biology and Biochemistry 125:10–26.

Poeplau, C., T. Kätterer, M. A. Bolinder, G. Börjesson, A. Berti, and E. Lugato. 2015. Low stabilization of aboveground crop residue carbon in sandy soils of Swedish long-term experiments. Geoderma 237–238:246–255.

Poisot, T., R. Mounce, and D. Gravel. 2013. Moving toward a sustainable ecological science: Don't let data go to waste! Ideas in Ecology and Evolution 6:11–19. https://doi.org/10.4033/iee.2013.6b.14.f

Raczka, B., M. C. Dietze, S. P. Serbin, and K. J. Davis. 2018. What limits predictive certainty of long-term carbon uptake? Journal of Geophysical Research: Biogeosciences 123:3570–3588.

Ramnarine, R., R. P. Voroney, C. Wagner-Riddle, and K. E. Dunfield. 2011. Carbonate removal by acid fumigation for measuring the $\delta^{13}C$ of soil organic carbon. Canadian Journal of Soil Science 91:247–250.

Rasmussen, C. K., et al. 2018*a*. Beyond clay: Towards an improved set of variables for predicting soil organic matter content. Biogeochemistry 137:297–306.

Rasmussen, C., H. Throckmorton, G. Liles, K. Heckman, S. Meding, and W. R. Horwath. 2018*b*. Controls on soil organic carbon partitioning and stabilization in the California Sierra Nevada. Soil Systems 2:41.

Rasmussen, C., M. S. Torn, and R. J. Southard. 2005. Mineral assemblage and aggregates control carbon dynamics in a California conifer forest. Soil Science Society of America Journal 69:1711–1721.

Richter, D. D., et al. 2018. Ideas and perspectives: Strengthening the biogeosciences in environmental research networks. Biogeosciences 15:4815–4832.

Richter, D. B., M. Hofmockel, M. A. Callaham, D. S. Powlson, and P. Smith. 2007. Long-term soil experiments: Keys to managing Earth's rapidly changing ecosystems. Soil Science Society of America Journal 71:266–279.

Richter, D. D., and D. Markewitz. 1995. How deep is soil? BioScience 45:600–609.

Richter, D. D., D. Markewitz, S. E. Trumbore, and C. G. Wells. 1999. Rapid accumulation and turnover of soil carbon in a re-establishing forest. Nature 400:56–58.

Robertson, G. P., D. C. Coleman, C. S. Bledsoe, and P. Sollins. 1999. Standard soil methods for long-term ecological research. Oxford University Press, New York, New York, USA.

Robertson, G. P., J. R. Crum, and B. G. Ellis. 1993. The spatial variability of soil resources following long-term disturbance. Oecologia 96:451–456.

Robinson, D. A., J. W. Hopmans, V. Filipovic, M. van der Ploeg, I. Lebron, S. B. Jones, S. Reinsch, N. Jarvis, and M. Tuller. 2019. Global environmental changes impact soil hydraulic functions through biophysical feedbacks. Global Change Biology 25:1895–1904.

Ryals, R., M. Kaiser, M. S. Torn, A. A. Berhe, and W. L. Silver. 2014. Impacts of organic matter amendments on carbon and nitrogen dynamics in grassland soils. Soil Biology and Biochemistry 68:52–61.

Sanderman, J., T. Hengl, and G. J. Fiske. 2017. Soil carbon debt of 12,000 years of human land use. Proceedings of the National Academy of Sciences USA 114:9575–9580.

Sanderman, J., T. Maddern, and J. Baldock. 2014. Similar composition but differential stability of mineral retained organic matter across four classes of clay minerals. Biogeochemistry 121:409–424.

Scharlemann, J. P. W., E. V. J. Tanner, R. Hiederer, and V. Kapos. 2014. Global soil carbon: understanding and managing the largest terrestrial carbon pool. Carbon Management 5:81–91.

Schimel, J., and O. Chadwick. 2013. What's in a name? The importance of soil taxonomy for ecology and biogeochemistry. Frontiers in Ecology and the Environment 11:405–406.

Schlesinger, W. H., and E. W. Bernhardt. 2013. Biogeochemistry: an analysis of global change. Academic Press, New York, New York, USA.

Schrumpf, M., K. Kaiser, G. Guggenberger, T. Persson, I. Kögel-Knabner, and E.-D. Schulze. 2013. Storage and stability of organic carbon in soils as related to depth, occlusion within aggregates, and attachment to minerals. Biogeosciences 10:1675–1691.

Shade, A., et al. 2012. Fundamentals of microbial community resistance and resilience. Frontiers in Microbiology 3:417.

Six, J., E. T. Elliott, and K. Paustian. 2000. Soil macroaggregate turnover and microaggregate formation: a mechanism for C sequestration under no-tillage agriculture. Soil Biology and Biochemistry 32:2099–2103.

Six, J., S. D. Frey, R. K. Thiet, and K. M. Batten. 2006. Bacterial and fungal contributions to carbon sequestration in agroecosystems. Soil Science Society of America Journal 70:555–569.

Smeaton, C., N. L. M. Barlow, and W. E. N. Austin. 2020. Coring and compaction: best practice in blue carbon stock and burial estimations. Geoderma 364:114180.

Smith, P., et al. 2019. How to measure, report and verify soil carbon change to realize the potential of soil carbon sequestration for atmospheric greenhouse gas removal. Global Change Biology 26:219–241. https://doi.org/10.1111/gcb.14815

Smith, A. P. B., B. W. Bond-Lamberty, M. M. Benscoter, C. R. Tfaily, C. L. Hinkle, and V. L. Bailey. 2017. Shifts in pore connectivity from precipitation versus groundwater rewetting increases soil carbon loss after drought. Nature Communications 8:1335.

Sohi, S. P., N. Mahieu, J. R. M. Arah, D. S. Powlson, B. Madari, and J. L. Gaunt. 2001. Procedure for isolating soil organic matter fractions suitable for modeling. Soil Science Society of America Journal 65:1121–1128.

Soil Survey Staff. 1999. Keys to soil taxonomy. U.S. Department of Agriculture, Natural Resources Conservation Service, National Soil Survey Center, Lincoln, Nebraska, USA.

Sollins, P., M. G. Kramer, C. Swanston, K. Lajtha, T. Filley, A. K. Aufdenkampe, R. Wagai, and R. D. Bowden. 2009. Sequential density fractionation across soils of contrasting mineralogy: evidence for both microbial- and mineral-controlled soil organic matter stabilization. Biogeochemistry 96:209–231.

Sollins, P., C. Swanston, M. Kleber, T. Filley, M. Kramer, S. Crow, B. Caldwell, K. Lajtha, and R. Bowden. 2006. Organic C and N stabilization in a forest soil: evidence from sequential density fractionation. Soil Biology and Biochemistry 38:3313–3324.

Spencer, S., S. M. Ogle, F. J. Breidt, J. J. Goebel, and K. Paustian. 2011. Designing a national soil carbon monitoring network to support climate change policy: a case example for US agricultural lands. Greenhouse Gas Measurement and Management 1(3–4):167–178.

Strickland, T. C., and P. Sollins. 1987. Improved method for separating light-fraction and heavy-fraction organic material from soil. Soil Science Society of America Journal 51:1390–1393.

Sullivan, P. L., M. W. Stops, G. L. Macpherson, L. Li, D. R. Hirmas, and W. K. Dodds. 2019. How landscape heterogeneity governs stream water concentration discharge behavior in carbonate terrains (Konza Prairie, USA). Chemical Geology 527:118989. https://doi.org/10.1016/j.chemgeo.2018.12.002

Sulman, B. N., R. P. Phillips, A. C. Oishi, E. Shevliakova, and S. W. Pacala. 2014. Microbe-driven turnover offsets mineral-mediated storage of soil carbon under elevated CO_2. Nature Climate Change 4:1099–1102.

Swift, R. S. 1996. Organic matter characterization. Pages 1011–1069 *in* D. L. Sparks, editor. Methods of soil analysis: Part 3: chemical methods. SSSA Book Series. No. 5. Soil Science Society of America, Madison, Wisconsin, USA.

Thomas, G. W. 1996. Soil pH and soil acidity. Pages 475–489 *in* D. L. Sparks, editor. Methods of soil analysis: Part 3—chemical methods. Book Series No. 5. Soils Science Society of America, Madison, Wisconsin, USA.

Throop, H. L., S. R. Archer, H. C. Monger, and S. Waltman. 2012. When bulk density methods matter: Implications for estimating soil organic carbon pools in rocky soils. Journal of Arid Environments 77:66–71.

Tiemann, L. K., A. S. Grandy, E. E. Atkinson, E. Marin-Spiotta, and M. D. McDanial. 2015. Crop rotational diversity enhances belowground communities and functions in an agroecosystem. Ecology Letters 18:761–771.

Tisdall, J. M., and J. M. Oades. 1982. Organic matter and water-stable aggregates in soils. Journal of Soil Science 33:141–163.

Todd-Brown, K. E. O., et al. 2014. Changes in soil organic carbon storage predicted by Earth system models during the 21st century. Biogeosciences 11:2341–2356.

Tombacz, E., Z. Libor, E. Illes, and A. Majzik. 2004. The role of reactive surface sites and complexation by humic acids in the interaction of clay mineral and iron oxide particles. Organic Geochemistry 35:257–267.

Torn, M. S., S. E. Trumbore, O. A. Chadwick, P. M. Vitousek, and D. M. Hendricks. 1997. Mineral control of soil organic carbon storage and turnover. Nature 389:170–173.

Upton, R. N., E. M. Bach, and K. S. Hofmockel. 2019. Spatio-temporal microbial community dynamics within soil aggregates. Soil Biology and Biochemistry 132:58–68.

USDA NRCS. 2014. Kellogg soil survey laboratory methods manual. Report No. 42, Version 5.0, Soil Survey Investigations, Lincoln, Nebraska, USA.

van Gestel, M., R. Merckx, and K. Vlassak. 1996. Spatial distribution of microbial biomass in microaggregates of a silty-loam soil and the relation with the resistance of microorganisms to soil drying. Soil Biology and Biochemistry 28:503–510.

van Wesemael, B., et al. 2011. How can soil monitoring networks be used to improve predictions of organic carbon pool dynamics and CO_2 fluxes in agricultural soils? Plant and Soil 338:247–259.

Verde Arregoitia, L. D., N. Cooper, and G. D'Elía. 2018. Good practices for sharing analysis-ready data in mammalogy and biodiversity research. Hystrix, the Italian Journal of Mammalogy 29:155–161.

Vicca, S., et al. 2018. Using research networks to create the comprehensive datasets needed to assess nutrient availability as a key determinant of terrestrial carbon cycling. Environmental Research Letters 13:125006. https://doi.org/10.1088/1748-9326/aaeae7

Viera, M., and R. Rodríguez-Soalleiro. 2019. A complete assessment of carbon stocks in above and belowground biomass components of a hybrid eucalyptus plantation in southern Brazil. Forests 10:536.

von Lützow, M., I. Kögel-Knabner, K. Ekschmittb, H. Fless, G. Guggenberger, E. Matzner, and B. Marschner. 2007. SOM fractionation methods: relevance to functional pools and to stabilization mechanisms. Soil Biology and Biochemistry 39:2183–2207.

Wagai, R., L. M. Mayer, and K. Kitayama. 2009. Nature of the occluded low-density fraction in soil organic matter studies: a critical review. Soil Science and Plant Nutrition 55:13–25.

Walter, K., A. Don, B. Tiemeyer, and A. Freibauer. 2016. Determining soil bulk density for carbon stock calculations: a systematic method comparison. Soil Science Society of America Journal 80:579–591.

Walthert, L., U. Graf, A. Kammer, J. Luster, D. Pezzotta, S. Zimmermann, and F. Hagedorn. 2010. Determination of organic and inorganic carbon, $\delta^{13}C$, and nitrogen in soils containing carbonates after acid fumigation with HCl. Journal of Plant Nutrition and Soil Science 173:207–216.

Wang, S., H. Y. Chen, Y. Tan, H. Fan, and H. Ruan. 2016. Fertilizer regime impacts on abundance and diversity of soil fauna across a poplar plantation chronosequence in coastal Eastern China. Scientific Reports 6:1–10.

Webster, R., and M. A. Oliver. 2001. Geostatistics for environmental scientists. John Wiley and Sons, Chichester, UK.

Weintraub, S. R., et al. 2019. Leveraging environmental research and observation networks to advance soil carbon science. Journal of Geophysical Research Biogeosciences 124:1047–1055.

Wendt, J. W., and S. Hauser. 2013. An equivalent soil mass procedure for monitoring soil organic carbon in multiple soil layers. European Journal of Soil Science 64:58–65.

White, E. P., E. Baldridge, Z. T. Brym, K. J. Locey, D. J. McGlinn, and S. R. Supp. 2013. Nine simple ways to make it easier to (re) use your data. Ideas in Ecology and Evolution 6:1–10.

White, D., W. M. Davis, J. S. Nickels, J. D. King, and R. J. Bobbie. 1979. Determination of the sedimentary microbial biomass by extractable lipid phosphate. Oecologia 40:51–62.

Wickham, H. 2014. Tidy data. Journal of Statistical Software 59:23.

Wieder, W. R., et al. 2020. SOils DAta Harmonization database (SoDaH): an open-source synthesis of soil data from research networks ver 1. Environmental Data Initiative. https://doi.org/10.6073/pasta/9733f6b6d2ffd12bf126dc36a763e0b4

Wieder, W. R., A. S. Grandy, C. M. Kallenbach, and G. B. Bonan. 2014. Integrating microbial physiology and physiochemical principles in soils with the MIcrobial-MIneral Carbon Stabilization (MIMICS) model. Biogeosciences 11:3899–3917.

Wieder, W. R., M. D. Hartman, B. N. Sulman, Y.-P. Wang, C. D. Koven, and G. C. Bonan. 2018. Carbon cycle confidence and uncertainty: Exploring variation among soil biogeochemical models. Global Change Biology 24:1563–1579. https://doi.org/10.1111/gcb.13979

Wieder, W. R., B. N. Sulman, M. D. Hartman, C. D. Koven, and M. A. Bradford. 2019. Arctic soil governs whether climate change drives global losses or gains in soil carbon. Geophysical Research Letters 46:14486–14495.

Wilkinson, M. D., et al. 2016. The FAIR guiding principles for scientific data management and stewardship. Scientific Data 3:160018.

Williams, E. K., M. L. Fogel, A. A. Berhe, and A. F. Plante. 2018. Distinct bioenergetic signatures in particulate versus mineral-associated soil organic matter. Geoderma 330:107–116.

Wuest, S. B. 2009. Correction of bulk density and sampling method biases using soil mass per unit area. Soil Science Society of America Journal 73:312–316.

Yang, Y., D. Tilman, G. Furey, and C. Lehman. 2019. Soil carbon sequestration accelerated by restoration of grassland biodiversity. Nature Communications 10:718.

Yeasmin, S., B. Singh, C. T. Johnston, and D. L. Sparks. 2017. Organic carbon characteristics in density fractions of soils with contrasting mineralogies. Geochimica et Cosmochimica Acta 218:215–236.

Zhang, H., et al. 2020. Microbial dynamics and soil physicochemical properties explain large-scale variations in soil organic carbon. Glob Change Biology 16:1–18.

Zhao, K., X. Jing, N. J. Sanders, L. Chen, Y. Shi, D. F. B. Flynn, Y. Wang, H. Chu, W. Liang, and J.-S. He. 2017. On the controls of abundance for soil-dwelling organisms on the Tibetan Plateau. Ecosphere 8:e01901.