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Article type : Report

Networking our science to characterize the state, vulnerabilities, and management opportunities of soil organic matter

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running head: soil carbon networking
keywords: soil management, agricultural practices, network, C cycling, soil, soil carbon, C sequestration, global CO_2

Abstract

Soil organic matter supports the Earth’s ability to sustain terrestrial ecosystems, provide food and fiber, and retain the largest pool of actively cycling carbon. Over 75% of the soil organic carbon (SOC) in the top meter of soil is directly affected by human land use. Large land areas have lost SOC as a result of land use practices, yet there are compensatory opportunities to enhance productivity and SOC storage in degraded lands through improved management practices. Large areas with and without intentional management are also being subjected to rapid changes in climate, making many SOC stocks vulnerable to losses by decomposition or disturbance. In order to quantify potential SOC losses or sequestration at field, regional, and global scales, measurements for detecting changes in SOC are needed. Such measurements and soil-management best practices should be based on well-established and emerging scientific understanding of processes of C stabilization and destabilization over various timescales, soil types, and spatial scales. As newly engaged members of the International Soil Carbon Network, we have identified gaps in data, modeling, and communication that underscore the need for an open, shared network to frame and guide the study of soil organic matter and SOC and their management for sustained production and climate regulation.

Introduction

Soil organic matter (SOM) governs many physical, chemical, and biological characteristics of soils, and is one determinant of a soil's capacity for fertility, ecosystem productivity, and CO_2 sequestration. Thus SOM, and its main constituent soil organic carbon (SOC), interacts with several aspects of the Earth system and its services to society (Banwart et al., 2014), including food, fiber, water, energy, cycling of carbon (C) and nutrients, and biodiversity. Large land areas (up to 6 billion ha) are estimated to be in some state of soil degradation (Gibbs and Salmon, 2015), associated in many cases with deficient stocks of SOM. Increasing SOM content, and thus SOC storage, can improve the state of soil and ecological sustainability, and because SOC stocks are large globally, widespread adoption of sustainability can also contribute to climate change mitigation by capturing atmospheric CO_2.

SOM and SOC research has traditionally been dominated by at least two scientific communities that have been publishing in rather disparate types of journals (Supplemental Materials SM2a), one focused on soil science/soil health and the other focused on the terrestrial C cycle and global biogeochemistry. Soil health or quality is a concept formalized in the 1990s to describe soil management practices that enhance the biological, chemical, and physical properties of soil. Terrestrial C cycling typically refers to the exchange of land-based C with atmospheric CO_2 and CH_4 although aquatic systems and flows are closely intertwined as well. Owing to the very large and dynamic stocks of soil C globally, the role of soils in climate regulation has been increasingly studied in the context of ecological and geological perspectives that link organic matter processing to C, nutrients, productivity, hydrology, and landscape dynamics. As a result, conceptual frameworks and simulation models have become quite elegant and sophisticated in representing both site-based, land management options and global scale syntheses. As the goals of these communities converge, we are presented with an opportunity to combine and transform our knowledge, databases, and mathematical frameworks for the benefit of environmental health and humanity.

At the global scale, SOM is one of the largest and actively cycling C reservoirs (Cias et al., 2013; Jackson et al. 2017) and is subjected to direct human activities impacting over 70% of C stocks in the upper meter of soil. Globally soils store 1,300-1,500 Pg of C in the top meter (Fig. 1a; Batjes, 2016). Much of this SOC is in lands impacted directly by cropping, grazing, and forestry practices, with 30% residing in lands only indirectly impacted by human activities such as peatlands and permafrost soils (Hugelius et al., 2014; Köchy et al., 2015; Loisel et al., 2017). The distribution of soils in managed lands follows the distribution of human land use (Fig. 1b, c) and overlaying the estimated SOC stocks with human land-use data shows that the majority of near-surface SOC stocks are directly affected by human activities today (Fig. 1c).

Efforts such as the '4-per-1000' program, a global initiative to reduce atmospheric CO_2 through soil C sequestration (Minasny et al., 2017), demonstrate that many soils in managed systems could offer an opportunity for climate regulation. While uncertainties are very large, it is evident that land management practices can lead to C gains from 0.01 kg C m^{-2} yr^{-1} up to 0.07 kg C m^{-2} yr^{-1} (Minasny et al., 2017, Paustian et al. 2016, Smith et al. 2007). If these numbers are applied across all Earth's managed lands, there is an opportunity to sequester several Pg C yr^{-1} globally (Fig. 1d). While not all lands are likely to be managed consistently, this maximum estimate could potentially offset future C emissions from permafrost (Koven et al., 2015) or the combined projected emissions from land use change and agricultural management (Pugh et al., 2015; projected emissions in Fig. 1d).

The ability to detect shifts in SOC and to potentially increase SOC storage is important for scientific and societal challenges in the face of rapidly changing terrestrial landscapes. However, detecting changes in SOC is problematic owing to the complex temporal and spatial scales at which we need to measure and predict change. For example, estimates of future SOC dynamics range widely, and recent compilations of soil radiocarbon suggest that global models underestimate the transit time of C in soil, biasing estimates for soil C sequestration in future years (He et al, 2016). Meanwhile conceptual frameworks for SOC stabilization are also changing, challenging the science community to shift methods and measurements to test alternative models. For example, paradigms and metrics of SOC stabilization and destabilization (herein referred to as SOC (de)stabilization) have been shifting (Schmidt et al., 2011 ; Lehmann and Kleber, 2015). Emerging paradigms de-emphasize the chemical properties of SOM and SOC and focus more on mechanisms that isolate or stabilize C, such as sorption of biopolymers and their decomposition products on mineral surfaces and the entrapment of organic matter in aggregates. These and other recent developments call for model development and new datasets to address aggregate dynamics, carbon-use efficiency of microorganisms, the role of dissolved organic matter, priming to enhance SOC decomposition, and mineral protection of organic matter.

We posit that there is a need and an opportunity for the scientific community to: 1) better identify datasets to characterize ecosystem and landscape properties, processes, and mechanisms that dictate SOC storage and stabilization and their vulnerabilities to change; 2) identify, rescue, and disseminate existing datasets; 3) develop platforms for sharing data, models, and management practices for SOC science; and 4) improve the connection between global C cycle and soil management research communities. The International Soil Carbon Network (ISCN) is a community devoted to open and shared rigorous science for characterizing the state, vulnerabilities, and opportunities for managing SOM. To this end, the ISCN targets SOM and SOC-related science questions in Section 2 that are potentially actionable through good science and informed management. Challenges and strategies for the ISCN to function as a community platform for communication, modeling, and data sharing, as well as to increase interoperability among SOC-relevant networks, are outlined in section 3.

Challenges for characterizing the state, vulnerabilities, and management opportunities of soil organic matter

Most needed from our community is detection of changes in SOM and SOC, yet such changes vary spatially and temporally because of the many processes that are linked to variations and changes in climate, land use, vegetation, topographic, and geologic factors. Broad-scale ecosystem models generally build on mechanistic understanding originating from much finer temporal or spatial scales. Upscaling – the scaling or application of knowledge and data from finer to broader scales or from shorter to longer timescales – requires insight, data, and models at various scales, types and complexity because the responses of soil processes to forcing factors are typically different on different spatial scales (O'Rourke et al, 2015). At fine scales, the response might be related to a specific landscape or climate attribute. When aggregating over broad spatial scales, however, information on the relationship between the driver and the response may be lost or obscured. One such example is the apparent control of temperature, rather than precipitation, over tropical and global ecosystem fluxes (Cox *et al.*, 2013; Wang *et al.*, 2013; Wang *et al.*, 2014). The smaller apparent role of precipitation globally or across the tropics results from large spatial heterogeneity in precipitation. Unusually dry and wet regions cancel each other out when averaged globally, which can obscure an often stronger local/regional precipitation control of ecosystem fluxes (Ahlström *et al.*, 2015; Jung *et al.*, 2017).

Long-term changes in SOC are particularly difficult to capture with measurements. Fluxes of heterotrophic respiration, for example, can be measured only at fine spatial and temporal scales

(Bond-Lamberty et al., 2016) whereas observing short-term changes in SOC pools is reduced to detecting small changes relative to a large pool of bulk SOC (Stockmann et al., 2013). While radiocarbon measurements suggest that the majority of bulk SOC is much older (He et al., 2016), and hence not very active, long-term changes in SOC storage could be governed by processes other than those that determine short term fluxes. It is increasing clear that understanding changes and variations in SOC requires a robust understanding of processes and mechanisms that underlie stabilization, protection, and destabilization of SOC.

Understanding mechanisms underlying storage and (de)stabilization of SOC

Changes in SOC are generally based on assessments of stocks and some metric of turnover, residence, or transit time (Sierra et al. 2017 ; He et al, 2016). Assessments of SOC stocks and transit times remain a critical constraint on the ability of models to predict CO_2 exchanges and their responses to environmental and land use pressures (Todd-Brown et al, 2013). Advancements in measurements and numerical models must be grounded in our best understanding of the processes controlling SOC dynamics across scales (Hinckley et al, 2014).

Currently, most global model frameworks rely on state-factor theory (Campbell and Paustian, 2015), where soil properties are the product of a suite of factors including climate, biota, topography, parent material, and stage or age of pedogenesis (Jenny,1941), superimposed with major land uses such as deforestation or agriculture (Amundson and Jenny, 1991). Under this framework, global-scale spatial heterogeneity of SOC is a direct reflection of variation within these factors and, accordingly, will vary with climate and land use change. A quantitative and predictive understanding of how soil and ecosystem properties interact to regulate SOC remains elusive due to interactions and interdependencies of the state variables with local-scale physicochemical, and biological processes that also influence the (de)stabilization of SOC.

Mechanisms of C stabilization and destabilization are of particular importance for establishing a predictive understanding of SOC dynamics because these same mechanisms presumably drive vulnerabilities (to emission) and opportunities (accumulation or sequestration) under changes in climate, management, or other disturbances. A quantitative understanding of SOC pool dynamics requires a quantitative understanding of both processes and mechanisms leading to (de)stabilization. A process represents a fundamental sequence of actions or steps that leads to a particular outcome, whereas a mechanism reflects the combined interaction of processes (Fig. 2). Processes are often more directly measureable than mechanisms and, therefore, a more fundamental construct for incorporation into models. We tend to classify mechanisms of SOC (de)stabilization as being primarily biological, physical, or chemical (Six et al., 2002; Fig. 2), but many mechanisms cross these boundaries due to interactions among processes. The past two decades brought substantial advances in our conceptual understanding of mechanisms of SOC (de)stabilization (Schmidt et al., 2011 and Lehmann and Kleber 2015). Yet, quantitative representations of these concepts in global and regional models lags, due in part to a lack of data synthesis to connect concepts and models, as well as a lack of incorporation of local-scale understanding of SOC dynamics.

Understanding the mechanisms of SOC (de)stabilization, the underlying processes driving soil change, and the relationships between processes and drivers at various spatial scales is needed to evaluate potential changes in SOC stocks. To address this need, an emerging priority is to conduct and synthesize manipulative field, greenhouse, and laboratory experiments that specifically target processes and drivers at a variety of spatial and temporal scales (see section 2.2. and Fig. 3). Examples include experimental manipulations that target specific processes, such as the Detritus Input and Removal Treatments (DIRT) that manipulate organic inputs to soil (e.g., Lajtha et al. 2014), the international Soil Experimental Network (iSEN) that warms deep soil (Torn et al. 2015), Drought-Net that manipulates precipitation, as well as natural environmental gradients of temperature and soil moisture (Giardina et al. 2014). By coupling broadly distributed and comparable data synthesis efforts with process-based models, we have the opportunity to capture mechanistic understanding and to constrain the SOC storage and its sensitivity to disturbance.

Prioritizing soil data to empower our science

There are many types of data, beyond SOC stock data, used to investigate C dynamics at different spatial and temporal scales (Fig. 3). Data consolidation and archiving efforts so far have focused principally on SOC stocks (e.g. Batjes et al. 2016; Scharlemann et al. 2014), but SOC stocks typically change slowly over timescales of decades to millennia, providing limited sensitivity for investigating shorter-term processes such as land use and climate impacts (Jastrow et al. 2005; Kravchenko and Robertson 2011; Phillips et al. 2015). At the same time, technique advancements over the last several decades have seen an escalation in methods pertinent for investigating SOC change at shorter timescales (Fig. 3). For instance, utilization of the enriched atmospheric ^{14}C signal (“bomb C”) has allowed tracing and dating of SOC at annual timescales (Trumbore 2000). Density and size fractionation techniques have helped to distinguish more rapidly cycled SOC from protected, less rapidly-cycled C (Jastrow 1996, Kong et al. 2005, Gregorich and Janzen 1996). More recently, *in situ* chemistry techniques have been used to investigate SOC transformation over timescales of hours to days (Mackelprang et al. 2016; Haggerty et al. 2014).

The many of the data types that are most relevant for measuring SOC change at experimental timescales, however, have not been consolidated and are generally not archived, thus impeding two of the more important lines of inquiry in SOC science, namely 1) the biochemical mechanisms of SOC stabilization and destabilization, and 2) the anticipated impacts of changing climate and land use (see top panels of Fig. 3). Part of the challenge in assembling and archiving diverse SOC data types is social--they are collected by different sub-communities of soil science and microbiology, and part is logistical--the data have different structures and storage formats (see Supp. Material SM4). Nevertheless, some of these data types have been widely collected, and archiving efforts could open several novel research opportunities.

For instance, the soil-to-atmosphere CO_2 flux (soil respiration or R_S) is one data type that has been measured extensively and offer a unique window into terrestrial carbon dynamics at fine temporal and spatial resolution where questions about temperature, moisture sensitivity and respiratory pathways are addressed (Fig. 3). The main reason field Rs is not used in model validation is because it spans two sub models which are generally developed in isolation (vegetation and soil). Field-based, in-situ *Rs* data provide an instantaneous measurement of root respiration and soil metabolism, whereas laboratory incubations potentially can isolate soil metabolism from root respiration. While a considerable effort has been made to synthesize seasonal and annual averages for field-based R_S fluxes (e.g., Bond-Lamberty and Thomson, 2010a), flux datasets including isotopic measurements (isofluxes), time series and experimental manipulations that include soil moisture, and laboratory-based incubation data have only sparingly archived in centralized repositories (e.g.; Kim et al., 2012). Field-based R_S data have been used only sparsely for soil C model validation (Wang et al., 2014) or model benchmarking (Shao et al., 2013) despite having characteristics ideal for these purposes; they reflect fundamental metabolic processes, are geographically widespread, and do not require extensive post-observational processing. High-temporal-resolution R_S data may also present unique possibilities for constraining and validating fluxes inferred from eddy covariance (Phillips et al., 2016) and spatiotemporal analyses (Lavoie et al. 2014; Leon et al. 2014). Finally, because soil-to-atmosphere C fluxes (in particular soil heterotrophic respiration) cannot be directly measured at scales larger than ~1 m^2 (Bond-Lamberty et al., 2016), data compilations have enormous value for upscaling and for synthesizing our understanding of soil metabolism. While R_s is but one example of data that will help meet challenges for characterizing SOM and SOC, their relevance to mechanistic questions of SOC (de)stabilization has the potential to address higher level questions related to landuse practices, policy, and long-term consequences of change (Fig. 3).

Land management and its potential to increase SOC: an emerging priority

Increases in SOC play a key role in climate regulation through sequestration of CO_2, but there also co-benefits relevant to land managers through increased land yield, soil water retention, resilience to extreme weather and nutrient retention. Land managers are primary agents governing changes to SOM and SOC stocks, thus in order for scientists to help shape and drive more successful and scalable practices, it is important to view SOC research as a social enterprise as well as a scientific enterprise.

Successful management of SOC requires collaboration among scientists, land managers, landowners, and policy makers. A science-land manager-policy partnership can be initiated at any stage of a problem, for example as a science question or a land management challenge. One example (Fig. 4) starts with research question and tethers field/lab experiments to ecological and social issues important to land managers. Seeking feedback from stakeholders at each phase of inquiry also generates new inquiries, which can be visualized in Fig. 4 as movement from right to left on the research-to-policy progression. A cooperative research approach introduces more sources of feedback and points of iteration than an isolated scientific process, but is instrumental for influencing SOM management practices.

Grazing lands (rangelands) represent a largely untapped global potential for SOC sequestration as they occur across a wide range of bioclimatic conditions, cover ca. 40% of ice-free land and store ca. 30% of the terrestrial SOC pool to 1 m depth (Fig. 1) The global potential for rangeland C sequestration has been estimated to range from 0.3 to as much as 1.6 Pg CO_2-eq yr^{-1} (Paustian et al, 2016). Many grazing lands have degraded SOC stocks due to historic poor management practices and changes in land use intensity. Stocks of SOC in grazing lands are vulnerable to losses through erosion, compaction, and reductions in plant C inputs from plant community shifts or overgrazing. Improved grazing, irrigation, plant species management, and the use of organic or inorganic fertilizers of these lands can significantly increase soil C stocks (Conant et al. 2017). Application of composted organic waste streams has been demonstrated to be an economic and beneficial proactive that contributes to both rangeland productivity and climate regulation (Ryals et al 2013, DeLonge et al. 2013; see SM5). Lifecycle assessments, in which broader implications for land management are tracked, (e.g., the waste management and energy systems; DeLonge et al. 2013) and other ecosystem services and values (e.g. biodiversity or endemic plant impacts) are also important issues that drive land management choices.

Forest SOC management often focuses on minimizing losses to erosion and disturbance and less on building SOC through residue and vegetation management, as is common in grazinglands and croplands (Binkley and Fisher 2013). While there are robust, broadly consistent methods for accounting for and predicting future C stocks in forest aboveground biomass, there is less consensus on methods for assessing belowground SOC. Long-term monitoring (Johnson and Todd 1998; McLaughlin and Phillips 2006), experimental manipulation (Edwards and Ross-Todd 1983; Gundale et al. 2005), expert review (Jandl et al. 2007; Lal 2005), quantitative synthesis (Laganiere et al. 2010; Nave et al. 2010), and ecosystem modeling (Kurz et al. 2009; Scheller et al.

2011) have all produced valuable insights into forest management impacts on SOC. At the same time, the many conflicting results of these studies raise the question of whether responses of SOC to forest management can be generalized across soil and ecosystem types. In addition, the lack of spatially explicit assessments (e.g., maps, geostatistical models) of forest management impacts on SOM highlights our challenge to quantify SOC stocks and the complex spatiotemporal processes involved in scaling. Given these limitations, methods of quantifying the spatial distribution and controls on forest SOM across scales are needed for forest practices. These applications may be aided by promising advances in digital soil mapping (Mansuy et al. 2014; Mishra and Riley 2015) and spatially explicit soil carbon assessments (Domke et al. 2017; Soil Survey Staff 2013).

Croplands have been managed for more than two decades in ways that benefit soil conditions and reduce greenhouse gas emissions (e.g., Smith et al. 2007, Paustian et al. 2016). There are many practices influencing SOC storage in croplands. These include tillage management (in some cases, Powlson et al. 2014); crop rotations and cover crops (Poeplau and Don 2015); improving crop production through fertilization and irrigation management; selection of high residue-yielding crops; crop intensification by removing bare-fallow management in a cropping system; application of silica residues to reduce greenhouse gas emissions (Gutekunst et al. 2017), and application of organic amendments with manure or biochar.

Despite existing knowledge, there is a limited ability to accurately estimate the changes in SOC, particularly at smaller scales (Ogle et al. 2010, Paustian et al. 2016) . For example, mechanistic understanding such as the effect of tillage management on aggregate dynamics (Six et al. 2000), has not been effectively incorporated into modelling frameworks. Biochar amendments have emerged as one of the most promising practices for sequestering C in agricultural soils (Lehmann, 2007), but there are still questions about the impact of biochar on SOM dynamics (Knicker, 2011). Efforts to incorporate agricultural SOC sequestration into policy programs have been plagued by lack of understanding about the longer term impacts of pervasive warming on SOC pools (Conant et al. 2011), which could vary widely depending on the response of microbial communities (Wieder et al. 2015).

The ISCN as a platform for communication, modeling, and data

While science communities targeting soil health or climate regulation are making great strides in the science of SOC, a combined and coordinated effort could take advantage of technological and communication advances to meet challenges discussed in section 2. The International Soil Carbon Network or ISCN along with partnering entities seeks to establish the basis (platforms) by which we share openly our means of communication, modeling, and data sharing.

Communication of our science starts with restructuring and broadening the soil data that are shared within and by ISCN, allowing for different types of data, and discovering new ways to share data without compromising its attribution and credits. To increase the potential impact of SOC science and to better impact land management practices, it also is beneficial to frame and disseminate our information in the context of both soil health and climate regulation. For example, given some knowledge of the dominant processes leading to C stability in a given soil (path A, Fig. 5), one may evaluate which disturbances may release SOC and what measurements would mitigate SOC losses. Conversely, we may apply this framework in the reverse direction. Given some ongoing or historical management practices (path B, Fig. 5), we can work inward and to assess what processes could be most affected. Carbon cycle science can also be reframed from the biological, chemical and physical processes paradigm presented in Fig. 2 to a land management perspective (Table 1). See supplementary materials SM2 for more precise definitions and references.

Modeling with computational and conceptual paradigms is an integral part of the scientific process that greatly enhances our ability to understand variations among spatial and temporal scales and to precisely and accurately estimate and predict changes in SOC. Conceptual paradigms that form the scientific basis for our computational models were initially based on “humification” processes (Hedges, 1988; RothC model (Jenkinson and Rayner, 1977) and Century model (Parton et al., 1987). The community is increasingly recognizing the role of microbial access to SOC and its stabilization involving specific mechanisms described in Fig. 2 (Jastrow et al. 1996, Six et al. 2000, Kaiser and Kalbitz 2012, Averill et al. 2014, Keiluweit et al. 2015, Cotrufo et al. 2015, Lehmann and Kleber 2015). Measurements used to drive and test these models vary and are often not structured experimentally to test one model over another. As discussed above in section 2, issues of **spatiotemporal scaling** must address whether mechanisms and functions change or vary between spatial and/or temporal scales. Thus as models increasingly incorporate these new ideas into mathematical frameworks, new paradigms can emerge (e.g., Allison et al. 2010, Wieder et al. 2013, Sulman et al. 2014). Moreover, soil datasets and databases are needed to evaluate models (Todd-Brown et al. 2013, Shao et al. 2013). The ISCN strives to openly share modeling code and specific parts of models along with data used to drive and test model performance.

In addition to simply sharing model codes, it is also becoming clear that a **community-based model** could emerge from the soils community. In particular modular frameworks with water, temperature, and plant production modules would allow for “plug and play” with new SOC modules that are under development. Plug and play modules would not likely be the focus of development, but are needed to realistically simulate SOC dynamics from experiments and regional analyses. The design of such supporting modules could be informed by or rely on recent progress with multi-model comparative frameworks (e.g. PeCAN project http://pecanproject.github.io/index.html). As new models are published and shown to work better than the existing SOC community model, the community model would be replaced with improved mathematical frameworks for SOC dynamics. In turn, scientists and investigators evaluating SOC dynamics could incorporate the latest science embodied in the SOC community model housed on the platform into their assessments. ISCN would effectively encourage the use of the latest science in national assessments such as evaluating climate change impacts, greenhouse gas emissions and soil health (e.g. Ogle et al., 2014).

As soil or belowground datasets are collected, compiled, and assembled for specific questions or assessments there is an emerging opportunity for **Big soil data** to be incorporated into a searchable database for soil properties, and serve as a platform for syntheses of soil dynamics and large spatial and temporal scales. Empirical models could be structured from a searchable, robust database, but we could also challenge our conceptual and computational models with robust data. The ISCN network database (http://doi.org/10.17040/ISCN/1305039 or http://ameriflux-data.lbl.gov:8080/ISCN/DOI.html.) afforded early opportunities to design common data templates, promote data synthesis, and generate publications. The ISCN-gen3 database **(http://ameriflux-data.lbl.gov:8080/ISCN/DOI.html)** is poised to move beyond observational soil point data and associated drivers, and into the realm of process-level attributes such as soil fractions and spectral data. These data types have been envisioned and piloted since its earliest generations, but have only recently gained attention and use among the broader community of scientists interested in SOM .

Currently the ISCN database has a mix of overlapping and unique data as compared with other databases (Supplemental Material SM1). For example, most closely aligned are the World Soil Information Service (WoSIS) and ISCN, both of which report soil profile data but for different attributes: The ISCN reports over 100 (carbon plus other attributes) soil properties for ~70,000 profiles and their constituent layers, whereas WoSIS reports 12 properties for over 150,000 profiles. ISCN currently hosts solid phase attributes for soil, and the data are structured in a way compatible with ecosystem CO_2-land-atmosphere flux data served by the FLUXNET and AmeriFlux networks. Despite the large number of soil profiles included in both WoSIS and ISCN, however, there remains an enormous amount of un-archived soil data. Compiling and harmonizing these data could help answer questions of C turnover; soil properties related to mechanisms controlling SOC (de)stabilization; soil respiration fluxes in context of soil and environmental measurements; and metrics of pools or forms of bioavailable vs non-available SOCC.

This so-called ‘long tail’ of data has been identified in other fields (Dietze 2013) and represents data that have been collected but, for one reason or another, are not easily available for re-analysis or syntheses (Wolkovich, Regetz, and O’Connor 2012). A comparison of literature and data repository records suggested that process and biological data are underrepresented in repositories, relative to descriptive, chemical and physical data (Suppl. Materials Figure SF1, methods in supplementary materials SM3). Comparison of the top keywords in the literature to data repositories suggested that other data types ripe for synthesis in context of SOC include soil incubation and temperature sensitivity, soil chronosequence studies, wildfire emissions/retention, nitrogen and phosphorus cycling, root and fungal dynamics, and soil microbiology. For example, a soil carbon-related data repository search suggests that only 1% of the entries in the broader literature have been archived in data repositories (Suppl. Materials SM3). Therefore rescuing data from the literature and making them accessible and compatible with other contributions and databases is a high priority, and particularly important given that climate change effectively makes older soil observations irreproducible (Wolkovich, Regetz, and O’Connor 2012).

Harmonizing disparate datasets poses unique challenges due to the diversity in types of measurements and their associated methods, unlike larger national and regional survey campaigns which operate under a single protocol. For example, the Biomass And Allometry Database (BAAD) (Falster et al., 2015) has been a highly successful example of a community-based data aggregation effort. Public repositories, including Dryad, FigShare, and ORNL DAAC, have emerged and enjoyed enthusiastic support. As these data repositories have grown, issues around discoverability have emerged such as getting people in a common community to agree on a common technical vocabulary has been challenging. Many efforts (e.g. DataONE) have focused on semantics and linked many of these repositories in a unified search framework. Finally, data harmonization is required not only for typical data cleaning operations like correcting unit mis-matches and transparent reproducibility, but also to reconcile different methods and evaluate reliability. This final step requires not only computational skills but also domain expertise.

Interoperability of ISCN

While these international efforts of the ISCN gain momentum, there are parallel requirements to coordinate and share technology, data, protocols, and experiences to maximize resources and generate knowledge. Arguably, this can only be achieved by increasing interoperability within ISCN and among partner networks, organizations, and members. Interoperability is broadly defined as the ability of a system to work with or use the parts of another system (Chen et al. 2008; Vargas et al. 2017).

Challenges related to conceptual barriers include syntactic and semantic differences in the types of information (Madin et al. 2008); technological barriers such as incompatibility of information technologies (e.g. methods to acquire, process, store, exchange, and communicate data; Peters et al. 2014); organizational barriers related to current institutional responsibility and authority such as with institutions, networks, or governments (Supp. Table ST3); and cultural barriers that can be country-specific but must be considered to increase interoperability of networks (Vargas et al. 2017).

Conclusions

Soils have entered an ‘anthropogenic state,’ with most of the global surface area either directly managed by humans or indirectly influenced by human activities. As a result, soils globally have lost SOC since at least the Industrial Revolution, with direct impacts on climate, ecosystem productivity, and resilience to disturbance. There is a crucial need to improve our science and to communicate our findings. In this paper, we identified the following goals: (1) identify key data needed to improve our detection soil organic matter and SOC trends using our understanding of SOC stabilization and destabilization mechanisms, (2) set up communication and sharing infrastructure to rescue, centralize, and disseminate currently disparate soil datasets relevant to critical soil processes, (3) develop a robust and modular modeling platform for comparing process-based models that would move field data and localized experiments into a framework to test Earth System processes at local to broader scales and (4) improve the connection between soil C-cycle science and land management science and practices. These goals can be achieved through improving the exchange of ideas, data, modeling tools, and by sharing information and supporting other networks, organizations, and institutions.

Processes that influence changes in SOC have been defined and quantified over the past several decades, and metrics for soil health, degradation, and storage are beginning to reflect the interdisciplinary science needed to link soil/land/ecosystem/crop productivity to CO_2 budgets at various scales. Growing populations, increased land use, and intensified land use compel us to merge the sciences of soil health with SOC biogeochemistry. The current state of our soils, as well as the opportunities and vulnerabilities that result from different land management practices, are of particular importance. In addition, quantifying the optimal SOC storage capacity of soils would provide a benchmark to further assess human impact on soils and help quantify potential benefits of altered soil management practices.

Acknowledgments:

This article resulted from a weeklong workshop funded by Stanford University Earth System Science held in Feb. 2017 by the first 15 authors (listed alphabetically after the two lead authors) and from additional participation by the remaining authors. We thank attendees of the ISCN all-hands meeting Dec. 11, 2016 held in San Francisco; Ankur Desai, and Marjorie Schulz, and members of the John Wesley Powell Center for Analysis and Synthesis Working Group "What lies below? Improving quantification and prediction of soil carbon storage, stability, and susceptibility to disturbance," for their supportive and constructive ideas; and USDA Forest Service, the U.S. Geological Survey, the Bolin Climate Research Center at Stockholm University for support. G.H. was supported by the Swedish Research Council (E0641701) and the EU JPI-Climate consortium COUP.BBL was supported by the Office of Science of the U.S. Department of Energy as part of the Terrestrial Ecosystem Sciences Program. KTB was supported by the Linus Pauling Distinguished Postdoctoral Fellowship program at the Pacific Northwest National Laboratory.

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Table 1. Linkages between soil health indicators and SOC. Soil health indicators are readily-measured soil properties that are used to diagnose the ability of soil to provide services such as nutrient cycling, erosion mitigation, water storage, or microbial activity. Many of these soil health indicators relate directly to SOC content, and many can be ameliorated through restorative practices that increase SOM and SOC. For all examples listed, the practices that enhance soil health also restore (and enhance) SOM and SOC, thus what is good for the goose (soil) is good for the gander (atmosphere). Based on these example, scientists and land managers can readily agree that management practices that protect, promote, and conserve soil carbon are practices that prevent erosion, provide and preserve water and nutrient capacity.

Health Indicators	**Functional Problems**	**Explanatory C Variables**	**Restorative Practices**
Physical			
Microaggregate Stability	Erosion, Compaction	Root growth, fungal biomass, biological crusts	Conservation tillage, "no-till"
Water Infiltration Rate	Low infiltration, erosion	SOM content	High residue inputs, cover crops, conservation tillage
Water Holding Capacity	Arid region water management	SOM content	Organic matter additions
Chemical			
Potentially mineralizable N	Poor fertility	Potentially mineralizable C	Fertility management
Available P	Poor fertility	Applied organic matter	Fertility and pH management
Biological			
Microbial Biomass C	Limited soil life	Applied organic matter, root biomass	High residue inputs, conver crops, conservation tillate, "no-till"

Figure 1. Soil organic carbon stocks and areas currently under land use practices. (a) Spatial variability of soil SOC stocks in the upper meter of soil (where 1 kg C m^{-2} = 10 Mg C ha^{-1}) , based on the WISE 3.1. database (Batjes, 2016). (b) Fractional human use of the land surface through forestry, grazing and agricultural crops based on the data by Erb et al. (2007); grey areas represent unused land. (c) Global SOC stocks (0-1 m) distributed under different land-use categories. (d) Potential opportunities for gross annual SOC sequestration in presently managed forest, crop, and grazing lands (assuming average management C gains of 0.04 kg C m^{-2} yr^{-1} with error bars showing the range of 0.01-0.07 kg C m^{-2} yr^{-1}; Minasny et al., 2017) could compensate for total

emission projections from permafrost-C due to the climate feedback (Koven et al., 2015; mean and range of projection until 2100 under RCP8.5) and the projected impact of “human land use”, defined as land use change, agricultural representation, crop harvest, and management (Pugh et al., 2015; mean and ensemble range of projection until 2100 under RCP8.5). Note that harvest from forestry is not included in this last projection.

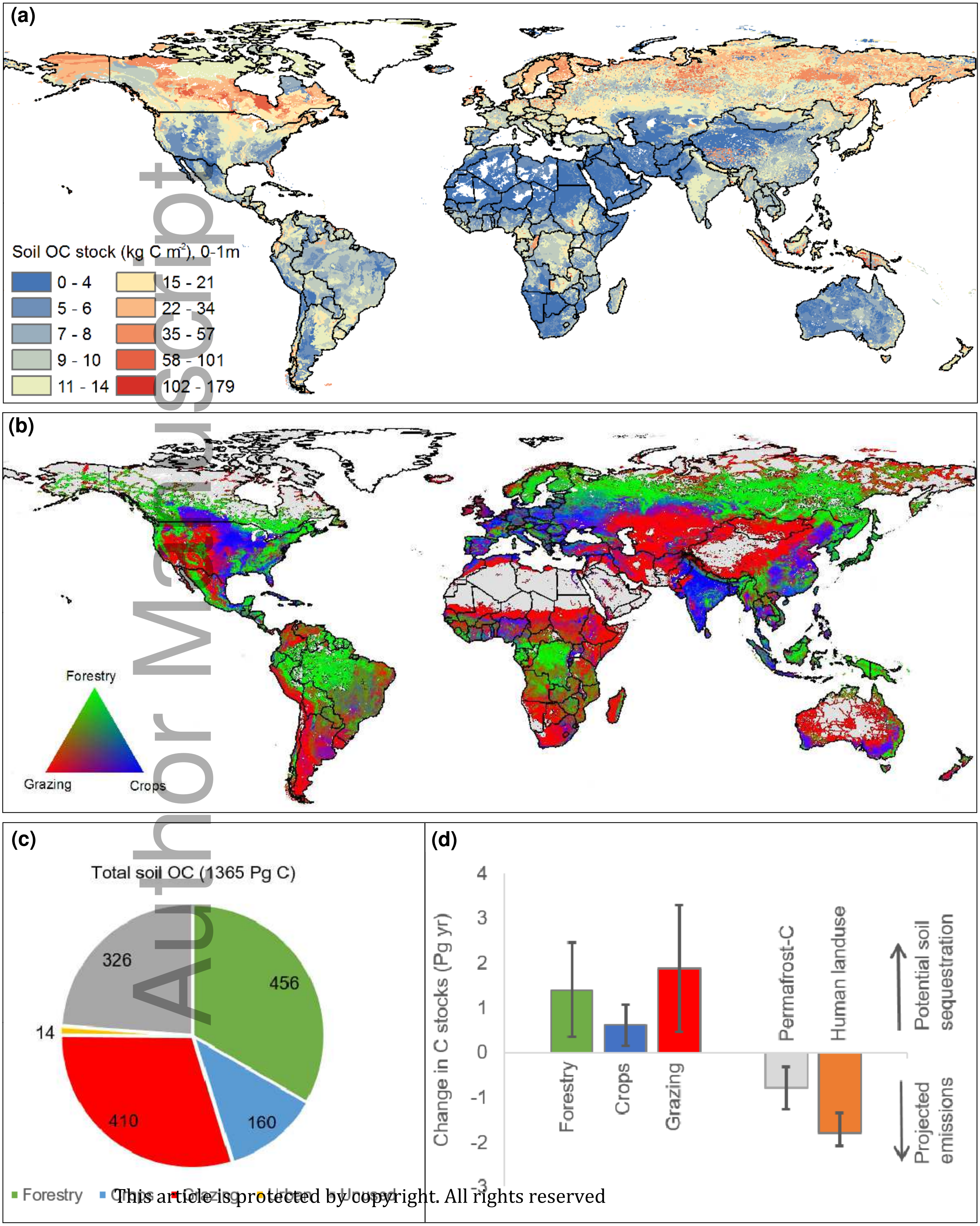
Figure 2. Processes controlling SOC pools and the mechanisms involved in stabilizing SOC. Isolation = physical disconnection (e.g. Schimel & Schaeffer 2012); Cryo = cryopreservation; Pyrogenesis = fire residues; Mineral = mineral interaction; Inputs = microbial and plant residues that influence desirability or access to microbes (e.g. Kallenbach *et al*. 2016 *Nature Communications*); Nitrogen = nitrogen or other nutrient limitations (e.g. Averill *et al*. 2014 *Nature*)

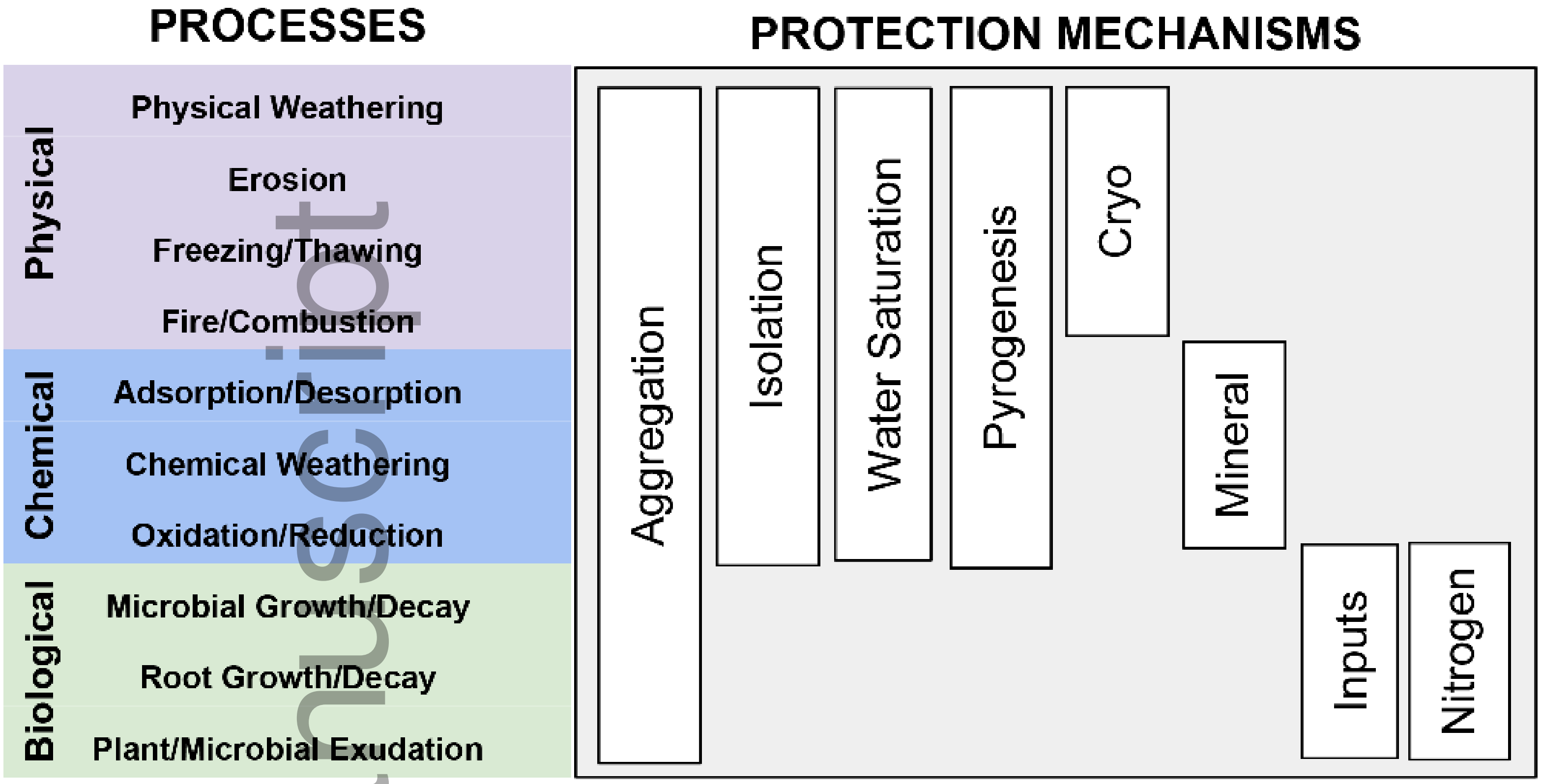
Figure 3. Example research questions and datasets useful for investigating SOC change at different timescales. Blue lines indicate relevance of the topic and question to the timescale of measurement. Colors for measures indicate status of data archiving efforts. Measurements can be well aggregated in centralized repositories (green), have had limited compilation (yellow), or have had very limited compilation (red). R_S, soil respiration; R_H, heterotrophic respiration; ^{13}C n.a., ^{13}C natural abundance; TBCA, Total belowground total allocation; POM, particulate organic matter.

Figure 4. Creating conditions to optimize the effectiveness of land use to sequester SOC . Actors involved in managing lands for soil management change in response to the scale and level of information needed. Evaluating and implementing practices (Y axis) starts with scientists working with land managers and propagates through broader spatial scales and policies as goals are defined, communicated, and met. Major actors can vary with each step, with activities shown in the gray boxes. Arrows represent flows of information. In this example, the step-wise progress from local to more regional scales represent the increasing opportunity to impact both productivity and CO_2 sequestration through soil C sequestration.

Figure 5. An approach for applying management options to the science of SOC (de)stabilization. Three general classes of soil carbon (de)stabilization processes (biological, chemical and physical) are fundamental to understanding the susceptibility of soils to disturbance (e.g., compaction and erosion, etc). As such, knowledge of the relevant mechanism at play for a given soil can inform key measurements needed (e.g., soil infiltration and sediment transport) and effective management strategies (e.g., diversify vegetation/minimize use and plant stabilizing vegetation/control runoff).

Fig 6: Examples of organizations, groups or entities addressing data, modeling and management relevance of soil carbon. These currently disparate niches need bridging to address complex problems in soil C science. The soil community is data- and knowledge-ready for a platform like ISCN that can bridge data, tools, best management practices and outreach. We propose a way forward to improve soil C data curation with a focus on process variables, which can be applied into a community model framework and actionable science that harnesses mechanistic understanding to address questions on soil health management.


(a)
Soil OC stock (kg C m-2), 0-1m
0 - 4
5 - 6
7 - 8
9 - 10
11 - 14
15 - 21
22 - 34
35 - 57
58 - 101
102 - 179
(b)
Forestry
Grazing
Crops
(c)
Total soil OC (1365 Pg C)
456
160
410
14
326
Forestry
Crops
Grazing
Urban
Unused
(d)
Change in C stocks (Pg yr)
4
3
2
1
0
-1
-2
-3
Forestry
Crops
Grazing
Permafrost-C
Human landuse
Potential soil sequestration
Projected emissions



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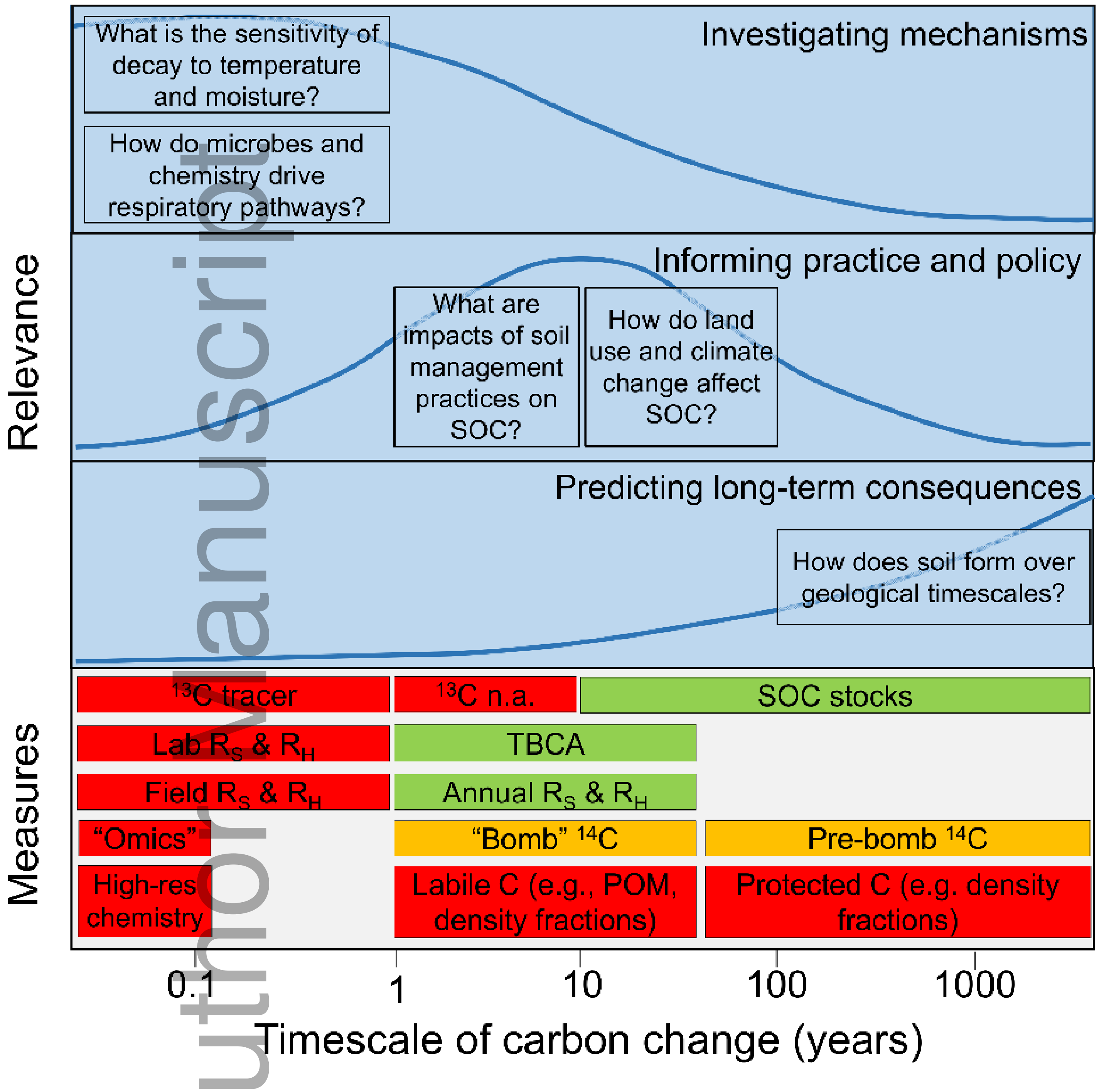

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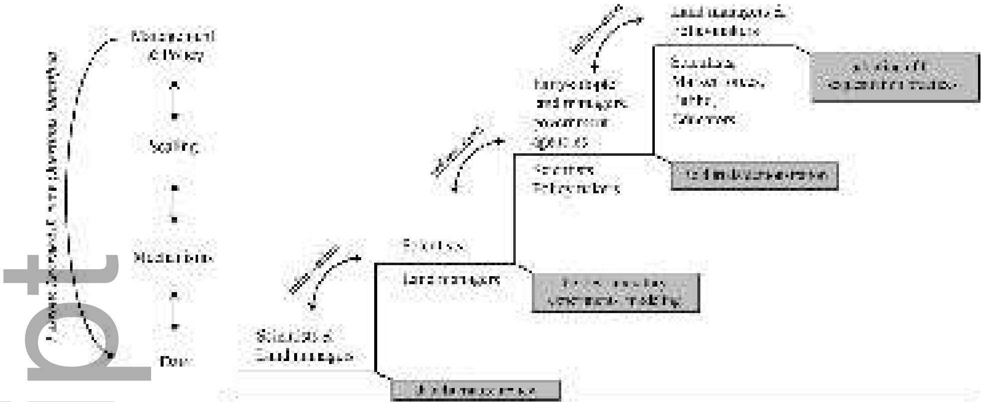

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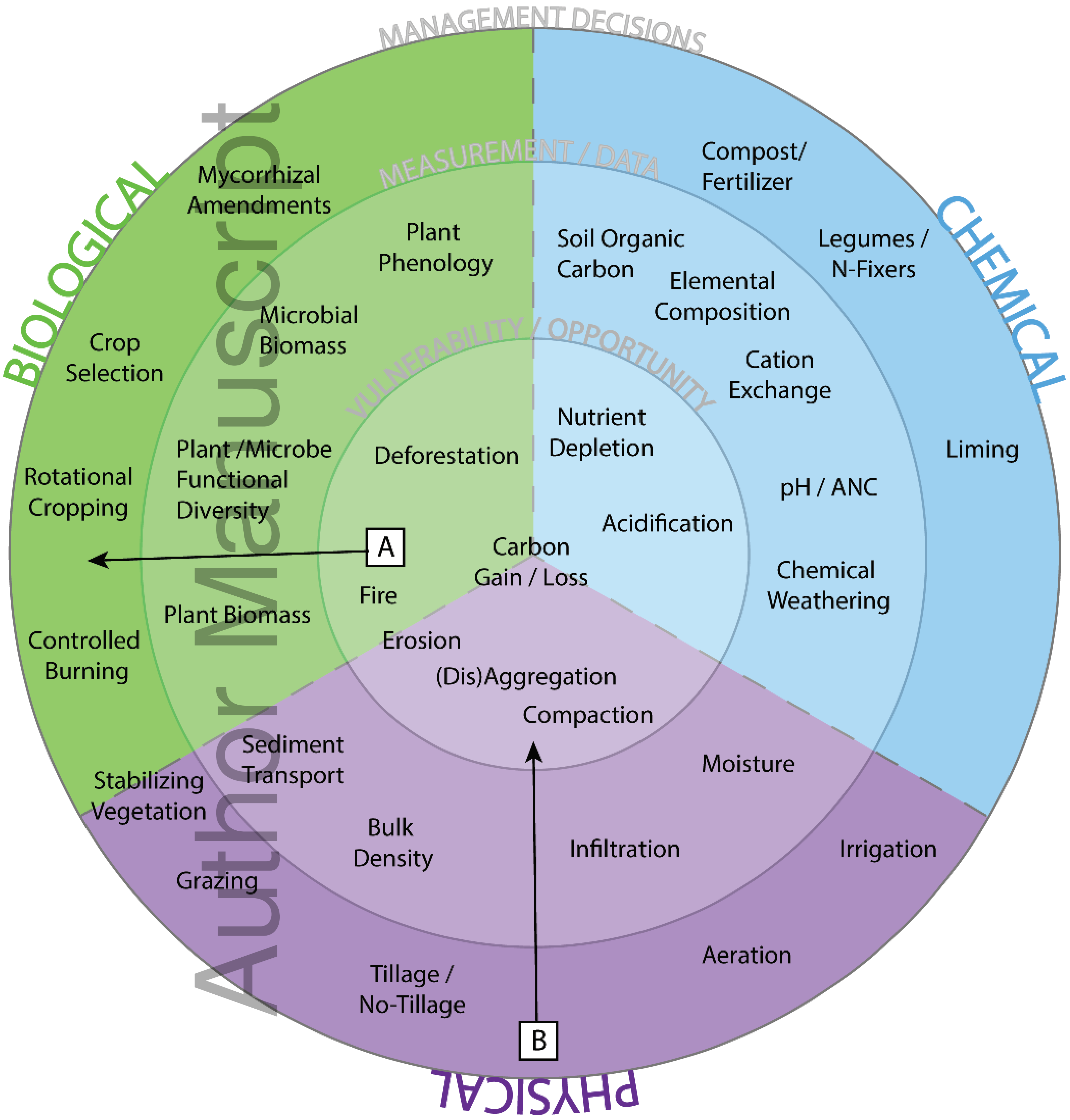

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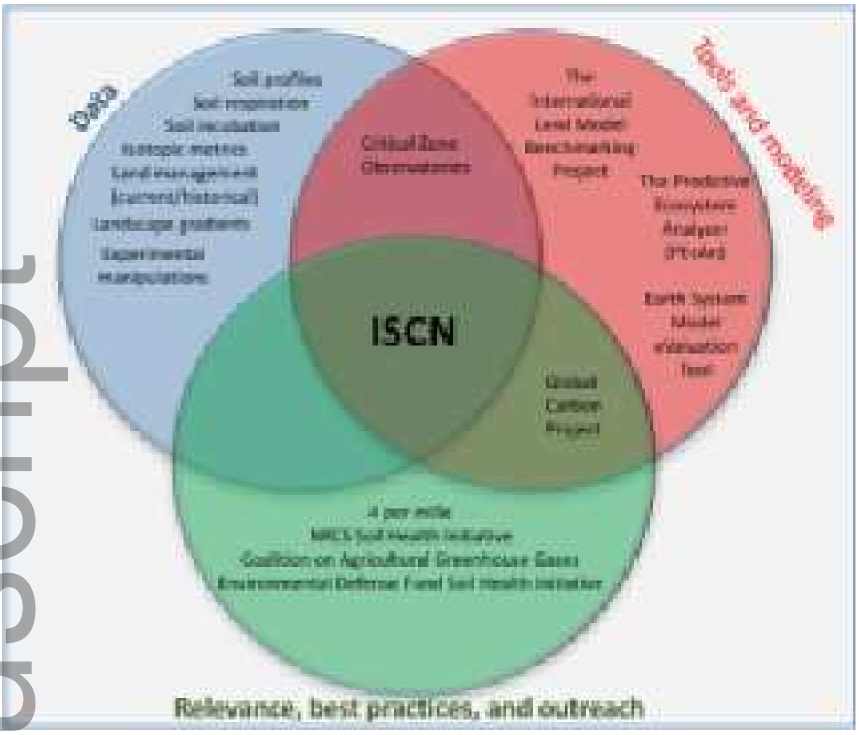

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