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ISSUES

Forming regional soil carbon networks to support effective climate change solutions

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Abstract

Sequestration and storage of organic carbon (C) in soil is an essential component of climate change mitigation and fundamental in promoting the health and climate resilience of soils. Sources of available soil C data are increasing, which complicates efforts to consolidate the data in forms that can be readily used by stakeholders. Spatial and temporal gaps in data availability also limit the quantification of changes in soil C through space and time. Improved coordination among producers and users of soil C data would provide data compatibility at the spatial and temporal resolution required for C monitoring, accounting, and verification of policy implementation. These challenges can be addressed by forming regional-scale networks to coordinate the collection and use of soil C data by promoting consistency in methods, collecting new data to fill critical gaps, integrating existing data from multiple sources, and providing data interpretation to stakeholders in readily usable forms. Forming networks in regions such as the Northeastern United States would require close

Abbreviations: GHGs, greenhouse gases; IPCC, Intergovernmental Panel on Climate Change; NESMC, Northeastern Soil Monitoring Cooperative; SOC, soil organic carbon.

coordination with existing programs that are involved in collecting or aggregating soil C within that region. Network formation could be accomplished by (1) producing a planning document, (2) designing a network structure tailored to the region, and (3) acquiring the institutional support to establish and operate the network. Increasing the availability and usage of soil C data through regional networks would support the development of climate change solutions and increased ecosystem services through land management efforts that increase soil C storage.

1 | SOILS AS A COMPONENT OF CLIMATE CHANGE SOLUTIONS

The Intergovernmental Panel on Climate Change Assessment Report 6 (IPCC, 2023) makes clear that global warming is on track to exceed pre-industrial temperatures by >1.5˚C, resulting in severe global consequences. However, this report also makes clear that accelerated reductions in emissions of greenhouse gases (GHGs) and technologies to remove CO_2 from the atmosphere offer opportunities to constrain the negative effects. Furthermore, the region-specific characteristics of many climate change effects are becoming well recognized (Howarth et al., 2019), as is the need for action at regional, state, and local levels (Fernandez et al., 2020).

To avoid or minimize warming that exceeds 1.5˚C, aggressive approaches have been recommended, such as removal of CO_2 from the atmosphere via natural processes that include fixation of carbon by trees that can eventually be stored in soils as organic matter (Paustian et al., 2016; Rogelij et al., 2018). Soils have been estimated to contain approximately three times the C stocks that occur in vegetation (Smith et al., 2020) and 75% of total terrestrial C stocks (Lal, 2008), although soils also exhibit substantial variation in C storage across latitudes, biomes, and regions that vary in climate, land-use history, and land cover. Collectively, soils offer great potential for lowering atmospheric GHGs through sequestration and long-term storage of organic C (Amelung et al., 2020; Minasny et al., 2017; Rumpel et al., 2020; Wiesmeier et al., 2019). However, soil C pools also present a risk if stores are decreased by land use practices or effects of climate change that alter complex processes of soil C cycling, retention, and release (Bossio et al., 2020; van Groenigen et al., 2014).

Closely coupled with the goal of increasing soil C storage to offset emissions of GHGs is the need to improve soil health to support a wide range of ecosystem services including basic needs for food production and clean water (Rumpel et al., 2020). Improvement of soil health generally involves increasing organic matter content, which enhances soil as a general ecosystem service, as well as providing a means to offset emissions of GHGs, which can also be included as an ecosystem service (Weng et al., 2022). In the United States, the dual benefits of increasing soil C storage to improve soil health and help mitigate atmospheric GHGs is helping to fuel federal initiatives to accomplish this goal (e.g., NSTC, 2016), numerous state initiatives such as the Massachusetts Healthy Soils Action Plan (MHSAP, 2020), and efforts by nongovernmental organizations such as the Soil Health Institute (SHI, 2023). This momentum toward better utilization of soil resources is resulting in an increased demand for data and soil science expertise from those who require these data for making policy and land management decisions but are often not soil scientists themselves.

2 | CHALLENGES TO PROVIDING NEEDED INFORMATION ON SOIL C STORAGE

Greater investments are being made to produce and use soil C data through the climate change response initiatives in the United States and other countries. These investments will achieve maximum benefit if they are directed at the least developed parts of the overall process that extends from the production of reliable, consistent soil data, to data sharing among producers and users, to expert synthesis of the information gained from these data. Below we identify some of the key challenges to successfully implementing this process. Ways to address these challenges to increase the use of soil C data are likely to vary across states and regions. The following list of challenges highlights areas that could be advanced by targeted allocations of resources.

1. *Soil carbon analyses are made with different methods in different laboratories with little or no standardization.*

One of the challenges to integrating data from multiple sources is the need for standardization. Efforts to address this problem have been initiated in various spheres including activities of the Intergovernmental Panel on Climate Change (IPCC, 2018). Methodological standardization across the conterminous United States was developed by the United States Department of Agriculture (USDA) Natural Resources Conservation Service in their Rapid Carbon Assessment Project (https://www.nrcs.usda.gov/resources/data-and-reports/rapid-carbon-assessment-raca) based on 17 regions. Analysis of agricultural soils has some degree of standardization across different laboratories, but methods used in studies of forest soils or other land use types generally have little or no standardization (Ross et al., 2015). Further work to develop and apply standardization procedures such as done by Ross et al. (2015) would greatly improve method compatibility of soil C data from differing sources within regions.

2. *Direct methods for quantifying soil C stocks require sampling designs that address variability that occurs with depth and horizontal area.*

Direct methods of soil collection commonly include coring from the surface and removal from the face of an excavated pit. Sampling a pit face is advantageous because the exposed soil profile enables the variability that occurs with depth to be visually examined (Lawrence et al., 2016). However, soil characteristics can also be highly variable across a landscape or land use type. This variability can be addressed by replicating sampling locations, but the degree to which areal variability is addressed through replication tends to vary among studies depending on their specific objectives (Lawrence et al., 2016). Direct sampling methods can provide a high level of accuracy and precision but require substantial project resources if they are to be applied over large areas with high soil variability.

3. *Quantification of soil C stocks needs to be mapped across varying landscapes and land-use types.*

As the scale of interest for estimating C stocks expands to states and regions, methods to propagate point measurements across the landscape need to be applied, ideally with spatial data that are digitally available. Mapped landscape properties that can be correlated with soil C can be used to approximate the areal variability of soil C, including variations with depth (Sulman et al., 2020). The success of this approach is likely to vary depending upon a number of factors related to the landscape of interest (e.g., minimal relief vs. rugged land surfaces), as well as the spatial resolution and predictive value of available data. How soil characteristics vary within the same locale versus across large-scale gradients such as climate is an important factor in extrapolating spatial data (Nave et al., 2021). Further work to quantitatively incorporate these concepts would advance methods for estimating soil C across landscapes and land-use types.

4. *Processes controlling soil C storage and release need to be more thoroughly understood.*

Storage of C in the soil is understood to be the result of multiple processes through which C is transformed from

Core Ideas

- Sequestration of C in soils is a potentially important climate change solution.
- Accurate quantification of soil C stocks is lacking.
- Soil C data are produced in incompatible forms that are difficult to use.
- Regional coordination would increase soil C data use in climate solutions.

aboveground plant litter and roots to litter residue and microbial biomass stored at various soil depths, with widely varying resistance to mineralization (Cotrufo et al., 2015). A better understanding of these interacting processes would be useful to develop approaches to enhance sequestration of atmospheric CO_2 without increasing soil emissions of other types of GHGs. Increasing the transfer of organic C into soil could potentially stimulate microbial activity under changing soil moisture and temperature conditions that could also increase gaseous emissions of methane (CH_4) or nitrous oxide (N_2O), thereby offsetting benefits of sequestering organic C (Oertal et al., 2016). The many ways through which soils cycle, store, and release C continues to be an area of intense scientific investigation.

5. *Little data are available on whether soil C storage is increasing, decreasing or stable in most land-use types.*

Human activity is well recognized as a dominating influence on our environment that has altered most if not all aspects of the natural world, including soils (Richter, 2007). Changes in soils have been recorded through numerous studies (Dror et al., 2022), but much of the direct documentation of long-term changes in soil C has been done in agricultural lands in studies such as those conducted in Rothamsted, England (https://www.rothamsted.ac.uk/). Limited understanding on how, and how fast, soil C storage may increase or decrease adds to the challenge of improving soil C management as well as the development of evolving soil C offset markets (Oldfield et al., 2022). Soil C monitoring programs outside of agricultural systems have not been sufficient to provide accurate quantification of changes in soil C on time intervals that could be used in management efforts (Lawrence et al., 2013).

6. *An understanding of relationships between ecological factors and the ability of soils to store organic C continues to be developed.*

Soil C stocks can vary considerably among soil types, and factors such as soil texture (Cotrufo et al., 2019) and vegetation (Ross et al., 2011) are often related to soil C stocks, but an understanding of what controls this variability is limited, particularly in nonagricultural soils. Controlling factors are likely to include land use history, soil management, climate, vegetation, and parent material (Bedison & Johnson, 2009). The ability to identify and map soils with the highest potential for increased C storage is a key element in efforts to enhance soil C sequestration.

7. *Investments in improving soil C storage for mitigation of GHGs are not well-coordinated with those directed toward environmental quality and other ecosystem services.*

One of the primary methods for improving soil health is to increase soil organic C, which increases nutrient and water retention, increases crop yields and forest productivity, reduces erosion, and limits nutrient loss to surface and ground waters. Increasing C sequestration in soils and reducing emissions of GHGs from soils can be added to this list of ecosystem benefits. The low organic C content of most croplands relative to other soils offers an opportunity for increasing storage of C in soils that are already being managed. Efforts to establish a C market for agricultural soils have begun through formation of private C registries, but these activities are directly focused on crediting C storage and protection (Oldfield et al., 2022). The degree to which improved C storage in agricultural or other types of soils would economically enhance the ecosystem services of soils is not well quantified even though the potential benefits are widely recognized.

3 | REASONS FOR ORGANIZING SOIL CARBON MONITORING AT THE REGIONAL LEVEL

An interest in better management of soil C to enhance C sequestration and improve soil health has led professionals from government agencies, academia, and the private sector to increasingly generate and use large amounts of soil C data from a variety of sources (Figure 1). However, even with the growing interest in soil C storage, the number of groups involved in monitoring changes in soil C is limited and strategies for increasing or maintaining C stored in soil are still in the early stages of development. Improved coordination among those producing and using soil C data could substantially increase the amount of information available to support effective actions at state, regional, and national levels, as well as by landowners and the private sector.

Soil C data are collected in a wide variety of forms, in part because much of these data have been produced for purposes other than to address climate mitigation issues. Soil C data have long been collected to evaluate agricultural soil resources, help select farming practices to maximize agricultural efficiency, and reduce negative environmental effects of farming activities. These data are valuable for developing strategies to both enhance agricultural production and increase C stocks in soils where depletion of soil C is greatest due to past practices (Rejesus et al., 2021; Smith et al., 2020), but often are only available for the uppermost mineral soil (Ap horizon). The societal importance of agricultural soils has led to much greater collaboration and transfer of information between organizations and farmers than what is occurring for soils of other land uses and is now being reflected in efforts to also use agricultural practices to support climate change solutions.

Outside of agricultural land use, ecological research programs in the United States have provided decades of research on the dynamics of soil C in managed and unmanaged forests, freshwater and coastal wetlands, and other ecosystems (e.g., Dynarski et al., 2020; Malhotra et al., 2019; Ross et al., 2021). In the past decade, changes in C in forest soils have been investigated as possible recovery responses to large decreases in acidic deposition achieved through improved air quality (Bailey et al., 2021; Cincotta et al., 2019; Lawrence et al., 2012). All these research activities are highly important in supporting the development of management policies, but their varying objectives and approaches have produced disparate data with regard to spatial and temporal scales, types of measurements, measurement methods, method documentation, quality assurance, and data-set management. Stakeholders who need these data for decision-making are usually not research scientists and may lack the resources and expertise to navigate through the technical complexities of soil C data to obtain the information that they need. Furthermore, because the widespread acceptance of long-term soil monitoring to detect change over time is relatively new in North America, long-running soil monitoring programs that provide the type of data needed to quantify temporal changes in soil C storage are particularly scarce (Lawrence et al., 2016).

The cultural shift in the scientific community toward open data sharing in the last decade has increased opportunities, incentives, and in some cases mandates for data producers to make soil data publicly accessible online. Federal agencies such as the United States Geological Survey and United States Forest Service require that all data produced are published online, and an increasing number of journals are requiring that all data used to produce an article are published online. However, not all soil data being produced are publicly available for reasons that include lack of resources needed to publish and proprietary reasons.

Organizations like the International Soil Carbon Network enable data from multiple sources to be stored on the same website (Harden et al., 2018; Todd-Brown et al., 2022), and as a result, some progress has been made in developing methods for consolidating existing data to provide information that better addresses the needs of researchers, managers and policy

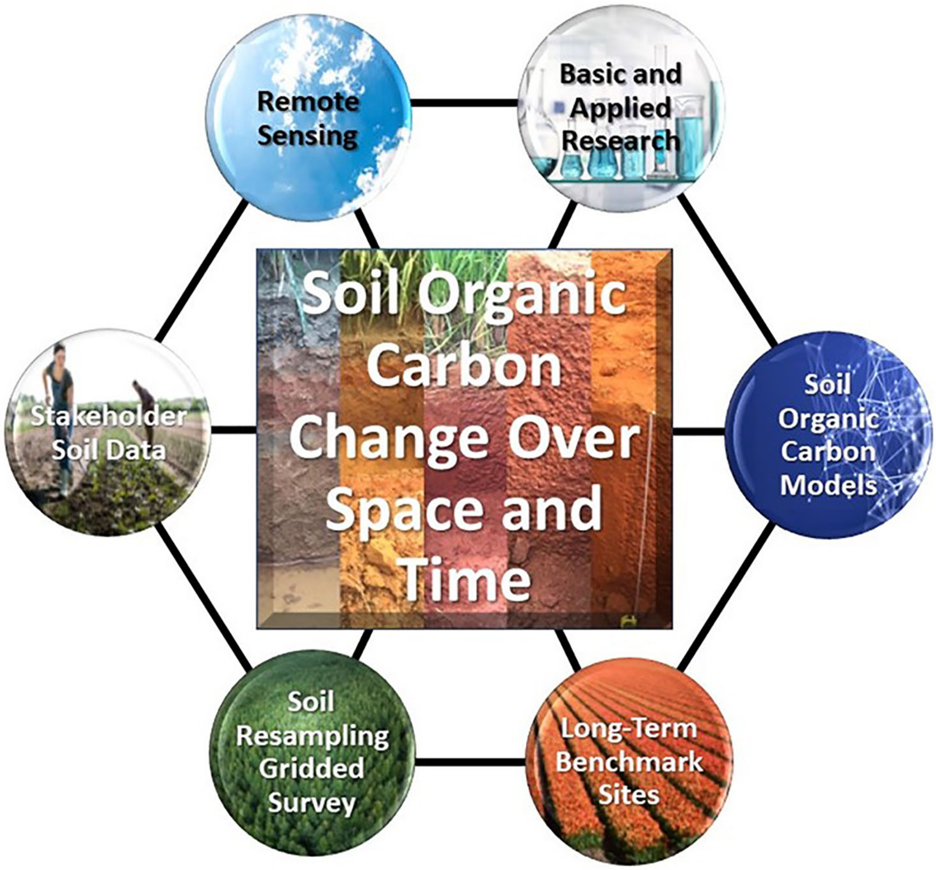

FIGURE 1 Conceptual elements of soil organic carbon (SOC) measurement programs. Adapted from Smith et al. (2020).

makers (Malhotra et al., 2019). Nevertheless, data may need to be retrieved from multiple sources that can often leave the end user with challenging compatibility issues that may require specialists in soil C measurement and analysis to resolve. If retrieval of extremely large data sets is needed, the user may face data transfer and storage challenges. Further efforts are needed to advance the accessibility and usability of these data sets as they grow in size and number, as described by Malhotra et al. (2019). In some cases, data incompatibility will be unresolvable due to lack of metadata, differences in sample collection, or different measurement approaches. If archived soil samples are available, reanalysis of samples collected years in the past can be compared with that of recent samples to ensure analytical consistency that is essential for accurate detection of changes over time (Lawrence et al., 2016).

Adding to these challenges, the types of soil data produced can vary depending upon the governmental level and the specific questions being asked. Working at a national scale has the potential benefit of ensuring consistent approaches to data collection, management, and distribution for a significant land area. National and international programs, such as the National Soil Survey Geographic Database (https://www.nrcs.usda.gov/resources/data-and-reports/gridded-national-soil-survey-geographic-database-gnatsgo), the National Ecological Observatory Network (NEON, 2023), the U.S. Forest Service Forest Inventory and Analysis Program (Domke et al., 2017), and the Long-Term Ecological Research Program (https://lternet.edu/), provide soil data that could also be used in regional networks, although the density of sites would often be insufficient for regional and state applications on their own. Achieving the spatial resolution needed for many state and local applications with data from national programs alone would require massive investments of resources. Potential complications also can arise if the temporal scale of adaptation and mitigation planning is mismatched with the frequency of soil measurements. Soil monitoring programs designed to detect change in soil C storage are relatively rare and often operate at time steps of a decade or longer (Lawrence et al., 2013). Development of methods that could identify changes in soil C as frequently as annually would be highly advantageous for managing soil C. Designing new soil monitoring programs to produce data in forms that can be readily integrated with existing data would also increase availability of information on temporal changes in soil C.

Taken in sum, the factors discussed above can make acquisition and consolidation of soil C data an undertaking of considerable scope particularly when focused on national and international scales. Users of soil C data often have goals such as the development and operation of C markets, the application of best land management practices to increase C storage or the compilation of state C budgets that lack data on specific types of lands. State governments in particular are now being tasked with developing policies and programs to promote land use practices that increase sequestration of C in the soil. This requires information produced through interactions among those who produce and interpret soil C data and decision makers who understand the social, economic, and political aspects of using these data.

Regional coordination among neighboring states, which is often undertaken when states share common challenges, could help support the development of monitoring programs that produce compatible soil C data. Regional-scale organization has been recommended as the optimum level to provide the consistency of measurements and implementation needed to generate confidence in C accounting programs that depend on quantifying soil C for specific locales (Oldfield et al., 2022). Regional coordination could also support state-level decisions by pooling soil resource assessments, products, and scientific practices among states through joint federal, state, and county agencies, and academic institutions conducting state-of-the-science soil research. This type of organizational approach could also serve as a model for other regions of the country.

4 | LESSONS LEARNED FROM COLLABORATIONS IN THE NORTHEASTERN UNITED STATES

One example of sharing soil monitoring expertise through an organized regional collaboration has been demonstrated by a group of academic researchers, state and federal scientists, and environmental program managers who formed the Northeastern Soil Monitoring Cooperative (NESMC). The NESMC was founded in 2007 to promote the coordinated collection of data that could be used to identify changes in soils. Through annual workshops held from 2008 to 2018 and publications demonstrating successful application of shared soil monitoring knowledge developed in the cooperative (Fraser et al., 2019; Lawrence et al., 2016, 2013; Ouimet et al., 2017), the NESMC helped to increase recognition of soil monitoring as an important tool for documenting environmental change. Activities of the NESMC collaboration included publication of a paper and video on methods for monitoring forest soils to detect change (Lawrence et al., 2016) and sharing of reference soil to evaluate the consistency of analytical results among 17 laboratories (Ross et al., 2015). NESMC participants also pooled soil monitoring data from the Northeastern United States (hereafter Northeast) and eastern Canada to document pronounced changes in soils resulting from reductions in pollutant sulfur emissions (Hazlett et al., 2020; Lawrence et al., 2015).

The work of the NESMC was accomplished on a voluntary basis through the common interests of the participants and their understanding of the importance soil resources play in ensuring a sustainable society. In all cases, participants held positions within their own institutions that allowed them the freedom to apply salaried time to NESMC activities. This organizational model achieved success because the products of the NESMC were of value to the institutions as well as the participants and the region in general. However, the NESMC model also demonstrated that the accomplishments achieved through the collaboration were limited by the shifting capacity of volunteers to carry out the work while meeting the compulsory requirements of their positions. Nevertheless, the NESMC did show that coordination at the regional scale can accomplish important advances in the acquisition and distribution of high-quality soil data.

Interest in collaborative activities within the Northeast is being demonstrated beyond the NESMC as the interest in soils as a method of climate change mitigation has grown. For example, Massachusetts, Vermont, and Maine are coordinating on the development of GHG accounting to facilitate regional land sector C sequestration markets (D.N. Carpenter, Massachusetts Executive Office of Energy and Environmental Affairs, written communication, July 27, 2022). Like other regions, the Northeast has highly variable physiography and land use that must be accounted for to obtain reliable C data (Nave et al., 2021, 2019, 2022). However, much of this variation shows similar patterns within and across neighboring or nearby states and is often tied to a common land-use history such as agriculture in valleys and logging in rugged upland terrain. Within a given region, specific landscape types can be identified that are important sinks for storing soil C (Figure 2). In the Northeast, mature forests, early successional woodlands, coastal and inland wetlands, and urban and suburban environments provide substantial potential for increased soil C storage, but some landscapes such as wetlands could also be potential sources of GHGs (Zhang et al., 2017), and increased CO_2 emissions might result from forest harvesting (Buchholz et al., 2013).

Regional soil C networks offer significant opportunities for increasing the availability and use of soil C data. Nevertheless, a regional network to facilitate acquisition and use of soil C data has not occurred in the Northeast, or to our knowledge elsewhere. In the following section, suggested steps to develop and operate a soil C network are presented.

FIGURE 2 Examples of the diversity of land use types to be considered in the development of a comprehensive regional soil C monitoring network.

5 | STEPS TO DEVELOP A REGIONAL SOIL CARBON MONITORING NETWORK

Based on information from soil monitoring conducted in the Northeast and elsewhere, we propose steps for developing a regionalized soil C monitoring network. These steps could be used to help guide the formation of networks in regions where improved access to soil C data is desired to better support science and decision-making. A general approach for how this type of network could be initiated, designed, and implemented is summarized in Figure 3 and described in the following three steps.

Step 1: *Produce a scoping document that justifies a network and proposes a plan for its formation.*

A soil monitoring network could be formed in a variety of ways, but regardless of the approach, activities to generate collaborative interest and attract participants is a first step. Approaches for drawing attention to the effort could include producing a peer-reviewed publication, such as this article, giving conference presentations, and developing and managing websites that are linked to other networks with strong common interests and activities. One such network is the Coastal Carbon Research Coordination Network (https://serc.si.edu/coastalcarbon; https://ccrcn.shinyapps.io/CoastalCarbonAtlas/;), which conducts multiple activities similar to those that would be needed by a regional soil C network using an organizational structure that could be meshed with a network that collects and disseminates soil C data. This article serves as a scoping document that describes the current limitations of soil C data as a tool to inform science-based actions, explains how a network could improve availability and usage of soil C data, and proposes steps to guide the establishment of a regional soil C monitoring network.

Step 2: *Design a regional network structure that can effectively deliver soil C information to managers and policy makers.*

To design the network, a committee could be formed to include members like those who worked on this scoping document, as well as others involved in regional soil collaborations and the acquisition and use of soil C information. Diverse stakeholder participation in the committee would help to ensure that the network design would deliver what the stakeholders need, in a form that they can readily use. Institutional representation on this design committee could include government agencies, nongovernment organizations, representatives from relevant industries, tribal nations, and academic institutions. Those with experience in forming collaborative partnerships and a vested interest in the formation of a network would be likely participants, as would members with a high level of expertise in soil C science who are interested in developing methods of soil C measurement. Inclusion of representatives from each state within the defined region as well as regional representatives that work across states would support the regional collaboration.

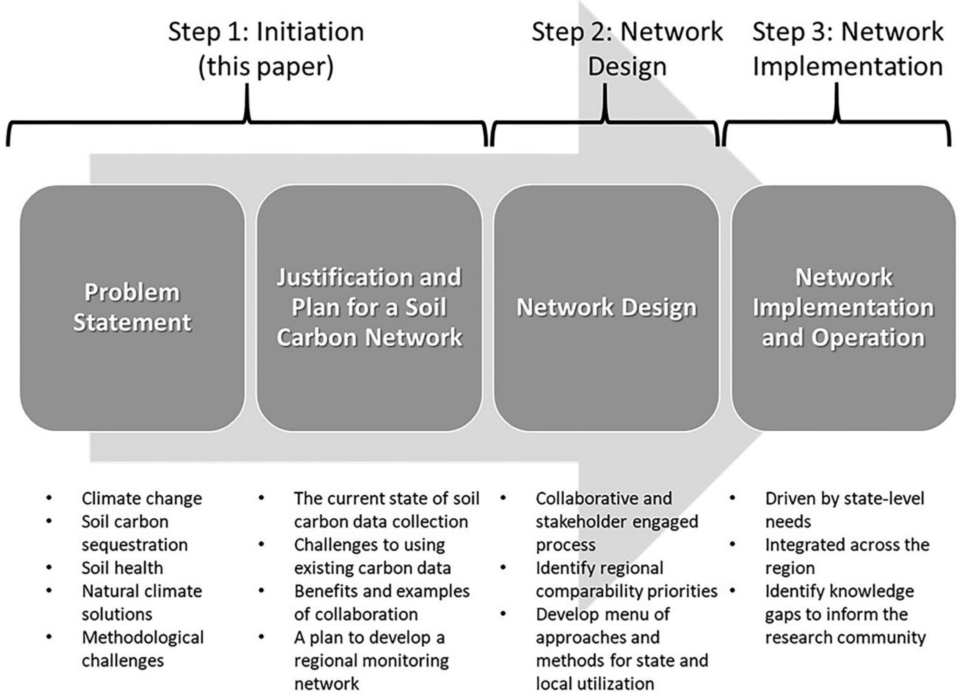

FIGURE 3 Steps to develop a regional monitoring network to provide soil carbon data.

Defining specific objectives or tasks to be accomplished by the network early in the process would help guide formation of the network structure. Early and ongoing communication with existing programs within the region that are involved in collecting soil C data would help to avoid redundancies at this step and beyond. To accomplish this, scientific resources and research teams that produce information on soil C would need to be included in the design phase. The nature and extent of these potential resources will be key in identifying gaps in data availability within the region. Resources such as existing databases and sample archives are particularly important because they have the potential to deliver information quickly.

Creation of capabilities that do not exist in the region may be necessary. Soil sampling and resampling, spatial and statistical modeling, and remote sensing could all be explored during the design phase as ways to acquire necessary data. Methodological issues that influence the compatibility of soil data should also be evaluated and resolved, and platforms and/or protocols for data harmonization, management, and access could be planned at this stage.

Information required by the design committee may be possessed or obtainable by committee members themselves, but some information retrieval may require time commitments or expertise beyond that which committee members could provide. Tasks such as compilation of scientific resources throughout the region and development of a data management plan to enable retrieval, aggregation, integration, and distribution of diverse data sets may best be accomplished by someone with specialized skills or knowledge who can dedicate the necessary time to accomplish these tasks. To ensure timely completion of the task, institutional support could be contributed through staff time or funding to fill critical positions. Without this type of support, many networks struggle or ultimately fail to deliver relevant information needed by end users on a timely basis (Todd-Brown et al., 2022).

Step 3: *Implement and operate the network to provide high-quality soil C data to those who make the decisions regarding the role of soils in collective climate change responses.*

Once the network design is complete, the organizational structure can be populated by enlisting commitments (both institutional and individual) from those who would operate the network. A working group familiar with the programs and people involved in soil C data collection within the region could be used to staff the network with people who possess the appropriate skills and knowledge (Figure 4). The network would ideally be operated by core staff who receive guidance from science and policy experts who have positions that allow them to provide salaried time as in-kind support. Network operation may need institutional commitments that could come from multiple sources such as state, federal, and private entities to cover costs for staffing, facilities, fieldwork, laboratory analyses, data management and transfer, and computer support. Cost sharing by multiple entities across local/county, state, tribal, and federal levels, as well as partnerships with nongovernmental organizations and the private

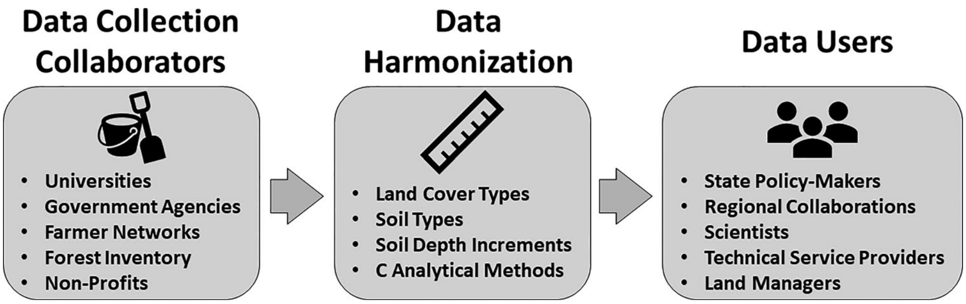

FIGURE 4 A regional soil carbon monitoring network could serve to (1) coordinate diverse collaborators who support soil carbon data collection, (2) establish standards for soil carbon data collection and data sharing that would enable information collected to be used in appropriate ways despite the complexity of the data, and (3) support access, delivery, and interpretation of data delivered at multiple scales for diverse data users.

sector could increase network sustainability. In building the collaboration for a soil C monitoring network, in-kind contributions could be used, as well as coordination with existing soil programs that may not focus on soil C sequestration but have overlapping interests such as the promotion of soil health. The Coastal Carbon Research Coordination Network, cited above, provides a specific example of how this type of network might be organized, governed, and sustained.

Once implemented, all aspects of the operation could be periodically evaluated to ensure that the network is functioning successfully in achieving its objectives. This evaluative process could be carried out by an advisory committee that includes those from within the network as well as those providing support and external stakeholders. Scientists with a high level of expertise in methods of soil C monitoring could be used to recommend adjustments when necessary to ensure the quality of the soil C data made available by the network. Inclusion of quality assurance procedures will be essential to ensure the success of routine operations. The specific quality assurance measures that would be implemented will vary with the characteristics of the data sets used. The development of those quality assurance protocols would draw on established practices by those experienced in assessing the quality of soil data. Most importantly, the transfer of soil information could be managed by an employee of the network with a clearly defined responsibility for data distribution. This person would maintain contact with all interested stakeholders working as a liaison between the data producers and users. Periodic meetings with stakeholders and the public would also be held to maintain the visibility of the network. At these meetings, activities of the network would be reported and feedback on network operations and products could be solicited from end users. An operational network could help to maximize the availability of existing resources, produce (or facilitate production of) data to fill information gaps, and most importantly, provide soil C data and information to those who are responsible for developing and implementing policies to mitigate GHGs and improve the health and climate resilience of soils.

6 | CONCLUSIONS

The substantial and growing evidence for the negative consequences of anthropogenically driven climate change is resulting in societal efforts to eliminate emissions of GHGs to the extent possible and reduce atmospheric concentrations of GHGs using all available strategies, including technologies such as increasing C storage in soil. The recognized importance of soil C has led to an increasing number of collaborative efforts to pool data, focusing primarily on building national and international databases to increase our knowledge of soil C across nations and beyond. This paper offers additional perspective to that work by discussing the benefits of a regional network and proposing how it could be initiated, designed, and implemented to engage the land managers and policy makers who are directly responsible for the actions that will affect soil C storage in a region such as the Northeast. With institutional support, the network could provide a formal structure to ensure that scientific advances in understanding soil C dynamics are successfully used in policy development and on-the-ground implementation of practices.

The growing base of knowledge about techniques to increase C storage in agricultural soils while improving soil health and climate resilience represents an example of how improved soil C management can be implemented. However, strategies to incentivize agricultural practices to improve soil C storage are not fully developed, and methods to efficiently monitor the efficacy of various practices are lacking. Furthermore, in some regions, agricultural lands comprise a relatively small fraction of total land area. Much less is known about methods for increasing long-term C storage in the soils of forests, grasslands, wetlands, urban and suburban areas, and landscapes transitioning from prior intensive uses to unmanaged conditions governed by natural processes and undirected human influences. The growing interest in increasing soil C storage and improving soil health has revealed deficiencies in our current ability to collect and integrate soil C data at the appropriate spatial and temporal scales to monitor changes in soil C over time, which is necessary to evaluate actions intended to protect and increase soil C.

Improvements in the accessibility and utility of existing soil C data and the collection of new data to fill critical gaps can be accomplished through the development of regional soil C monitoring networks that would facilitate the integration of activities outlined in Figure 4. Linking this work through a northeastern soil C monitoring network could provide a proof-of-concept for a regional network design that could be applied in other regions of the United States. Focusing these efforts at the regional scale would provide multi-scale information relevant to the environmental and socioeconomic challenges that decision makers are currently facing across the United States, and likely make soil C networks more responsive to rapidly changing needs in the future. The regional-scale approach can support assessments at scales that can cross territorial and state boundaries, while also providing data that support state-level climate planning and landowner decision-making. Within the United States, regional-scale assessments of climate impacts, such as are provided in the National Climate Assessment, and regional research and outreach coordination, such as the USDA Climate Hubs, are well poised to guide regional soil C monitoring in the Northeast and elsewhere.

AUTHOR CONTRIBUTIONS

Gregory Lawrence: Conceptualization; funding acquisition; project administration; supervision; writing—original draft; writing—review and editing. **Ivan Fernandez**: Conceptualization; project administration; supervision; writing—original draft; writing—review and editing. **Scott Bailey**: Conceptualization; writing—original draft; writing—review and editing. **Colin Beier**: Conceptualization; writing—original draft; writing—review and editing. **Alix Contosta**: Conceptualization; writing—original draft; writing—review and editing. **Erin Lane**: Conceptualization; writing—original draft; writing—review and editing. **Peter Murdoch**: Conceptualization; writing—original draft; writing—review and editing. **Lucas Nave**: Conceptualization; writing—original draft; writing—review and editing. **Angelica Quintana**: Conceptualization; writing—original draft; writing—review and editing. **Donald Ross**: Conceptualization; writing—original draft; writing—review and editing. **Alissa White**: Conceptualization; writing—original draft; writing—review and editing.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

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