Soil Carbon Monitoring Network Framework

Summary

This document presents a conceptual framework for the Soil Carbon Monitoring Network's (SCMN) site selection, sampling, and analysis strategies to systematically assess soil carbon change on working lands based on climate, geography, management practices, and soil properties. The goal of this document is to outline site selection and sampling rationale, processes and procedures to guide initial site selection, ongoing assessments, and prioritize future SCMN sites. This document is part of a set of documents sharing the Natural Resources Conservation Service (NRCS) protocols for the SCMN. Protocols will be updated as needed.

Background

USDA NRCS established SCMN to support the implementation of Sec. 21002(a)(2) of the Inflation Reduction Act (IRA) Pub. L. 117-169, § 21002, 136 Stat. 2018 (2022).

The goal of the SCMN is to collect field-based data to assess and track trends related to soil carbon sequestration associated with conservation programs and management practices on working lands across the country. Data will improve outcome estimates of the impact of management on soil carbon by improving models and analyses.

Approach

The SCMN is meant to provide a broad, dispersed network of sites that can be monitored over time and support the assessment of change in soil carbon stocks for groups of categories or at an individual location. SCMN will support model calibration, validation, and assessment of soil carbon change under typical and important conservation practices and management systems. These findings improve NRCS applications of conservation practices and recommendations.

Soil carbon stocks vary by regions, across landscapes, within management units, and according to soil type. This network uses a broad-based replication across regional scales based on soil types, geography, land use and cover categories, targeted management systems, and conservation practices. Replication is also used within sites to capture variability in soil carbon and vegetation due to soil and management action. The same sites are revisited over a minimum of five-year intervals to capture changes in soil carbon over time at the same locations. This multi-scale replication provides the best opportunity to meet multiple objectives of this monitoring network.

The SCMN will implement three general approaches to identifying sites for sampling:

- Opportunity sites—sites that leverage existing cooperators spread across working lands, climates, and soils and are identified through State offices, partners, and local contacts.
- NRI sites—sites located around National Resources Inventory (NRI) points
- Nodes—groups of mini-sites based around other networks such as the USDA, Agricultural Research Service (ARS) Long-Term Agroecosystem Research (LTAR); university research; or demonstration farms.

Note: Sites are a general term used to describe a defined area of working lands, such as fields, pastures, and rangelands, with consistent land use and management.

Network Site Design

Soil monitoring networks consist of locations where changes in soil characteristics are documented through periodic assessment of an extended set of soil parameters. For soil monitoring networks, a harmonized methodology is essential to provide data that are comparable among sites. The overall SCMN site selection objectives are to characterize the influence of land use and land management on soil carbon stocks for working lands, such as croplands, pasture, and rangelands.

The SCMN team will disperse SCMN sites across the country using the expectations from the NRI sampling algorithm (see below). Spencer et al. (2011) and Ogle (personal communication) indicated that 5,000 sites would be an ideal target for a robust soil carbon network based on allocations by land cover type and major land resource areas (MLRAs). That number is not feasible given resource and time limitations; however, 3,000 sites that can be revisited as part of a monitoring scheme would provide replication adequate to improve NRI-based reporting and understanding, which was the original intent with the larger number of sites. State administrative units were provided yearly targets after rebalancing that number based on available resources. Initially, all sites will be opportunity sites until adequate data systems are developed to collect and store data securely. The data are protected from unauthorized use and unauthorized disclosure pursuant to the administrative and civil remedies and criminal penalties as identified in applicable Federal statutes, including the Privacy Act of 1974 (5 U.S.C. § 552a); the Freedom of Information Act (5 U.S.C. § 552); Section 1619 of the Food, Conservation and Energy Act of 2008 (7 U.S.C. § 8791); and Sections 1770 and 1244 of the Food Security Act of 1985 (7 U.S.C. § 2276 and 16 U.S.C. § 3844, respectively).

Table 1.—SCMN site visit targets by fiscal year and site type.

Site Types	FY 24 – Q1 FY25	Rest of FY25	FY26	FY27	FY28	FY29	FY30	FY31	Total
Opportunity sites	50	700	250	25	25	25	200	200	**1,475**
NRI sites		750	1,250	50	50	50	750	750	**3,650**
Node-based mini-sites	-	50	25	25	25	25	75	75	**300**
Total Yearly Site Visits	50	1,500	1,525	100	100	100	1,025	1,025	**5,425**

Opportunity Site Prioritization

Site selection is based on tracking soil carbon change over time rather than the status at any single time. Baseline carbon stocks and the rates of carbon stock change are observed independently of one another with differing variability and interpretations. Due to this complexity, capturing soil carbon variability requires a strategic, hierarchical sampling strategy across multiple scales based on a prior knowledge to accurately measure regional and national soil carbon dynamics. The SCMN team will use the following criteria to select SCMN initial sites, evaluate adequate representation, and guide future network site selection:

- MLRAs will be the basis of further stratification (USDA NRCS, 2022) to capture the range of soil conditions that exist under cropland, rangeland, and agroforestry systems. MLRAs are geographically defined areas of similar climate, soil, capabilities, and potentials for management.
- Site-specific variability will help to further stratify each site. Such site-specific variability consists of climate, soil system characteristics, land use, land cover, and management practices. Soils and landscape factors considered include soil taxa, texture, slope, and climatic factors known to be important to soil carbon (Nunes et al., 2022; Wills et al., 2010). Stratified sampling will allocate potential sampling locations based on the proportional area and variability of soil carbon change based on initial estimates of within-stratum variance (this work is under development).
- The major and important practices within an MLRA, as informed by both the breadth and diversity of crops and forage, will help allocate and evaluate that MLRA's management systems and conservation practices.
- Under-evaluated management systems and scenarios that support the needs of historically underserved customers will receive particular attention. Filling these gaps is important for ensuring that NRCS has robust datasets for the range of practices that producers use. This will equitably support the needs of all producers.
- The starting amount of carbon and resampling of well-defined monitoring sites (such as previous national carbon sampling programs or areas around previous soil inventory pedon locations) are crucial for both baseline and follow-up measurements due to the additive nature of change over time.
- Future network site locations and gaps in the SCMN will help the SCMN team re-evaluate site selection based on within-strata sampling.

NRI Site Prioritization

The SCMN team will prioritize NRI sites that were previously assessed for soil carbon (Brejda, 2001; Ogle, personal communication). The team used a Neyman stratification algorithm based on previous concepts in Spencer et al. (2011) to identify additional points. In short, this algorithm generated a statistically balanced draw across MLRAs based on the proportion of NRI points (and thus land area) in grazing land and cropland. For each selected point, the SCMN team will provide replacement sites to maintain the representativeness of the sample draw in the case of access failure (i.e., contact difficulties, denied permissions, or land use or cover changes). The SCMN team will prioritize the stratification based on sampling capacity within any given year to maintain the integrity of the sampling draw. Current selected points are only in the conterminous United States; additional sites will be selected from other States and Territories.

Node Site Prioritization

Nodes represent a special case where groups of management units are present in one location. They present the opportunity to evaluate multiple kinds of soils, management systems, and conservation practices. Nodes are often located on public sites that have highly detailed management records that can be shared publicly.

The SCMN team will use the same regional soil and management system factors that are important for all sites to target and prioritize nodes. In addition, nodes will include experimental units with direct comparisons of conservation practices of interest. The team will modify site design of nodes for these situations by limiting the number of pedons and samples.

- In phase 1, planned sites include LTAR and other research networks using the same criteria as opportunity sites.
- In phase 2, node sites will expand to include agroforestry, riparian, easements, and other useful sites, as feasible. Work with the National Agroforestry Center (a joint USFS-NRCS group) supports planning for agroforestry node sites. Agroforestry is more specialized and less standardized than many other areas and spans USDA agencies. The deliverables will include agroforestry protocol development, training, and assistance with sample and data collection on sites that will be part of the SCMN.

Site Management Information

The SCMN team developed a questionnaire for collecting management data for the sampling areas. The team developed the questionnaire by considering information that will improve model estimates of how key management practices impact soil carbon. The questionnaire will draw from existing questions on management data (e.g., S2.6 Land Use and Management Questionnaire, Conservation Effects Assessment Project Survey) and will reference the NRCS Climate Smart Agriculture and Forestry Mitigation Activity list.

Individual SCMN Site Design

The SCMN team developed a hybrid approach to meet the multiple objectives of this project (model support and practice assessment) to allow for precise monitoring of exact locations over time and to capture the full range of characteristics for management units. For the purposes of the SCMN, a management unit is managed with consistent crops, implements, livestock grazing, treatments, applications, or other vegetation.

Each site begins with a single point that represents an existing observation scheme or a target situation or that has previous data available. When used, National Resource Inventory (NRI) points are the starting point and the exact location of that point is maintained. SCMN sites expand from that single point to approximately ten acres. To capture site variability, Bradford and others (2023) suggest within-field sampling density of at least 1.2 ha (approximately 3.0 acres) per sample. This means that one sample is assigned per 1.2 ha (3.0 acres). To be well within that recommendation, SCMN teams collect six samples at each 4.04 ha (10-acre) field, resulting in a sampling density of 0.7 ha (1.7 acre) per sample.

Stratification Tool

The SCMN team applies a stratification scheme across the site to ensure general characteristics of the site are represented in the collected sample. A web-based soil sample stratification tool (Soil Strata V.1 Google Earth Engine) was designed to help select farm-level soil sampling sites by optimizing the characterization of within-field soil variability. To do this, the tool first instructs a user to delineate an area of interest (AOI) to sample. The user does this by navigating to the desired sampling location and using a set of drawing tools to define the AOI. Next, the tool identifies distinct zones or areas within the AOI based on variability in slope, the Normalized Difference Vegetation Index (NDVI), and clay percentage using k-means clustering. The tool then performs stratified random sampling to allocate a set number of sites within each zone. Potash et al. (2023), Bradford et al. (2023), and Potash et al. (2022), and others support the use of stratified random sampling using k-means of spatial layers.

Soil Sample Collection

The accurate estimation of soil carbon stocks requires the measurement of both bulk density and soil carbon concentrations and their conversion to volumetric equivalents. The SCMN team collect a pedon (3-dimensional soil body) at each point identified in the stratification tool to a depth of 100 cm. While 30 cm is often used for minimal inventory, there are benefits to using 100 cm in a monitoring scheme. Recent research suggests that soil carbon stocks below a 30-cm depth can also change in response to agricultural management within decades. One meta-analysis of agricultural soil profiles found that within 20 years, nearly a quarter of newly accumulated soil carbon was below 30 cm (Balesdent et al., 2017). Similarly, a recent long-term experiment in California found that compost additions and winter cover crops resulted in substantial soil carbon accumulation below 60 cm after 19 years (Tautges et al., 2019; Rath et al., 2022). Thus, soil carbon monitoring programs that do not consider soils below 30 cm risk incompletely accounting for total soil carbon stocks and their changes over time. Measuring soil carbon to 100 cm depth provides a more accurate assessment.

Given that surface soil or topsoil contains the majority of soil carbon and is more variable than at deeper depths, the SCMN team supplements pedons with satellite samples. Satellite samples consist of three additional surface samples taken 5 m around each pedon to allow better estimation of variable surface soil carbon across the site. Since soil carbon percent is more variable than bulk density (Holmes et al., 2011), many soil carbon monitoring programs collect less samples for bulk density than for soil carbon. Satellite samples are composited to provide efficient estimation of surface soil carbon around the pedon location. FAO (2020) and Spencer et al. (2011) recommend compositing to reduce noise (or random variation) and increase efficiency. When locations are revisited as part of a monitoring program, the information from satellite samples helps to differentiate change from random chance.

Cubic splines or alternate mathematical equations can smooth and standardize depths to compare fixed depth or equivalent mass as described in Soil Survey Staff and Loecke (2016), Hengl et al. (2017), and others.

Opportunity Sites

For all sites, the SCMN team arranges pedons to collect in clusters. They assign six clusters per site via the stratification tool. Clusters are made up of one central pedon (soil core collected to 100 cm) and three satellite samples (shallower, smaller-diameter samples collected to 30 cm). The SCMN team will collect central pedons to a depth of 100 cm using one of the following methods in order of preference: pneumatic probe, hand-powered probes that extract a cylindrical core, bulk density ring, excavation pit, or compliant cavity. Team members will describe cores according to the “Field Book for Describing and Sampling Soils” (Soil Survey Staff, 2024).

The minimum required information for each horizon includes the following: horizon designation, depths, color, texture, rock fragment modifier (percent coarse fragments by volume), redoximorphic features, and structure (where possible). The SCMN extracts one additional core per cluster using the same sampling method to aid with the description. This core is not retained for sampling once the description is complete; the hole is backfilled with the excess core. The SCMN team removes samples from 10-cm increments of each of the horizons described in the core description from the central pedon and places them in the labelled sampling bags. They record the beginning and end of the sample depths as well as the diameter of the sample core to capture volumetric data. The team extracts satellite samples via a hand probe to a depth of 30 cm. They divide each of the three satellite samples into 10-cm increments. The increments are then composited across satellite samples of the same cluster (10-cm composite, 20-cm composite, and 30-cm composite) and placed in labelled sample bags. When revisiting an SCMN site, the team will move all sample collection points (pedons and satellite samples) 25 cm directly north unless there is an impediment, in which case the team will choose another direction and record it. The SCMN team repeats the entire sampling process for site layout, vegetative data collection, and soil sampling.

NRI Sites

For NRI sites, the arrangement of pedons and samples replicates the plan and prior efforts outlined in Spencer et al. (2011). The SCMN team designed the protocol to represent soil carbon stocks at the NRI point. The SCMN team establishes an 18-m equilateral triangle; each point is 10.4 m from the NRI point and has one point oriented towards magnetic north. They subdivide the triangle into three equilateral subtriangles that are arranged at each point of the main triangle for a distance of 6 m. The team collects three 75-cm pedons in each subtriangle (one at each point and 6-m distance from the point along the original trajectory of the main triangle), divided by depth increments of 0–10, 10–20, 20–30, 30–50, and 50–75 cm. These increments are then composited in the field within each subtriangle. When revisiting a site, the teams will shift each point clockwise along its subtriangle 50 cm and will resample in the same manner as before.

Vegetation Information Collection

The SCMN team collects vegetation information to estimate biomass and track the status of perennial systems over time. In herbaceous cover, the team uses the line-point intercept method to estimate live plant mass, volume, soil coverage, and herbaceous litter; the methods are adapted from the "National Resources Inventory Grazing Land On-Site Data Collection Handbook" (NRCS, 2024). The team anchors each of the three transects at the center pedon of the cluster and extends them through a satellite point to the end of the line. The plant identification expert estimates woody vegetation using a fixed plot design common in forestry, which identifies and measures all trees and shrubs in an area. The expert anchors fixed radius plots at the center pedon of the cluster and extends to 5 m for shrubs and 10 m for trees as described in the "National Forestry Handbook" (NRCS, 2004). Downed woody debris (woody material no longer attached to a live plant and in various stages of decomposition on the ground) has been shown to be useful information for characterizing soil carbon when paired with management and burning history (Brown, 1974). The SCMN team can use allometric equations to estimate above- and below-ground biomass (Lui, 2021; Lui, 2021).

Complete instructions for vegetation data collection and soil sample collection are in the "Field Sampling Instructions" document.

Soil Sample Analysis

The SCMN team weighs, processes, and sieves (to less than 2 mm) all collected soil samples for bulk density and coarse fragment calculation. Complete instructions are in the "SCMN Soil Survey Office Processing and Shipping" document.

” document.

Laboratory analysts will determine combustion carbon, particulate organic matter, pH, and mid-infrared spectra. Analysts will fine grind samples to less than 180 µm (80 mesh) using a planetary ball mill, as necessary. For samples that are not immediately processed, analysts will log and refrigerate the samples to 4° C until they are processed. This process is consistent with Kellogg Soil Survey Laboratory (KSSL) method 1B1b2d (Soil Survey Staff, 2022). The analysts will measure soil pH in a 1:1 water solution consistent with KSSL method 4C1a2a1 (Soil Survey Staff, 2022). Particulate organic matter (POM) is the portion of SOM that is associated with the physical fraction of soil defined at more than 53 µm in diameter. Analysts will measure POM-C directly by dry combustion analysis of the 53-µm or more fraction. They will calculate mineralizable carbon (MIN-C) by subtracting the POM-carbon values from the direct measurement by combustion of total carbon. This method is consistent with KSSL method 6A4 (Soil Survey Staff, 2022). Analysts will assess soil carbon with dry combustion through three possible scenarios. In the National Soil Survey Center, Research Branch Carbon Assessment Laboratory, analysts will measure total organic and inorganic carbon with temperature ramp dry combustion as demonstrated in Carter et al. (2024). Another approach is to assess total carbon through dry combustion and correct for inorganic carbon as in KSSL method 4H2a1 (Soil Survey Staff, 2022). Alternatively, analysts pretreat samples to remove inorganic carbon. They assess total carbon through high-temperature combustion as outlined in Cordova et al. (2024). Mid-infrared spectroscopy will be captured consistent with KSSL method 7A7 (Soil Survey Staff, 2022). Analysts will use models to predict soil carbon pools and soil texture classes and to evaluate for minerology and other relevant values as demonstrated in Seybold et al. (2019) and Sanderman et al. (2021). The full laboratory procedures can be found in the “SCMN Soil Sample Laboratory Procedures” document.

Data Collection and Storage Summary

The SCMN data collection and storage solutions are still under development (as of January 2025). Currently, the SCMN team is using ArcGIS Survey123 applications to collect a standard set of management and practice information and guide soil and vegetation field collection. The team is using Excel spreadsheets to record data from the field and from analysis laboratories. The Mission Delivery Optimization Division of NRCS is currently developing a custom solution for collection and storage of all data elements. The SCMN team will share data according to the relevant statute and privacy regulations.

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