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Beneath the surface: A 25-year review of soil monitoring in the U.S. Forest Inventory and Analysis program

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ABSTRACT

Soils are a critical component of forest ecosystems and the global terrestrial carbon cycle. They regulate the resources that limit plant and microbial activity, support biodiversity, serve as reservoirs of carbon, and influence forest health. Systematic soil data can help fill key knowledge gaps, such as the sensitivity of forest health and functioning to disturbances and agents of change and the capacity of soils to help mitigate climate change through carbon storage. Since 2000, the Nationwide Forest Inventory (NFI) conducted by the Forest Inventory and Analysis (FIA) program has systematically collected soil data from forested lands across the United States (U. S.). This includes metrics related to nutrient and water availability, carbon storage, toxic substance accumulation, soil acidification, erosion, compaction, and other attributes that are critical for assessing forest health and function. To date, nearly 10,000 forested NFI plots have been sampled nationwide, of which approximately 23 % have been resampled. By integrating these systematic forest soil data with site-level information, aboveground forest attributes, and other ecological data, the NFI aims to deepen our understanding of forest dynamics, inform sustainable management practices, and address challenges posed by global environmental change and forest disturbances. As information needs and the challenges faced by forests continue to evolve, there is an opportunity to adapt the sampling design, attributes measured, and protocols used. This paper reflects on the NFI's 25-year history of soil assessments, provides a status update, explores various data applications, and highlights both limitations and potential improvements to meet emerging research questions and management needs.

1. Introduction

Soils are a critical component of forest ecosystems and the global terrestrial carbon (C) cycle with feedbacks to atmospheric carbon dioxide concentrations (IPCC, 2021; Jobbágy and Jackson, 2000; Tian et al., 2015). Soils regulate the resources (e.g., water, nutrients) that limit plant productivity and microbial activity (Ni et al., 2022; Terrer et al., 2019), support biodiversity (Fitzsimons and Miller, 2010; Rodríguez-Loinaz et al., 2008; Van Der Heijden et al., 2008), serve as reservoirs of C (Cao et al., 2019; Domke et al., 2017; Georgiou et al., 2022; Jobbágy and Jackson, 2000), and influence forest health (Bal et al., 2015; Morales-Rodríguez et al., 2024; Schaberg et al., 2006). Systematic forest soil information can help fill key knowledge gaps, such as the capacity of soils to help mitigate climate change through storage of organic C and the sensitivity of forest health to disturbances and agents of change (e.g., climate change, permafrost degradation, insects and pests, diseases, fire, land use and management).

Given the importance of soils, a variety of soil assessments and

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databases have been established in the United States (U.S.) over the last ~125 years, with soil surveys initially focused on geology or cultivated lands to assess crop production and expanding as objectives and technologies evolved (Brevik and Hartemink, 2013). These assets vary widely in their strengths and limitations, reflecting the difficulty for a single soil assessment to simultaneously prioritize spatial balance and coverage, temporal continuity, sampling depth, the number of soil attributes measured, consistency in data collection and analysis methods, and quality assurance. There are several soil datasets focused on intensive site monitoring maintained by various agencies and organizations (e.g., some U.S. Department of Agriculture (USDA) Forest Service experimental forests and National Forests, Long Term Soil Productivity study, Long-Term Ecological Research sites, National Ecological Observatory Network, Critical Zone Exploration Network). These datasets increase our understanding of soil properties and dynamics in specialized, often ecological, contexts and support land management tailored to specific areas. Many have included strategically located sites that represent diverse ecosystems or ecological gradients but typically were not designed for nationwide spatial continuity.

In contrast, landscape-scale soil assessments may provide comprehensive coverage of soil properties across large geographic areas and are conducted using both bottom-up and top-down approaches. Bottom-up tabular and spatial soil databases and maps (e.g., International Soil Carbon Network, SoilGrids, POLARIS, Global Biodiversity Information Facility) use open data collection. Crowdsourcing of soil data collection enables the potential for broader spatial and temporal coverage across diverse geographic areas, but faces challenges related to data quality and consistency and spatial coverage disparities across regions. For example, SoilGrids produces spatially continuous global predictions of soil properties using digital soil mapping but is not built from a spatially balanced or representative dataset across soil types and ecoregions (Poggio et al., 2021).

Top-down, agency-led efforts have systematically collected and stored soil data in well-maintained public databases, with the advantages that such programs typically adhere to standardized protocols and quality assurance procedures. For example, the USDA Natural Resources Conservation Service (NRCS) maintains both the Soil Survey Geographic Database (SSURGO) and the State Soil Geographic Database version 2 (STATGO2), accessed through the Web Soil Survey (http://websoilsurvey.sc.egov.usda.gov/). SSURGO provides extensive soil property data collected by the National Cooperative Soil Survey across most of the U.S. at a relatively local scale (1:12,000 to 1:63,360 spatial scale; e.g., county level). STATSGO2 provides a less detailed set of soil properties at a coarser scale (mostly 1:250,000 spatial scale; e.g., regional or state level) compared to SSURGO, but statistically expands available data to fill in gaps where SSURGO and other detailed soil survey data are missing. The USDA-NRCS also initiated the Rapid Carbon Assessment, which sampled pedons (i.e., three-dimensional soil samples that generally include all horizons; maximum 1-m depth) and employed rapid, cost-effective methods (i.e., visible near infrared spectroscopy) to estimate soil C across different ecosystem types, enabling spatial mapping of soil organic C (SOC). However, the Rapid Carbon Assessment is limited in scope beyond C. These soil databases do not focus on temporal change and thus typically do not include repeat measurements for the same area over time. Instead, they provide a snapshot of soil properties reflecting the most recent survey period at each location.

In contrast, in 2000, the USDA Forest Service implemented a comprehensive, long-term soil monitoring program across all forestlands in the conterminous U.S. as part of its Nationwide Forest Inventory (NFI) conducted by the Forest Inventory and Analysis (FIA) program. By monitoring permanent sample plots across all ownerships on forestland over time, the NFI aims to identify forest trends, evaluate changes in forests, and inform policy decisions at local, regional, and national scales. A unique strength of soil sampling on existing NFI plots is that the >20 comprehensive physical and chemical soil properties can be paired with co-located site and vegetation data, whereas other landscape-scale inventories in the U.S. have focused only on soil-specific parameters (e.g., soil classification, soil C).

Globally, there are few other national-scale soil monitoring efforts, and they range widely in sampling design and focus (Table A1). Some, such as those in Canada, Sweden, Finland, and Norway, are also nested within broader national forest inventory efforts (Table A1), facilitating the integration of soil with vegetation data. A notable continent-wide soil survey is the BioSoil project, within the broader International Co-operative Programme on Assessment and Monitoring of Air Pollution Effects on Forests network (ICP Forests, http://www.icp-forests.net/), which spans most European forests and has been used to estimate baseline forest soil C stocks across the European Union (De Vos et al., 2015). Some countries (e.g., Canada and those involved in BioSoil, such as Finland, Germany, and the United Kingdom) have measured a broad suite of soil properties similar to FIA, while others (e.g., Mexico, Norway, South Korea, and Japan) have focused more narrowly on select attributes such as soil C or erosion (Table A1). The Swedish Forest Soil Inventory, one of the longest-running programs globally, is particularly notable for incorporating DNA-based soil fungal analyses since about 2015 (Lindahl et al., 2021) and is, to our knowledge, the only national program currently including microbial community monitoring at scale (Table A1; but see Section 4.2). The soil monitoring program of the U.S. NFI stands out for its scale and sample design, as well as its open data access. Unlike many national-scale inventories that use stratified or ecozone-based sample designs (e.g., Canada's National Forest Inventory or Mexico's National Forest and Soil Inventory), FIA employs a uniform, equal probability sampling grid, which can help to reduce bias. Whereas FIA soil data are openly available for download, access in other national programs often requires formal requests or is limited to partial datasets or summaries (Table A1). Despite differences among national soil monitoring efforts, these inventories share a growing recognition of forest soils as a critical component of national C accounting and forest health monitoring.

The U.S. NFI's soil monitoring program is the first and only national-scale forest soil inventory in the U.S. that explicitly includes detailed quantitative aboveground information with belowground data, but it has undergone regional changes in sampling schemes and protocols over time as information needs have evolved and budgets have changed. Our goal in this benchmarking paper is to describe the history, design, and status of the NFI's soil assessment, discuss how the data have and can be used, and review potential improvements and advances to address key limitations.

2. Overview of the NFI soil monitoring program

2.1. History

The FIA program within Forest Service Research and Development is a federal program that is congressionally mandated to deliver timely and nationally consistent information about trends in forest extent, productivity, and health within the U.S. and affiliated islands (Westfall et al., 2022a). Much has changed in the FIA program since the McSweeney-McNary Forestry Research Act of 1928 directed the Secretary of Agriculture to establish the NFI, which was then known as Forest Survey. What is now the soil monitoring component of the NFI was originally the "soil indicator" of the Environmental Monitoring and Assessment Program, a research program of the U.S. Environmental Protection Agency designed to develop tools for monitoring the status and trends of national ecological resources (Bechtold et al., 2007; Stolte and Lund, 1996). The soil indicator, along with other forest health indicators (crown condition, ozone bioindicator species, lichen abundance and diversity, down woody materials), was transferred to the USDA Forest Service Forest Health Monitoring (FHM) program with its formation by Federal and State agencies in the early 1990s due to increasing concerns about forest health with an initial focus on air pollution (Bechtold et al., 2007). The FHM program included four primary components: detection monitoring, evaluation monitoring, intensive site monitoring, and research on monitoring techniques. FHM further developed, tested, and implemented the indicators, which were selected as quantitative or qualitative variables that signal ecological information in a simple, cost-effective, repeatable manner (Kurtz et al., 2001) based on the indicators of the Montreal Process (Montreal Process Working Group, 1999). When assessed in conjunction with other monitoring and research data, indicators can help to assess the impacts of changes on ecosystem function (O'Neill et al., 2005).

Whereas the FHM program was focused on conducting forest health assessments, FIA, at the time, conducted forest inventories primarily to report on the status and trends of timber and woodland species, but FIA protocols did capture damaging agents and tree mortality. However, the detection monitoring part of FHM was transferred to FIA in 2000 with the passage of the Agricultural Research, Extension, and Education Reform Act of 1998 (Public Law 105–185; i.e., 1998 Farm Bill), effectively integrating the two plot networks to provide the means for repeated, systematic, nationally consistent sampling of forest health indicators while eventually extending FIA monitoring across all forestlands regardless of ownership. Thus, FIA expanded from primarily monitoring the area of the nation's forests and volume of the timber supply to also explicitly monitoring forest health and sustainability across all forestlands, such as reserved lands and National Forests. Beginning in 2001, the soil indicator was fully implemented as part of the FIA Forest Ecosystem Health Indicators program within the NFI (Randolph et al., 2020). While the 1998 Farm Bill led to a nationally consistent plot design, annual sampling, and a national database of publicly available data from the NFI (Burrill et al., 2024), much of the FIA program, including the soil monitoring component, is delivered through coordination across four FIA regions (Fig. 1a): Northern Research Station (NRS, previously North Central Research Station and Northeastern Research Station), Southern Research Station (SRS), Rocky Mountain Research Station (RMRS), and Pacific Northwest Research Station (PNWRS).

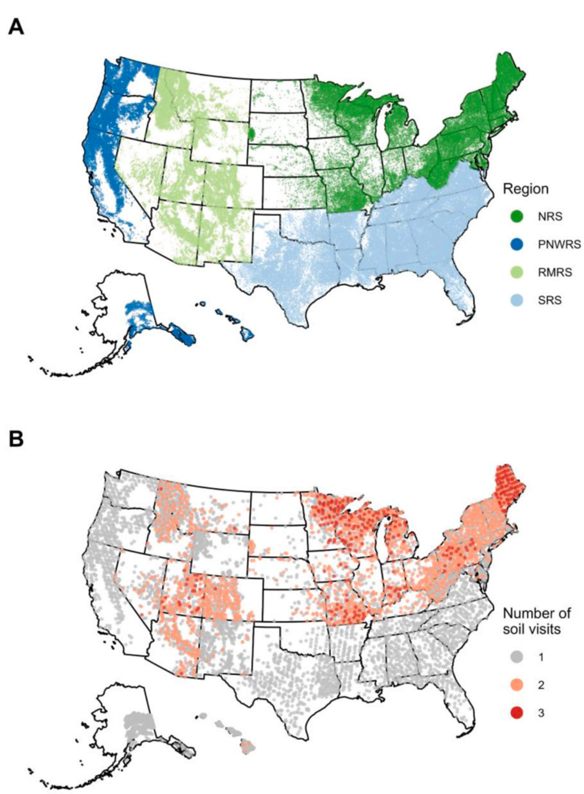

Fig. 1. (A) NFI base plots with at least one forested condition, colored by region. NRS=Northern Research Station, PNWRS=Pacific Northwest Research Station, RMRS=Rocky Mountain Research Station, SRS=Southern Research Station. N = 145,719 plots. (B) NFI base plots with at least one forested condition that have been visited by field crews for soil sampling and measurements, colored by the number of soil visits. N = 9917 plots (7612 with 1 visit, 1992 with 2 visits, 312 with 3 visits). Note that plot locations are approximate.

2.2. Sampling design and plot layout

The NFI sampling design is based on a grid of hexagons (2428 ha each) overlaid across the U.S. with one permanent plot located in each hexagon, thus creating an equal probability sample of the country's surface. Since the 1998 Farm Bill, data collection transitioned from a periodic inventory to an annual system, meaning that a spatially balanced subset across all plots is visited every year. Thus, hexagons are assigned to panels, which are measured on a rotating basis such that all plots within a panel are generally measured over 5 or 7 years in the Eastern U.S. and 10 years in the Western U.S. A cycle is considered complete when all plots containing accessible forestland within all panels have been measured.

The FIA inventory program consists of what were historically referred to as "phases": stratification (previously "Phase 1"), a base sample of ground plots (NFI; previously "Phase 2"), and a subset of the base sample in which forest health indicators are measured as an enhancement of the NFI (previously "Phase 3" or, even further back in time, "FHM"). Stratification is a pre-field process in which remotely sensed information is used to determine the proportion of land area represented by each stratum (i.e., land classification such as forest or nonforest) and to assign plots to those strata to reduce variance in estimates. Field crews then visit all accessible permanent ground plots that contain forestland (at least 10 % canopy cover, 0.4 ha in size, and 36.6 m wide) (Fig. 1a) and collect data on hundreds of variables, such as land ownership, forest type, tree species, tree size, slope, aspect, disturbance, land use, and others (U.S. Department of Agriculture, 2024a). There is one base intensity core plot for every 2428 ha of land. A broader suite of forest health attributes from the FHM program are measured in a subset of the base intensity core plots (U.S. Department of Agriculture, 2024b).

When sampling of the FIA Forest Ecosystem Health Indicators began in 2001, the sample consisted of a 1/16 subset of NFI plots (one plot per 38,850 ha) and soil samples were planned to be collected on each of those plots every 10 years, with different panel schedules among regions. As priorities shifted with funding levels, soil sampling across most NRS, PNWRS, and SRS states between about 2005–2010 stopped, with soil sampling continuing across RMRS (Table 1). However, the soil monitoring program was reinitiated in the NRS in 2012 during an update to the Forest Ecosystem Health Indicators program.

The updated Forest Ecosystem Health Indicators program includes a national set of "core" protocols but allows for flexibility in spatial and temporal sampling intensities to adapt to budgetary constraints, user needs, and regional issues (Randolph et al., 2020). Indeed, differences among regions emerged. Since the national-scale update in 2012, the NRS has selected two distinct, alternating 1/16 subsets of NFI plots for soil sampling (i.e., a total of 1/8 of all NFI plots). One subset consists of the original 1/16 selection from the NFI and the other subset consists of a new 1/16 selection. The two subsets alternate every cycle such that it takes roughly 10 or 14 years, depending on the state, to measure the full 1/8 soil sample for the NRS. In contrast, the RMRS moved to an "all-NFI" sampling scheme, with a long-term schedule for the gradual completion of at least one soil visit on all field-visited NFI plots. The PNWRS now only samples soils in interior Alaska and Hawai'i. Base NFI plot density in interior Alaska is at a lower intensity (1 plot per 12,141 ha) than the national standard, but soil sampling occurs on all field-visited NFI plots. In Hawai'i, soils are collected from all field-visited NFI plots with a forested condition. There is a planned remeasurement of soils every 10 years for Hawai'i if funding is available. The SRS did not reinitiate soil sampling, and thus there have not been any soil measurements across

Table 1
Summary of measurement years with visits to NFI plots for soil measurements ("Visits") and years of published data available in FIADB soil tables: "Lab": SOILS_LAB[a] table (lab chemical analyses); "Field-General": SOILS_SAMPLE_LOCATION[a] table (general field data; e.g., forest floor thickness); "Field-Erosion": SOILS_EROSION[b] table (field data specific to erosion models; e.g., % soil compaction). For FIADB tables, note that a year is included if any record exists for any state within the region for that measurement year (MEASYEAR; based on FIADB data accessed on March 4, 2025). Key areas within the PNWRS footprint are shown separately due to soil protocol differences.

	NRS	RMRS	SRS	PNWRS-Contiguous	PNWRS-Coastal Alaska	PNWRS-Interior Alaska	PNWRS-Hawai'i
Visits	2000–2005, 2012–2024	2000–2024	2003–2006, 2009–2010	2001, 2003–2008	2008–2010	2014, 2016–2024	2011–2012, 2019–2022
Lab	2000–2005	2000–2010, 2012–2023	2003–2006	2001, 2003–2006, 2008	2008–2010	2014, 2016–2020[1]	2011, 2019–2022[1]
Field-General	2000–2005, 2012–2023	2000–2023	2003–2006, 2009–2010	2001, 2003–2008	2008–2010	2014, 2016–2020[1]	2011–2012, 2019–2022[1]
Field-Erosion	2000–2005, 2012–2023	2000–2023	2003–2006, 2009–2010	2001, 2003–2008	2008–2010	NA[2]	NA[2]

[a] Interior Alaska and Hawai'i data from 2014 onwards are contained in the SUBP_SOIL_SAMPLE_LOC table (some field data) and SUBP_SOIL_SAMPLE_LAYER table (lab and some field data).
[b] Erosion-related measurements were not included in the soil protocol for interior Alaska and Hawai'i.

that region since the early 2000s (Table 1). Note that soil sampling targets (e.g., 1/8 of NFI plots) may never be fully achieved because, for example, there may be hazardous conditions on a selected plot or access to the field crew may be denied by a landowner (Westfall et al., 2022b).

Plot design is mostly consistent across regions. Each NFI plot represents a sampling area of about 0.07 ha and consists of 4 circular subplots (7.32 m radius) with subplots 2, 3, and 4 arranged in a triangle around the first, central subplot (36.6 m between plot centers, Fig. 2) (U.S. Department of Agriculture, 2023, 2024b). Standard forest inventory measurements and most forest health measurements are made within the subplots. Each subplot contains a microplot (2.07 m radius) offset from subplot center in which seedlings and saplings are tallied and measured (Fig. 2). Additionally, each subplot is encompassed by a circular macroplot (17.95 m radius), although not every region uses the macroplot for measurements. The zone between the concentric subplot and macroplot circle is called the annular ring and is used in some regions for measuring rare occurrences, such as very large trees, as well as limited destructive sampling, such as soil sampling. It is important to note that for ground plots that may contain accessible forest, field crews map plots by condition classes, including accessible forestland, non-forestland, census water, non-census water, and non-sampled with probability of forestland (Burrill et al., 2024), allowing for analyses by domains of interest and population estimates.

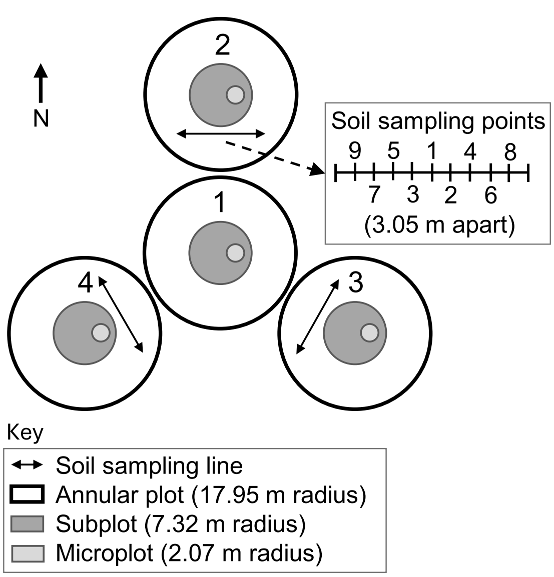

Fig. 2. FIA NFI plot design with soil sampling lines adjacent to subplots 2, 3, and 4. Each sampling line is located 9.14 m from subplot center at 180, 300, and 60° azimuths. The first soil sample is taken from soil sampling point 1, with subsequent samples alternating on opposite sides of the initial point. Adapted from Fig. 3 in O'Neill et al. (2005).

2.3. Soil measurements

The NFI's soil monitoring program measures a suite of soil attributes related to nutrient and water availability, degradation, the accumulation of toxic substances, acidification, and other metrics that help to inform the sustainability of forests (Table 2). This includes soil erosion and compaction assessments within all subplots, as well as soil sampling with associated physical and chemical measurements adjacent to subplots 2, 3, and 4 (Fig. 2). Details on soil erosion and compaction assessments are beyond the scope of this review and can be found in O'Neill et al. (2005) and U.S. Department of Agriculture (2024b). Briefly, soil compaction measurements include visual assessments of the percent compacted area and type of soil compaction (e.g., rutted trail) (Table 2). Bulk density measurements taken in association with soil sampling described below may also provide information about soil compaction. FIA collects information designed to be used for modeling rates of soil erosion, such as visual assessments of the percent bare soil and soil texture estimates "by feel" during soil sampling (Table 2), along with variables like slope angle and vegetation structure assessed during other, non-soil plot measurements.

We focus on soil sampling and associated measurements herein (Table 2) (U.S. Department of Agriculture, 2024b). The following describes the basic FIA soil sampling and measurement protocol, but we note regional variations in subsequent paragraphs. FIA only collects soil if the sampling location is in an accessible forested condition. Samples of the forest floor (i.e., combined litter and duff, which correspond to the O_i and $O_e + O_a$ soil horizons) and mineral soil are collected within the annular plots along sampling lines adjacent to subplots 2, 3, and 4 (Fig. 2). The first sample is collected at soil sampling site 1, with subsequent samples in following years taken from alternating positions on opposite sides of the initial sampling point (3.05 m apart, Fig. 2). During this process, the depths of the litter layer alone and entire forest floor (litter + duff) are measured at the edges of a 30 cm diameter circular sampling frame at 4 cardinal directions. All organic forest floor materials less than 0.64 cm diameter are then collected. Depth to a restrictive horizon is also measured within the sampling frame by probing the soil 5 times (center + 4 cardinal directions) and recording the median depth measured to a maximum of 50 cm. Mineral soil is only collected adjacent to subplot 2 along the sampling line as described above. Once the forest floor has been collected, mineral soil is collected volumetrically in two intervals from 0 to 10 and 10 to 20 cm depths using an impact-driven bulk density corer (Art's Manufacturing and Supply Core Sampler

Table 2

Physical and chemical soil properties measured as part of the NFI soil monitoring program and associated tables and codes in the FIA Database (FIADB)[a].

Physical property	FIADB Table	Code	Description
Forest floor thickness (duff + litter layers)	SOILS_SAMPLE_LOC	FORFLTHK	Average forest floor thickness for the subplot (also available for each cardinal direction).
Litter layer thickness	SOILS_SAMPLE_LOC	LTRLRTHK	Average litter layer thickness for the subplot (also available for each cardinal direction).
Soil texture	SOILS_SAMPLE_LOC	TXTRLYR1, TXTRLYR2	A code indicating the soil texture for mineral layers 1 and 2 as estimated by hand in the field.
Depth to restrictive layer	SOILS_SAMPLE_LOC	DPTHSBSL	Depth to a restrictive layer.
Percent bare soil	SOILS_EROSION	SOILSPCT	Percentage of the subplot that is covered by bare soil (mineral or organic).
Percent soil compaction	SOILS_EROSION	COMPCPCT	Percentage of the subplot that exhibits evidence of compaction.
Type rutted trail code	SOILS_EROSION	TYPRTDCD	A binary code indicating that the type of compaction is a rutted trail.
Type compacted trail code	SOILS_EROSION	TYPCMPCD	A binary code indicating that the type of compaction is a compacted trail.
Type compacted area code	SOILS_EROSION	TYPAREACD	A binary code indicating that the type of compaction is a compacted area.
Type other code	SOILS_EROSION	TYPOTHRCD	A binary code indicating that the type of compaction is some other form. An explanation is entered in the plot notes.
Field moist soil weight	SOILS_LAB	FIELD_MOIST_SOIL_WT	The weight of the soil sample as received from the field.
Air dry soil weight	SOILS_LAB	AIR_DRY_SOIL_WT	The weight of the soil sample after air-drying at ambient temperature.
Oven dry soil weight	SOILS_LAB	OVEN_DRY_SOIL_WT	The calculated oven dry weight of the soil sample based on an oven-dried subsample.
Total water content percent	SOILS_LAB	TOTAL_WATER_CONTENT_PCT	The sum of 'field-moist to air-dry' and 'air-dry to oven-dry' water contents in percent. Note that this is calculated from two fields that are not present in the public SOILS_LAB table.
Bulk density	SOILS_LAB	BULK_DENSITY	Soil bulk density calculated as oven dry soil weight per unit volume of soil[b].
Percent coarse fraction	SOILS_LAB	COARSE_FRACTION_PCT	The percentage of mineral soil sample greater than 2 mm in size.

Chemical property	FIADB Table	Code	Description
Percent organic carbon	SOILS_LAB	C_ORG_PCT	Organic carbon in percent.
Percent inorganic carbon	SOILS_LAB	C_INORG_PCT	Inorganic carbon (carbonates) in percent.
Percent total carbon	SOILS_LAB	C_TOTAL_PCT	Total carbon (organic + inorganic) in percent.
Percent total nitrogen	SOILS_LAB	N_TOTAL_PCT	Total nitrogen in percent.
Soil pH	SOILS_LAB	PH_H2O, PH_CACL2	Soil pH, as measured in either a 1:1 soil/water suspension or 0.01 M $CaCl_2$ solution.
Exchangeable sodium	SOILS_LAB	EXCHNG_NA	Exchangeable sodium in mg kg^{-1}.
Exchangeable potassium	SOILS_LAB	EXCHNG_K	Exchangeable potassium in mg kg^{-1}.
Exchangeable magnesium	SOILS_LAB	EXCHNG_MG	Exchangeable magnesium in mg kg^{-1}.
Exchangeable calcium	SOILS_LAB	EXCHNG_CA	Exchangeable calcium in mg kg^{-1}.
Exchangeable aluminum	SOILS_LAB	EXCHNG_AL	Exchangeable aluminum in mg kg^{-1}.
Effective cation exchange capacity	SOILS_LAB	ECEC	Exchangeable sodium + potassium + magnesium + calcium + aluminum in cmolc kg^{-1}.
Exchangeable manganese	SOILS_LAB	EXCHNG_MN	Exchangeable manganese in mg kg^{-1}.
Exchangeable iron	SOILS_LAB	EXCHNG_FE	Exchangeable iron in mg kg^{-1}.
Exchangeable nickel	SOILS_LAB	EXCHNG_NI	Exchangeable nickel in mg kg^{-1}.
Exchangeable copper	SOILS_LAB	EXCHNG_CU	Exchangeable copper in mg kg^{-1}.
Exchangeable zinc	SOILS_LAB	EXCHNG_ZN	Exchangeable zinc in mg kg^{-1}.
Exchangeable cadmium	SOILS_LAB	EXCHNG_CD	Exchangeable cadmium in mg kg^{-1}.
Exchangeable lead	SOILS_LAB	EXCHNG_PB	Exchangeable lead in mg kg^{-1}.
Exchangeable sulfur	SOILS_LAB	EXCHNG_S	Exchangeable sulfur in mg kg^{-1}.
Extractable phosphorous	SOILS_LAB	BRAY1_P, OLSEN_P	Extractable phosphorus in mg kg^{-1} as measured by the Bray 1 method (best used if pH ≤ 6) and/or Olsen method (best used if pH > 6).

[a] Soil data for interior Alaska and Hawai'i from 2014 onwards can be found in SUBP_SOIL_SAMPLE_LOC and SUBP_SOIL_SAMPLE_LAYER tables, which use different schemas.

[b] Note that coarse materials are not accounted for in reported bulk density values in SOILS_LAB, but see Lang et al. (2025) for methods to use the percent coarse fraction field to adjust FIA bulk density data.

Model #910) with two 10-cm liners (inner diameter of 4.8 cm). Once samples are brought back to the lab, all samples (mineral and forest floor) are analyzed for moisture content, bulk density, total % C, organic % C (only some labs), inorganic % C (only some labs), total % nitrogen, and soil pH. Mineral soil samples are also analyzed for coarse fragment content (>2 mm), exchangeable cations (exchangeable potassium, calcium, magnesium, sodium, aluminum), plant available (extractable) phosphorous and sulfur, and micronutrients and trace metals (exchangeable manganese, iron, nickel, copper, zinc, cadmium, lead). Lab procedures are documented in Amacher et al. (2003).

There have been some opportunistic enhancements and necessary differences in soil sampling protocols for certain states or regions. The RMRS has implemented three lab-based enhancements of FIA soil data, all of which are being applied to samples collected since 2000, including older samples from PNWRS states (California, Oregon, Washington, and coastal Alaska) that are physically archived within RMRS. The three enhancements include: (1) laser particle size analysis, (2) dry-end moisture release curve development, and (3) mid-infrared spectral analysis. Particle size analysis data involve analysis of 60 soil particle size bins intended to provide accurate USDA soil texture classification, which is not possible with standard FIA field texture assessments. Detailed soil texture data have been shown to be useful for analysis of forest characteristics, such as regeneration rates (Puhlick et al., 2021). Development of dry-end moisture release curves is intended to provide potential data to support analysis of drought-related mortality in western states. A mid-infrared spectral library is being developed using FIA samples with existing lab data with the goal of potentially estimating physical and chemical properties of future soil samples, thereby replacing costly lab analyses for some attributes. Enhanced soil data from the RMRS will be fully integrated into FIA systems where and when appropriate.

The PNWRS used the standard FIA soil sampling protocol in contiguous states until 2008 and coastal Alaska through 2011, but, due to limited funding, now only collects soils in Hawai'i and interior Alaska (Table 1). State partners and researchers in both states support these efforts by helping to review and/or analyze the soil data. Given unique soils and challenges in both states, Hawaiʻi and interior Alaska soil protocols have deviated from the basic protocol described above in several key aspects. In Hawaiʻi, forest floor depth is measured (with litter and duff layers measured separately), but no forest floor material is collected or analyzed. Mineral soils in Hawaiʻi are collected volumetrically in 20-cm increments down to a maximum depth of 100 cm along the standard sampling line adjacent to subplot 2. Each increment is only analyzed for bulk density, total (inorganic + organic) % C, and total % nitrogen. Additional details for the Hawaiʻi soils protocol can be found in Forest Inventory and Analysis (2021). In interior Alaska, soils are sampled along the standard sampling lines adjacent to subplots 2, 3, and 4, meaning that mineral soil is collected from three, rather than one, locations per plot. Crews measure the depth of the active layer (i.e., current depth of thaw) and attempt to collect a sample of the entire organic soil profile, including 10.16 cm of mineral soil, volumetrically using a drill soil sampler (5.4 cm inner diameter). If deep organic layers are present, crews core to the maximum depth possible (about 1 m) or until obstruction (frozen soil or rocks). Given the risk of soil compacting thick, low density organic layers when collecting deep cores, depth of the cored hole and length of the core are both recorded to help identify potential compaction. Depths of various horizons are recorded once the core is removed, including live moss/lichen, identifiable plant parts (similar to the O_i layer), unidentifiable plant parts (similar to the $O_e + O_a$ layer), mineral soil, and, rarely, unknown material if present at the bottom of the core. These layers are separately collected, and each is analyzed for bulk density, total (inorganic + organic) % C, and total % nitrogen. Soil pH is also determined for the mineral soil layer. Additional details for the interior Alaska soils protocol can be found in Forest Inventory and Analysis (2023).

3. Data availability and usage

3.1. Overview

Soil visits and the availability of soil data are variable across years and regions (Table 1, Fig. 1b) and are partly dependent on planned remeasurement intervals. To date, nearly 10,000 forested NFI plots have been sampled for soil analyses nationwide, representing about 7 % of NFI base plots containing forestland. Of the plots with soil visits, approximately 23 % have been visited more than once. Data collected in the field are generally available for all but the most recent years with soil visits (Table 1) as dictated by FIA data publication workflows. However, lab data availability has greatly lagged soil visits for the NRS due to logistical barriers that created a backlog in the processing of raw lab data. Efforts are currently underway at the NRS to publish lab data since 2012 and address bottlenecks. Despite this lag, individual NRS states have either nearly or fully completed soil visits for all forested plots selected for soil sampling, and thus the NRS intends to exclusively revisit soil plots as of the 2026 inventory year based on the current plan. The number of plots with two or more soil visits is rapidly growing in the NRS and RMRS regions, but soil remeasurements are scarce in the SRS and contiguous PNWRS regions, where soil monitoring has stopped.

Despite some gaps in data availability, the NFI soil data have been used for diverse publications and applications. New frameworks for estimating soil C stocks across the U.S. were developed with NFI and International Soil Carbon Network data (Domke et al., 2016, 2017), replacing older methods that did not use direct soil measurements and instead relied on models in which soil C estimates depended on geographic region and forest type or, for forest floor C, stand age (U.S. Environmental Protection Agency, 2008; Smith and Heath, 2002). These new methods resulted in a 44 % decrease (-2 Pg) in estimates of forest floor C stocks (Domke et al., 2016) and a 65 % increase (+11 Pg) in estimates of mineral SOC stocks (to a depth of 100 cm) (Domke et al., 2017) on U.S. forestlands. Estimates of forest floor and mineral soil (0–20 cm) C stocks were then combined with remotely sensed data (LANDSAT imagery and other environmental raster data) and spatially expanded from site-specific point measurements to continuous measurements across all pixels of the conterminous U.S., providing much greater spatial detail (Cao et al., 2019). This new estimation framework is used to produce authoritative forest sector C stock estimates reported in the National Greenhouse Gas Inventory for the United Nations Framework Convention on Climate Change (U.S. Environmental Protection Agency, 2024). Soil data from the NFI and International Soil Carbon Network were also integrated with remote sensing data to estimate C stocks in topsoil of cultivated lands, reforesting lands, and natural forests across the U.S. (Nave et al., 2018). Additionally, NFI forest floor and mineral soil C data have been used to assess the impacts of land use, disturbance, and management on SOC stocks in various U.S. regions (Nave et al., 2021, 2022a, 2022b, 2024, 2025).

Beyond quantifying C stocks, studies have used NFI soil data for investigations of aboveground-belowground dynamics, to enhance understanding of responses to disturbances, and for reporting. For instance, studies have paired coincident NFI forest floor, mineral soil, and forest community structure data to assess the drivers of tree-mycorrhizal fungal associations and investigate relationships between forest tree mycorrhizal types and soil biogeochemistry or understory plant invasions (Averill et al., 2018; Fei et al., 2022; Jo et al., 2018, 2019; Zhu et al., 2018). One finding from this work is that arbuscular mycorrhizal dominant forests, relative to ectomycorrhizal dominant forests, may be more vulnerable to understory plant invasions because they exhibit greater soil nutrient availability and thinner forest floor layers, indicating that current shifts towards arbuscular mycorrhizal dominated forests in the eastern U.S. could facilitate invasions and accelerate nitrogen cycling (Jo et al., 2018, 2019). NFI soil data were used to investigate the factors regulating soil and live tree C pools in interior Alaska, finding that wildfire-mediated shifts in forest type from coniferous to deciduous reduced soil C pools by 20 % (Cahoon et al., 2022). NFI soil properties have also been included in forest health assessments, such as for the Allegheny National Forest in Pennsylvania after multiple disturbance agents caused extensive tree mortality (Morin et al., 2006). The National Report on Sustainable Forests routinely includes NFI soil data, particularly to assess soil erosion potential, soil compaction, overall soil quality, and to monitor soil acidification (Amacher et al., 2020; McGinley et al., 2023). The RMRS has used soil data, including from enhanced texture analysis, to aid prediction of ponderosa pine reproduction (Puhlick et al., 2021). The RMRS and NRS have also included soil data in state-level reporting (e.g., DeBlander et al., 2010; McWilliams et al., 2007; Shaw et al., 2018; Thompson et al., 2010; Witt et al., 2012; Woodall et al., 2005).

Other potential applications of NFI soil data are diverse, ranging from analyses of change in soil attributes over time to investigations of aboveground-belowground relationships. Here, we demonstrate regional to national applications of these data with brief examples that focus on issues of interest across the U.S.

3.2. Case study: soil C stocks across space and time in the contiguous U.S

Understanding the spatial distribution of soil C content and its temporal dynamics is critical for assessing soil quality and function and for efforts to mitigate increasing atmospheric carbon dioxide concentration. Field measurements of soil C provide direct, region-specific data that may be used for targeted management, developing and verifying C budgets, and informing policies. We calculated total (organic + inorganic) mineral soil C stocks to a depth of 20 cm using direct measurements of soil C concentration, bulk density, and coarse fragment content from 2858 forested plots across the contiguous U.S. (Fig. 3). Average soil C stocks were 59 Mg ha^{-1} in the NRS region, 36 Mg ha^{-1} in the SRS region, 40 Mg ha^{-1} in the RMRS region, and 44 Mg ha^{-1} in the contiguous PNWRS region (Fig. 3a).

Given that the organic C fraction in fine soil is particularly sensitive to environmental changes and disturbances, we also evaluated temporal shifts in SOC stocks across plots with soil data available from two

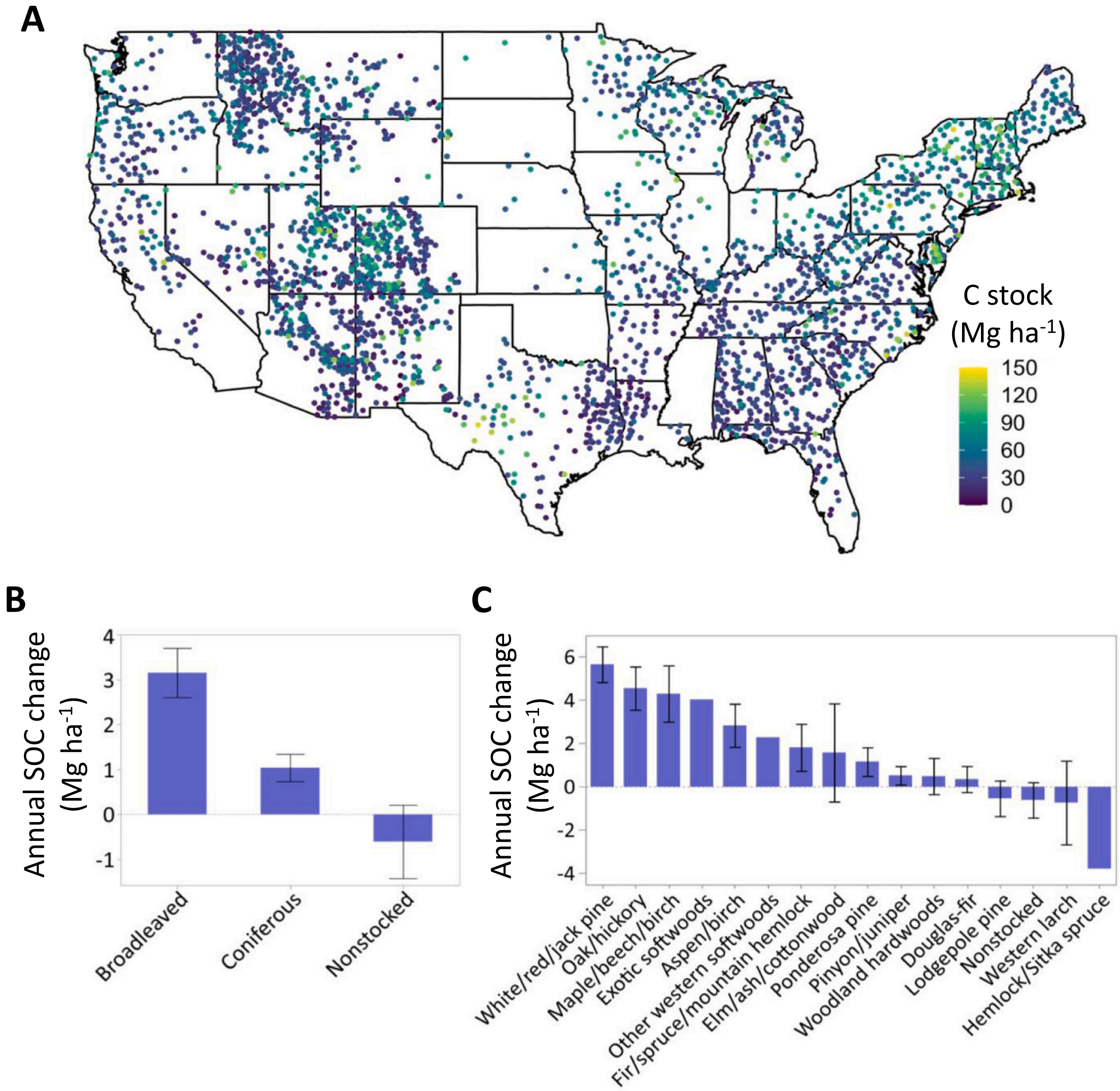

Fig. 3. (A) Mineral soil carbon stocks (Mg ha^{-1}) to a depth of 20 cm across plots containing forestland in the contiguous U.S. based on the most recent FIA soil measurement available for each plot. N = 2858 plots. (B) Mean annual change in soil organic carbon (SOC) to a depth of 20 cm in fine soil across broadleaved, coniferous, or nonstocked plots. Nonstocked forestland is land that currently has < 10 % stocking, but formerly met the definition of forestland. (C) Mean annual change in SOC in fine soil to a depth of 20 cm across forest types. N = 255 plots for panels B and C; only plots with values for both intervals of mineral soil depth at the first and second soil measurements were used. Error bars represent standard error. Note that plot locations are approximate.

measurement times. On average, SOC increased by 1.9 ± 0.3 Mg ha^{-1} per year (representing a ~5 % increase each year relative to time 1) across remeasured plots, of which 67 % are in the RMRS footprint, 26 % are in the NRS footprint, and 7 % are in the SRS footprint. Notably, mean annual SOC gains were 4x greater in deciduous dominated plots compared to coniferous dominated plots, while the few nonstocked plots sampled (n = 6) showed an average decline in SOC (Fig. 3b). Further classification of plots into specific forest type groups revealed a range of mean annual changes in SOC among groups, with the greatest gains in SOC for the white/red/jack pine forest type (5.7 Mg ha^{-1} y^{-1}), whereas lodgepole pine, western larch, hemlock/Sitka spruce, and nonstocked plots experienced SOC losses on average. It is important to note that as the data are split into more groups, sample sizes invariably decline (ranging from 1 to 66 plots for the categories in Fig. 3c), but the power to detect differences among finer classifications will increase as more remeasurement data become available. The direct measurements available to date suggest that broadleaved forests have generally gained more SOC than coniferous forests, possibly because coniferous forests may be more prone to fire and pest outbreaks.

3.3. Case study: sugar maple dieback and soil calcium:aluminum ratios in the northeastern U.S

FIA data can be used to investigate relationships between soil properties and forest health. In the northeastern U.S., sugar maple (*Acer saccharum*) decline has been a focal concern since the 1980s (Horsley et al., 2002; Schaberg et al., 2006). Sugar maple is an ecologically and economically important species, comprising a large proportion of northern hardwood forests in the northeastern U.S. region. Studies have suggested that increased aluminum mobilization and soil calcium depletion in association with acid rain may be a key contributor to sugar maple decline (Halman et al., 2013; Moore and Houle, 2023; Schaberg et al., 2006; Wilmot et al., 1995) and that the soil calcium:aluminum ratio may serve as a useful forest health indicator (Cronan and Grigal, 1995). However, few studies have jointly assessed the relationship of soil calcium:aluminum ratios and sugar maple health broadly across the northeastern region (but see Perry and Amacher, 2012). We used FIA data from plots containing sugar maple in the area most impacted by the deposition of sulfur dioxide and nitrogen oxides during the early 2000s (New York, Pennsylvania, West Virginia, and Ohio; U.S. Environmental

Protection Agency, 2025) to calculate mineral soil calcium:aluminum molar ratios and the proportion of sugar maple trees per plot with high (>15 %) crown dieback. We binned the data into "early" (2000–2005) and "late" (2012–2021) time periods based on soil data availability and the interval over which nitrogen and especially sulfur deposition declined (U.S. Environmental Protection Agency, 2025).

We found that average soil calcium:aluminum ratios increased from the early to the late period by 7.2x at a depth of 0–10 cm and by 6.3x at a depth of 10–20 cm (Fig. 4a), while the proportion of sugar maple crowns with high crown dieback declined by 67 % (Fig. 4b). Increases in soil calcium:aluminum ratios were due to both declines in aluminum and increases in calcium over time. Specifically, the average annual rate of change in soil exchangeable aluminum was −4.9 mg kg^{-1} y^{-1} from 0 to 10 cm and −3.8 mg kg^{-1} y^{-1} from 10 to 20 cm. For soil exchangeable calcium, the average annual rate of change was + 18.9 mg kg^{-1} y^{-1} from 0 to 10 cm and + 11.4 mg kg^{-1} y^{-1} from 10 to 20 cm. These observations indicate that regulations to mitigate emissions and acid rain have positively influenced soil and forest health, underscoring the critical role of soil chemistry in forest health assessments and demonstrating the utility of coincident above and belowground FIA data.

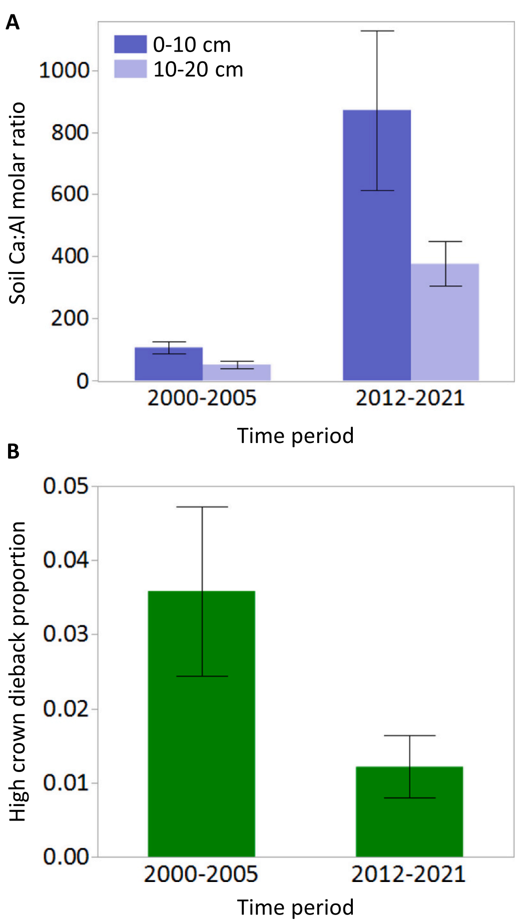

Fig. 4. Mean calcium to aluminum molar ratios (Ca:Al) in mineral soil at depths of 0–10 (dark blue) and 10–20 (light blue) cm (A) and mean proportion of live sugar maple trees (>12.7 cm diameter at breast height) per plot with high (>15 %) crown dieback (B) for NFI plots containing sugar maple in New York, Pennsylvania, West Virginia, and Ohio in the time periods 2000–2005 and 2012–2021. Panel A: N = 421 for 0–10 cm and N = 393 for 10–20 cm in 2000–2005; N = 654 for 0–10 cm and N = 627 for 10–20 cm in 2012–2021. Panel B: N = 181 in 2000–2005 and N = 294 in 2012–2021. Error bars represent standard error.

3.4. *Case study: the influence of tree species dominance on soil properties in Western U.S. forests*

FIA data provide a valuable opportunity to investigate relationships between forest species composition and several soil properties using direct, co-located measurements across large regions. While it is known that tree species can influence soil properties, the strength and nature of these effects can vary based on species, environmental context, and the soil properties or soil horizons measured. It may be expected that soil properties would strongly differ between pure (i.e., single species) stands, with mixed stands showing intermediate values. The widespread aspen (*Populus* spp.) and lodgepole pine (*Pinus contorta*) forests of the interior western U.S. present a particularly interesting opportunity to assess this relationship because they are largely unmanaged and tend to follow natural successional trajectories shaped by disturbances like insects, disease, and fire, which can variably shift species dominance over time. Thus, given the slow timescales over which many mineral soil properties change, it might be expected that mineral soil in these dynamic forests exhibits hysteresis – i.e., that properties are more reflective of the longer-term species dominance than current stand composition. We extracted FIA data for 10 soil properties from plots containing aspen or lodgepole pine. We classified the plots as either 'pure lodgepole' (>98 % lodgepole pine by basal area), 'pure aspen' (>98 % aspen by basal area), 'lodgepole dominant' (both species present; >50 % but <98 % lodgepole pine by basal area), or 'aspen dominant' (both species present; >50 % but <98 % aspen by basal area).

Our comparison (Fig. 5) revealed mixed results, but generally supported the expectation that mixed stands have mineral soil properties that are intermediate between those of pure stands of different species. For example, the values of most base cations (Ca^{2+}, Mg^{2+}, K^{+}), effective cation exchange capacity, pH, and inorganic C corresponded to the proportion of each species present (Fig. 5). Exchangeable sodium and aluminum showed no discernable patterns, although aluminum generally showed the expected pattern across pH levels (Aide, 2022). Although organic C and total nitrogen did not show the same clear ordering in mixed stands, the separation of these values between pure aspen and lodgepole pine plots overall was substantial (Fig. 5), indicating that upper mineral soil C and nitrogen are closely associated with the current dominant species.

Given the dynamic nature of these disturbance-prone forest types, our results can be interpreted as resulting from two possibilities: 1) upper mineral soil properties respond quickly to changes in cover type, or 2) the current forest types have been fairly persistent over time, such that mineral soil properties reflect the prevailing long-term cover. Future analyses could explore the role of disturbance, stand age, and other variables in determining whether soil properties are more reflective of long-term species dominance than current stand composition (i.e., hysteresis). Analyzing species mixtures as continua, rather than discrete categories, and comparing mineral soil properties to those of the forest floor, which may respond more quickly to change, may also offer deeper insights. Results from this type of analysis should become more definitive as soil characteristics are measured on an increasing variety of forest conditions, since this sample represents less than 7 % of the possible observations in the FIA plot network.

3.5. *Case study: spatial variation in C pools in Alaska's boreal forest*

Quantifying belowground physical and elemental characteristics in Alaska's boreal forest is a major focus of FIA due to the vast amount of C stored in the region (Genet et al., 2018; Jackson et al., 2017; Johnson et al., 2011). However, the remoteness and lack of infrastructure in the state present serious data collection challenges and have historically resulted in an unbalanced distribution of samples. Therefore, soil C data from the FIA network adds a critical element to existing estimates by sampling forest soils away from developed areas, broadening our inference of soil dynamics.

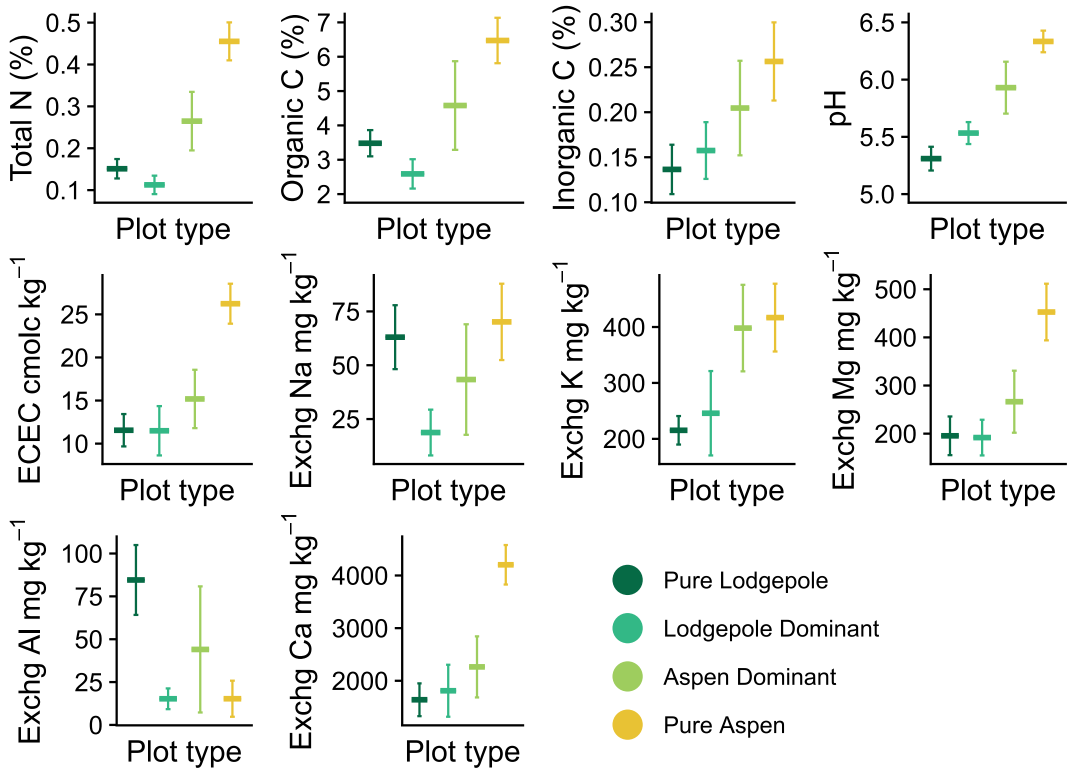

Fig. 5. Selected soil properties for stands with aspen, lodgepole pine, or both species present. Bars show means ± standard error and are organized from pure lodgepole pine (left) to pure aspen (right) to facilitate comparisons of soil properties across the compositional gradient. "Exchg"=Exchangeable. N = 40 for pure lodgepole pine; N = 9 for pine dominant; N = 8 for aspen dominant; N = 28 for pure aspen.

Between 2014 and 2019, FIA crews collected soil samples from 842 plots throughout two major inventory units in interior Alaska, an area roughly similar to the size of the state of Colorado (26 million hectares). Overall, the average soil C stock was 83.3 Mg ha^{-1}, and ranged from 51.2 Mg ha^{-1} in aspen forest types to 92.3 Mg ha^{-1} in black spruce forest types (Fig. 6a). Belowground patterns were broadly mirrored in live tree C, where the largest C stocks were found in deciduous forest types (17.7–24.5 Mg ha^{-1}) and mature white spruce (22.1 Mg ha^{-1}), but

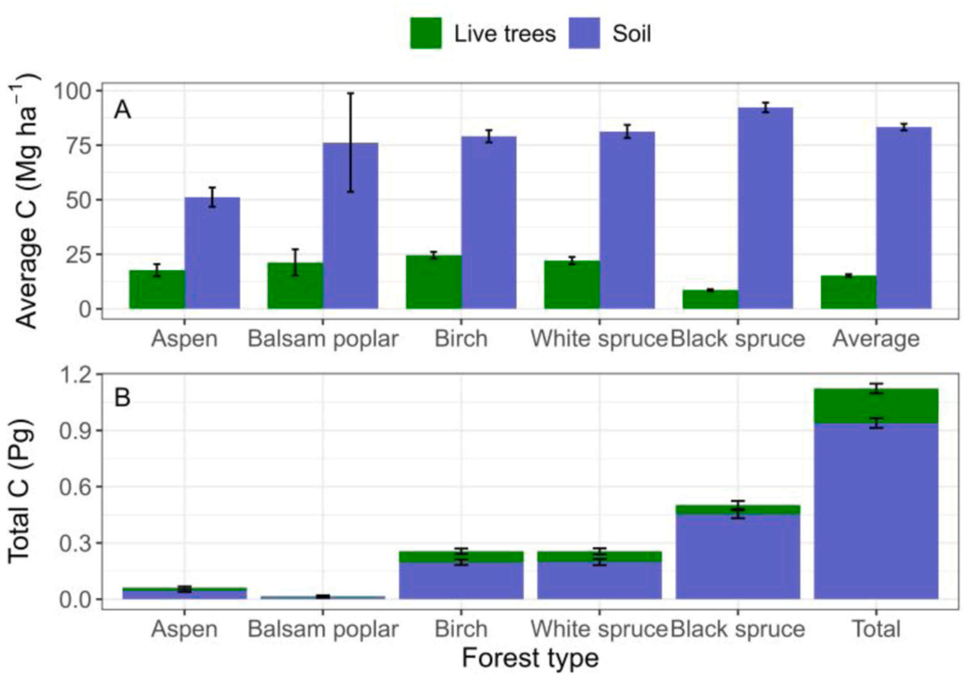

Fig. 6. Average (A) and total (B) C stocks in live trees and soil among forest types in the Tanana and Copper-Susitna inventory units in interior Alaska. Population estimates were generated using the methods outlined in Bechtold and Patterson (2005) and based on 842 forested plots. To ensure a complete sample of the soil profile and avoid the limiting influence of permafrost early in the growing season, soil C estimates excluded samples that did not include mineral soil.

smallest in black spruce stands (8.6 Mg ha^{-1}). When summed across live tree and belowground pools (Fig. 6b), soil C accounted for 77–90 % of ecosystem C, with the highest amount in black spruce forest types (0.453 Pg).

The variation among forest types in Fig. 6 represents the spatial heterogeneity among boreal ecosystems that is largely driven by species-specific adaptations to topo-edaphic characteristics and history of fire. For instance, black spruce is a slow-growing species capable of tolerating permafrost and anaerobic soil conditions that limit organic matter decomposition and lead to the build-up of soil C (Van Cleve et al., 1983). On the other hand, deciduous species often colonize areas with recent severe fires (Johnstone et al., 2010) and prefer warm, well-drained locations where organic inputs are rapidly decomposed. Our finding that nearly 50 % of total soil C is found among black spruce forest types has important implications for C management decisions and represents a large C pool that could be susceptible to disturbances such as fire and permafrost degradation.

3.6. Case study: variation in C pools and the influence of land use change in Hawaiian forests

The FIA soil monitoring program offers valuable insights into the spatial variability of soil C across the Hawaiian Islands, a region that is influenced by a complex interplay of climate, biophysical factors, land use history, and soil development. For example, steep gradients in rainfall, topography, and the age of parent material interact with legacies of plantation agriculture (mainly pineapple and sugarcane) to produce variation in soil C stocks across Hawaiʻi (Crow et al., 2023). Soil development stages vary between the young, and in some cases, still-forming volcanics of Kīlauea on Hawaiʻi Island compared to the progressively older islands to the northwest, with the main island chain culminating in the 5.1-million-year-old Kauaʻi (Moore and Clague, 1992). Additionally, moisture differences between the leeward and windward sides of the islands, driven by northeast trade winds, further affect vegetative communities and soil processes, including organic matter decomposition (Selmants et al., 2017). As a result, soils in tropical and subtropical environments differ from most temperate soils, with small-scale variations in vegetation and soil properties that are difficult to capture in predictive models.

We used data from 208 NFI plots sampled in 2019 to better understand the variation in soil and aboveground C stocks across the Hawaiian Islands. We observed a wide range of soil C stocks to a depth of 1 m, from 3.03 to 223.6 Mg C ha^{-1} (mean of 53.3 Mg C ha^{-1}) (Fig. 7a). Aboveground C stocks ranged from 0.19 to 717.6 Mg C ha^{-1} (mean of 86.1 Mg C ha^{-1}) (Fig. 7a). Site-specific climatic differences likely contributed to the observed variation in C stocks, as these plots have experienced varying rainfall, wet/dry periods, and temperature dynamics despite the absence of strong seasonality in Hawaiʻi's tropical climate. For instance, monthly rainfall ranged from 0 to 3290 mm, with a mean of 209 mm, and mean air temperature ranged from 15°C to 32°C (Hawaii Climate Data Portal, 1990–2024, Longman et al., 2024). Soil C stocks were generally greatest, and aboveground C stocks lowest, on mountain summits in Hawaiʻi (Fig. 7b), which may be due to higher rainfall, cooler temperatures, and less disturbance. Additional factors, such as land use

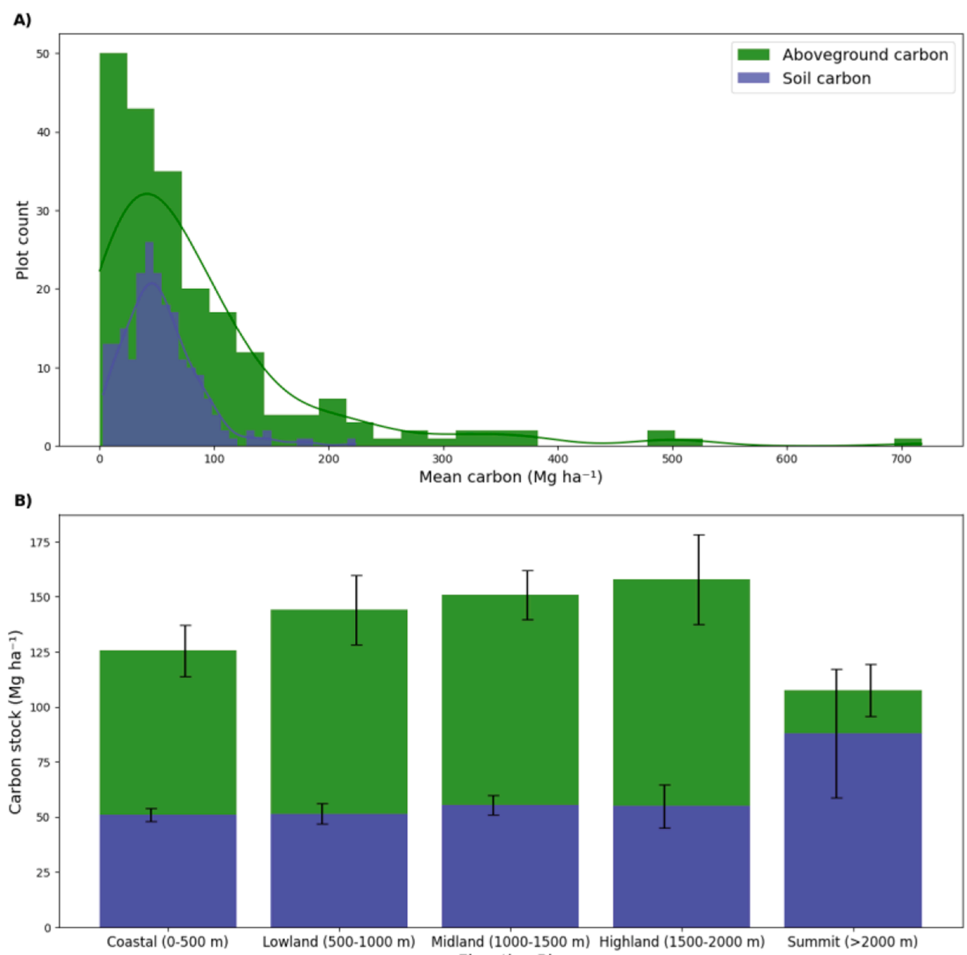

Fig. 7. A) Distribution of C stocks in aboveground biomass and soils to 1 m depth with smooth density estimation across 208 NFI plots sampled in 2019 in Hawaiʻi. B) Aboveground biomass C stocks and soil organic C stocks to 1 m depth by elevation bin for the same 208 NFI plots. Bars show means ± standard error.

legacies, also likely contributed to the observed C stock variation. To investigate the role of land use, we compared C stocks in forested NFI plots located on former intensive plantation lands (pineapple and sugarcane) to those in continuously forested areas with similar minimum and maximum annual temperature and rainfall. We found that, on average, soil C stocks in plots on former pineapple lands were 33 % higher than in plots on former sugarcane lands and 57 % higher compared to continuously forested plots (Fig. 8b). In contrast, aboveground C was greatest in plots on former sugarcane lands on average (Fig. 8a). These data can be used to generate hypotheses about land use effects on above and belowground C stocks. For example, perhaps selective plantation establishment on higher quality soil led to the greater soil C stocks observed in former pineapple lands. In contrast, continuously forested plots may be found in less desireable topographic positions, which were not conducive to developing extensive tracts of plantation agriculture. Most pineapple plantations were established at elevations above 180 m, while sugarcane plantations were in the lower, flatter areas that facilitated easier irrigation (Bartholomew et al., 2012). The combination of frequent irrigation and deep tillage may have led to lower soil C in former sugarcane relative to former pineapple lands. These patterns highlight how NFI data can be used to explore the diverse drivers of C pools and suggest that factors beyond climate, such as land use legacies, may be influencing C accumulation in Hawaiian forests.

Collectively, these examples demonstrate the diverse contributions of NFI data to monitoring spatiotemporal soil patterns and addressing key challenges in forest health across the U.S. The ability to integrate soil, aboveground, and other ecological data from direct measurements across large spatial scales has been critical for ecological research and forest management. Ongoing soil monitoring combined with potential refinements of FIA protocols would position the program to continue documenting and reporting the status and trends of U.S. forest health while addressing emerging challenges.

4. Potential adaptations to address limitations and advance the FIA soil monitoring program

4.1. Shorter-term opportunities for improving delivery of a national base program

FIA's national base program includes collecting soil data using protocols that were "core" to the Forest Ecosystem Health Indicators program (U.S. Department of Agriculture, 2016) and now could be more thoroughly integrated into the NFI. Historically, this approach has accommodated spatial and temporal variation in the intensity of implementation across regions due to budget fluctuations and partner interests (Randolph et al., 2020; Renwick, 2023), but there is growing user expectation for a more uniform approach (Bush, 2024; Mazza and Guldin, 2022; Nave et al., 2021, 2022a, 2022b, 2024, 2025). While maintaining these flexibilities, the program strives to publish health indicator data to the FIA Database annually and contribute indicator analyses to FIA reports (Renwick, 2023). As we described above, there are currently spatial and temporal gaps in soil data collection and publication, variations in protocols, and opportunities to expand the inclusion of soil data in FIA reports and scientific publications.

The delivery of a truly national base program would be improved by addressing significant spatial gaps (i.e., southern U.S., Oregon, California, Washington) and resolving delays in lab data processing and publication (notably in the NRS region; Table 3). The cessation of soil sampling in the SRS region and in contiguous states of the PNWRS region was a response to balancing regional priorities defined by partners and agency leaders, funding, and staffing. However, the newly adopted use of direct NFI soil measurements for national-scale C estimation, the importance of long-term soil data to evaluate temporal changes, emerging threats to soils through global changes and disturbances, and the growing recognition of links between soils, forest health, and ecosystem function elucidate the value of systematic soil data. For example, the SRS region is a globally important C sink, particularly along the Appalachian Mountains, and the PNWRS region contains key C sinks and sources, including fire-prone and valuable timberland areas where comprehensive ecosystem C monitoring is vital (Domke et al., 2023; Friedlingstein et al., 2023; Jiang et al., 2022). Capturing these regions in the NFI soil monitoring program would improve the accuracy of C storage estimates in U.S. forests and tracking changes over time. Additionally, logistical bottlenecks in the publication of NRS soil data are being addressed, including the development of new quality assurance and quality control procedures.

To facilitate the re-integration of key states and regions into the soil program, a streamlined set of minimum "core" soil attributes could be established (Table 3). Prioritizing essential measurements, such forest floor thickness, C and nitrogen concentrations, coarse fragment content, and bulk density, could optimize the program's effectiveness. Less critical analyses, such as those for slowly changing minerals (e.g.,

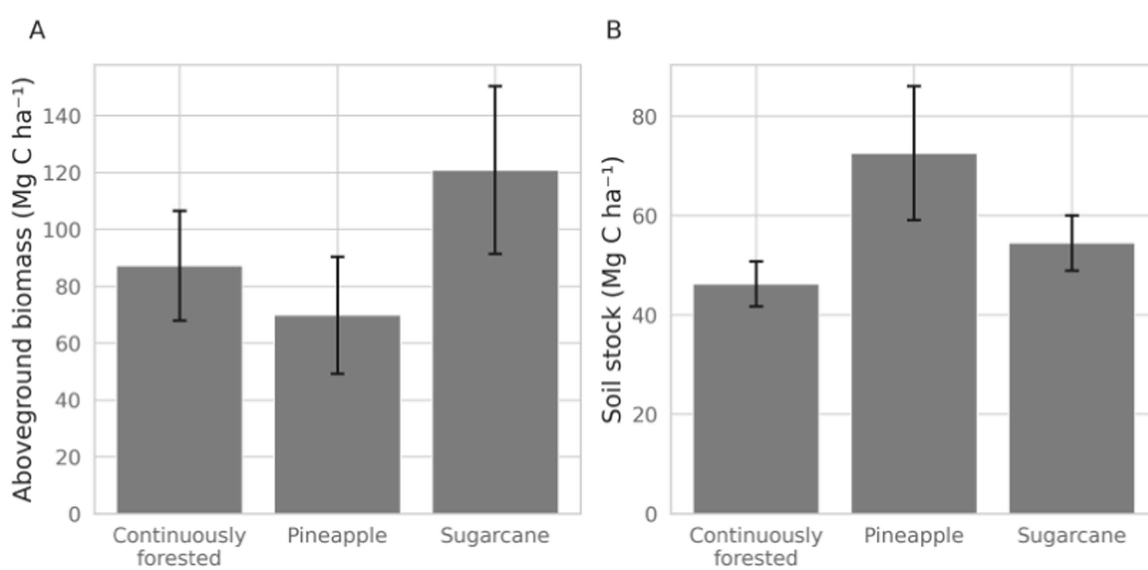

Fig. 8. Aboveground biomass C stocks (A) and soil organic C stocks to 1 m depth (B) in NFI forest plots that are located in reserved forests ("continuously forested"; N = 30), on former pineapple plantation lands ("pineapple"; N = 9), or on former sugarcane plantation lands ("sugarcane"; N = 20) in Hawaiʻi. Plots were sampled in 2019. Bars show means ± standard error.

Table 3
Potential adaptations to advance the FIA soil monitoring program.

Shorter-term opportunities for improving delivery of a national base program
• Define a set of "core" minimum soil attributes • Full national implementation of soil sampling • Address bottlenecks to distribute lab data in a timely manner • Develop national tables to store soil data from different protocols • Routine incorporation of soil data into FIA reports
Longer-term goals to enhance the research program
• Increase the sampling intensity of NFI plots • Increase the number of mineral soil cores extracted per plot (minimum of 3 cores) • Increase the depth of mineral soil core sampling (minimum of 30 cm) • Separately analyze litter and duff layers • Use advanced soil texture analyses • Characterize soil microbial communities

phosphorous, calcium, magnesium), might be performed less frequently or replaced by emerging predictive methods, such as those being piloted by the RMRS using soil spectra to estimate soil physical and chemical properties. These innovations could be used in certain years (e.g., every other remeasurement period), to increase sampling intensities while maintaining current costs, or to reduce costs while maintaining current sampling intensities.

While there is a desire to increase uniformity in the NFI soil protocol as implemented across the U.S., flexibilities are useful in locations like Alaska, where deep organic soil horizons and permafrost are common, and in Hawaiʻi, where there are young volcanic and highly sandy soils. While preserving necessary protocol differences, the program could develop data structures to incorporate the soils data collected via different methods in Alaska and Hawaiʻi into a new set of comprehensive FIADB soil tables where all of the national soil data could be housed (Table 3). This would facilitate national analyses both within and outside of FIA. Ultimately, developing a single national USDA database for harmonized soil data (i.e., integrating FIA and NRCS soil datasets) or an infrastructure allowing intercomparison among datasets would make it easier for researchers, land managers, and policymakers to access and use comprehensive soil information.

NFI soil data could be routinely included in FIA state reports (Table 3). These reports could include summarized data and trends for key soil health indicators like soil calcium:aluminum ratios, bulk density, toxic metal accumulation, pH levels, and nutrient availability, highlighting temporal trends if sufficient data are available. Integrating soil data with aboveground metrics, such as biomass, stand size and structure, biodiversity, forest type, crown dieback, and mortality shows promise for elucidating relationships between soil properties and forest attributes (Cahoon et al., 2022; Jo et al., 2019, 2018; Perry and Amacher, 2012; Perry and Zimmerman, 2012; Puhlick et al., 2021; also see case studies in sections 3.2 through 3.6 above). Additionally, soil data could provide insights into targeted regional or local issues of interest as demonstrated by the above case studies, such as wildfire impacts, potential effects of forest management practices, and declines in particular tree species due to pests or anthropogenic pressures, among others. Adding these summaries to FIA reports could provide a more comprehensive view of forest ecosystem health and enhance the basis for management decisions.

4.2. Longer-term goals to enhance the research program

The soil program of the NFI grew out of a direction to improve our understanding of forest productivity and sustainability, the conservation of soil and water resources, the accumulation of toxins, and contributions of forest soils to the global C cycle. The accelerating pace of global environmental change and impacts of other stressors have underscored soil data requirements related to understanding and monitoring disturbance effects (e.g., fire) and C pools, fluxes, and drivers. As FIA develops a new strategic plan, it is timely to consider changes to the NFI soil assessment to better address the growing use for detailed, systematic soil information focused on soil dynamics and responses to disturbances.

The ability of the NFI soil monitoring program to capture variation across different scales is limited and could be enhanced to improve C stock estimates and facilitate more accurate monitoring of changes over time. This could involve increasing sampling intensity and/or taking additional soil samples per plot (Table 3). With a 1/8 sampling intensity (as for NRS), each FIA soil plot represents 19,425 ha of forestland. While this scale is adequate for evaluating broad trends at state to national levels, it may not be as effective for guiding smaller-scale management or for evaluating disturbance impacts, especially given low sample sizes for specific disturbances. By gradually sampling soils from each base NFI plot (as the RMRS aims to do), each plot would represent 2428 ha of forestland. This could be done by using a panel system like the one for aboveground data but perhaps on a slower cycle, with consideration that soil samples represent soil attributes over varying time windows (e.g., months to years for soil pH and nitrogen, years to decades for C, decades to centuries for exchangeable nutrients or metals that are driven by parent material, such as magnesium). The higher spatial intensity could help to inform management decisions at smaller spatial scales (hundreds of thousands of hectares; e.g., forest, landscape, county), significantly improve coverage of environmental gradients (e.g., elevation, temperature, precipitation, soil type), and increase sample sizes across disturbances, management treatments, forest types, and successional stages. This approach may better support research, monitoring, and modeling efforts, such as by providing more comprehensive modeling inputs for digital soil mapping approaches. Each successive, spatially balanced panel would provide population estimates, but it could be several decades before an individual plot is remeasured depending on the length of the soil remeasurement period, resulting in a rolling view of temporal trends with less emphasis on repeat measurements.

Alternatively (or in addition), if the program is prioritized to capture small-scale spatial variability, refine the accuracy of plot measurements, or track changes within individual plots over time (e.g., in response to disturbances), then increasing the number of mineral soil cores taken per plot could be effective. Under the current protocol (except for interior Alaska), one mineral soil core is extracted adjacent to one subplot per plot, and “repeat” measurements in subsequent years are taken from a location 3 m away. Although resampling the exact same plots helps to reduce uncertainty in change estimates (Heim et al., 2009), small-scale soil variability can be substantial (Conant et al., 2003; Vanguelova et al., 2016). Therefore, it is challenging to effectively distinguish spatial variability from temporal change. This can be partly overcome by using high sample sizes in analyses (e.g., regional-scale); however, sample sizes invariably decline as data are stratified by factors like forest or disturbance type. Taking one or more mineral soil cores adjacent to 3 or all 4 subplots would capture more local variation and allow within-plot variance to be calculated, improving the ability to disentangle spatial from temporal change, but would require additional field effort and analytical costs. As an intermediate option, extracting and homogenizing mineral soil cores from subplots 2, 3, and 4 (i.e., where the forest floor is already collected) would allow within-plot spatial variability to be captured, but not quantified, with minimal to moderate increases in field effort but no change in analytical costs. This approach of using composite soil samples has been shown to have minimal impact on plot-scale SOC estimates compared to analyzing individual samples separately (Vanguelova et al., 2016). A pilot study is underway in the RMRS region to assess the cost-benefit scenario of collecting and separately analyzing mineral soil samples from all three forest floor sampling locations and to better understand within-plot variation. Overall, a combined approach of increasing the number of NFI plots sampled while also taking additional soil cores per plot could maximize both coverage and precision, although it would require balancing costs and logistical considerations.

The NFI soil program might benefit from extending the depth of mineral soil sampling beyond the current 20 cm (Table 3) given that (1) most SOC in forests occurs below a depth of 20 cm (Jackson et al., 2017), (2) FIA currently models SOC to a depth of 1 m, aligning with historical U.S. reporting standards (U.S. Environmental Protection Agency, 2024), (3) the Intergovernmental Panel on Climate Change (IPCC) recommends sampling to a depth of at least 30 cm for C stock assessments, adding that "good practice" involves deeper sampling if data are available and land-use impacts support it (IPCC, 2006, 2019), and (4) deep SOC plays an active role in global C cycling and is sensitive to global change drivers, disturbances, and management (Harrison et al., 2011; Hicks Pries et al., 2023, 2017; Li et al., 2020). However, deeper soil sampling presents increased costs and logistical challenges. The RMRS pilot study mentioned above includes collecting mineral soil cores at a 20–30 cm depth interval in addition to the standard 0–10 and 10–20 cm intervals sampled in contiguous U.S. states, which will provide valuable insights for potential updates to the national soil protocol. Additionally, current differences in mineral soil sampling depths among Hawai'i (20-cm intervals), Alaska (0–10 cm), and other U.S. states (0–10 and 10–20 cm) present challenges for calculating national-scale C stocks using direct field measurements. Protocols could be modified to facilitate internal data harmonization, such as by designating shared sampling intervals among regions (e.g., 0–10 cm) even where deeper sampling is conducted. Future FIA soil efforts could also seek compatibility with other international soil inventories to support data harmonization and more comparable reporting. This would be similar to how FIA established a forestland definition that better aligned with international standards (Murray et al., 2025) and the implementation of the national-scale volume and biomass (NSVB) framework (Westfall et al., 2024), suggesting that similar harmonization efforts could be pursued for soil monitoring.

To improve estimates of SOC storage and better understand its drivers among different ecosystem components, the NFI could consider separately collecting and analyzing the litter (O_i) and duff ($O_e + O_a$) layers that comprise the current "forest floor" sample (Table 3). The litter layer is the uppermost soil layer and consists of recently fallen organic matter, such as leaves and twigs. Analyzing this layer can provide insights into organic matter accumulation and its impact on soil fertility and C storage (Berg, 2018; Heuck et al., 2018; Heuck and Spohn, 2016; Prescott and Vesterdal, 2021). Below the litter layer, the duff layer consists of partially decomposed organic material and is important for understanding soil structure, water retention, nutrient cycling, C storage, and fire potential (Cowan et al., 2020; Heuck et al., 2018; Heuck and Spohn, 2016; Miyanishi and Johnson, 2002; Prietzel et al., 2020). Duff typically has a higher density than litter (Chojnacky et al., 2009), however current NFI soil protocols for the contiguous U.S. only allow for the calculation of density, and therefore C content, of the combined litter and duff material (i.e., forest floor). A pilot study conducted on NFI plots in North Carolina, Virginia, and West Virginia indicated that separate analysis of litter and duff layers in the NFI could enhance the accuracy of C stock estimates and provide more accurate forest type-specific densities for each layer, information that can be used to estimate C stocks in these layers when only depth measurements are available (Chojnacky et al., 2009). Additionally, determining the distinct drivers of soil C storage in these layers and their potentially different responses to global changes, disturbances, and management practices could be important for effective forest management and SOC estimation. Separately collecting and analyzing litter and duff may necessitate additional training for field crews and would increase laboratory costs. Additional pilot studies could help evaluate the value of this approach.

The existing soil texture classification method used in the NFI is subjective and restricted to broad categories, limiting the utility of this important soil variable. More advanced soil texture analyses would provide detailed information on soil particle size distributions, enhancing understanding of soil structure and function and providing a useful attribute for soil modeling and related applications (Table 3). Soil texture is a fundamental property that influences soil water retention, aggregation, organic matter stabilization, nutrient availability, and susceptibility to compaction and erosion. For example, clay and silt content are key regulators of SOC stabilization, with fine-textured soils offering protection of organic C against microbial decomposition (Angst et al., 2021; Wiesmeier et al., 2019). Furthermore, soil texture may be a critical regulator of soil sensitivity to forest biomass harvesting, with coarse-textured soils experiencing more severe impacts from intense silvicultural treatments (Thiffault et al., 2011). By integrating soil texture analyses with other soil properties, researchers and land managers could better predict how soils will respond to changes in land use, climate, and management practices, and develop strategies to optimize soil C storage. As mentioned above, the RMRS is using laser particle size analysis, a relatively low-cost technique after initial investment, in a pilot study to provide significantly more detailed soil texture data than the current NFI method. This advanced technique offers accurate USDA soil texture classifications and would eliminate the field time required for soil texture assessment, allowing for more time to be allocated to other procedural improvements.

The absence of soil biological community data in the NFI represents a key limitation in assessing soil quality, and incorporating microbial community measurements could provide a more comprehensive understanding of soil function and better inform land management decisions (Table 3). Soil microbes play key roles in nutrient cycling, organic matter decomposition, C storage, soil structure formation, and influence plant health. Changes in microbial abundance, diversity, and activity can signal shifts in soil health and function that might not be apparent from physical or chemical analyses alone (Bastida et al., 2008; Paz-Ferreiro and Fu, 2013). However, interpreting microbial metrics can be challenging and context dependent (Fierer et al., 2021). For example, higher enzyme activities can be interpreted as higher availability of the nutrient the enzyme is targeting or, conversely, that the targeted nutrient is particularly limiting (Fierer et al., 2021). Therefore, focusing on microbial attributes from which we can infer specific soil conditions or processes that are otherwise difficult or expensive to measure at scale (e.g., trace gas emissions) might be most beneficial (Schimel and Schaeffer, 2012). These measurements should be consistently interpretable across soil and forest types or interpreted in a context-specific manner. DNA-based microbial community analyses offer a promising approach as a relatively rapid, cost-effective bioindicator, as the DNA pool of microbial communities often changes on a scale of months to years (Carini et al., 2020; Lauber et al., 2013), providing a temporally integrated metric of otherwise highly variable processes (e.g., nitrous oxide and methane emissions) (Fierer et al., 2021). Additionally, microbial taxa can be linked to specific ecosystem functions (Wagg et al., 2019) and soil microbial community structure is sensitive to management (Hartmann et al., 2012). The NRS is developing a database of mycorrhizal fungi diversity and distribution across the U.S. using DNA sequencing techniques on archived NFI soil samples. These independent data tables can be related to NFI vegetation data to determine how mycorrhizal fungi vary over space and time as a function of plant community composition (e.g., Lang et al., 2023). Additional large-scale studies that assess relationships between microbial and vegetation attributes could build the knowledge base needed to create actionable microbial bioindicators. Our understanding of the microbial community as sampled on the NFI soil network could also benefit from increased within-plot sampling due to the high spatial variability of soil microbial communities (Carini et al., 2020).

5. Summary

FIA has systematically monitored soils across U.S. forestlands over the last 25 years, providing critical data that have deepened our understanding of forest dynamics, informed sustainable management practices, and addressed challenges posed by global environmental change and forest disturbances. A major strength of the program is the integration of field-based soil data with co-located vegetation and ecological data, enabling more comprehensive assessments of forest ecosystems and insights into aboveground-belowground relationships. Additionally, as more soil plots are remeasured, new opportunities arise to examine spatiotemporal patterns in soil properties and their connections to aboveground dynamics, such as shifts in forest composition, structure, and mortality. However, challenges have emerged as resources and priorities have shifted, and changing pressures on forests have led to constantly evolving research and partner needs. Current priorities include ensuring national consistency, closing spatiotemporal data gaps, and enhancing the utility of NFI soil data for C stock estimation and understanding disturbance responses. Developing a streamlined "core" soil protocol aligned with FIA priorities would facilitate full national implementation of soil monitoring within the NFI, ensuring a uniform base program across regions while allowing for regional expansions when needed and tractable. Once the base program is fully implemented, further improvements could include adjustments to the sampling design (e.g., increased sampling intensity within and across plots), protocol modifications (e.g., deeper soil sampling, enhanced soil texture analysis), and the inclusion of additional soil attributes (e.g., soil microbial communities). These enhancements to optimize and advance the FIA soil monitoring program would provide critical insights to safeguard the health and sustainability of U.S. forests for generations to come.

CRediT authorship contribution statement

Melissa A. Pastore: Writing – review & editing, Writing – original draft, Visualization, Validation, Investigation, Formal analysis, Data curation, Conceptualization. **Ashley K. Lang:** Writing – review & editing, Visualization, Validation, Investigation, Formal analysis, Data curation, Conceptualization. **John D. Shaw:** Writing – review & editing, Writing – original draft, Visualization, Validation, Investigation, Formal analysis, Data curation, Conceptualization. **Sean M.P. Cahoon:** Writing – review & editing, Writing – original draft, Visualization, Validation, Investigation, Formal analysis, Data curation, Conceptualization. **Hayley Peter-Contesse:** Writing – review & editing, Writing – original draft, Visualization, Validation, Investigation, Formal analysis, Data curation, Conceptualization. **Suzanne M. Owen:** Writing – review & editing, Validation, Investigation, Data curation, Conceptualization. **Randall S. Morin:** Writing – review & editing, Validation, Investigation, Formal analysis, Data curation, Conceptualization. **Johnathan A. Knott:** Writing – review & editing, Conceptualization. **Grant M. Domke:** Writing – review & editing, Validation, Investigation, Data curation, Conceptualization. **Belinda Esham:** Writing – review & editing, Validation, Investigation, Data curation, Conceptualization. **Erin M. Berryman:** Writing – review & editing, Validation, Investigation, Data curation, Conceptualization.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.foreco.2025.123023.

Data availability

NFI data were obtained from the USDA Forest Service, FIA program. Publicly available FIA data are available through the FIA DataMart (https://apps.fs.usda.gov/fia/datamart/datamart.html).

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