The Soil Indicator of Forest Health in the Forest Inventory and Analysis Program

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Abstract—Montreal Process Criteria and Indicators (MPCI) were established to monitor forest conditions and trends to promote sustainable forest management. The Soil Indicator of forest health was developed and implemented within the USFS Forest Inventory and Analysis (FIA) program to assess condition and trends in forest soil quality in U.S. forests regardless of ownership. The Soil Indicator differs from intensive site monitoring programs in that it is a nationally applied, landscape-scale, grid-based design across all ecoregions, forest types, and land ownership categories. To date, the Soil Indicator has provided the only national assessment of soil erosion potential, areal extent of soil compaction, measured organic C stocks inventory, and soil physical and chemical properties of forest soils in the United States.

Introduction

Forested lands comprise approximately 750 million acres in the United States, about 33 percent of total land area (Smith and others, in press). Forest soils have unique properties, in part because of the types of vegetation, microbial activity, and soil organisms that influence forest soil development. But organisms are not the only factor influencing soil development. Soils on the landscape are the result of five interactive soil forming factors (Jenny 1994): parent material, climate, landscape position (topography), organisms (vegetation and soil organisms), and time.

Many external forces can have a profound influence on forest soil condition and hence forest health. These include agents of change or disturbances to apparent steady-state conditions such as shifts in climate, fire, insect and disease activities, land use activities, and land management actions. Yet, until recently, a systematic monitoring or assessment program that tracks changes in indicators of environmental condition for many resource bases was lacking.

The Montreal Process Criteria and Indicators (MPCI) program was developed to assess the condition and trend of forest resources of member countries (Montreal Process Working Group 2005). This information is used for sustainable forest management and includes indicators of forest health. The condition and trend of forest soils is part of those indicators of forest health that are inventoried by the USFS Forest Inventory and Analysis (FIA) program. This paper will review the development of the Soil Indicator of forest health and present a review and summary of recent Soil Indicator condition assessments. Topics to be covered include:

- Overview of FIA and forest health indicators program
- History of Soil Indicator development
- Forest health monitoring and the USFS integrated monitoring framework
- Broad-scale (landscape-scale) versus intensive site monitoring
- Attributes and strengths of forest health indicators including the Soil Indicator
- Soil Indicator monitoring questions and objectives
- Sampling design
- Field and laboratory analysis methods

- Quality control/quality assurance
- Data analysis and reporting framework including post-analysis stratification approaches
- Status of U.S. forest soils—review and summary of recent findings
- Sampling variability
- Soil Indicator weaknesses
- Soil Indicator and Soil Quality Standards monitoring

Forest Health Indicators and the FIA Program

The Soil Indicator and all other forest health indicators are part of the FIA program. FIA is the nation's forest census. It began some 80 years ago as a periodic inventory of timber resources and has evolved into a continuous, annualized inventory of U.S. forest resources across all public and private ownership categories (Smith 2008; USDA Forest Service 2009a).

FIA collects and reports data on the status and trend of

- Forest area and locations,
- Species, size, and health of trees,
- Total tree growth, mortality, and removals,
- Wood production and utilization,
- Forest land ownership, and
- Forest health.

Various indicators of forest health are included as part of the FIA program:

- Crown condition (Schomaker and others 2007)
- Ozone injury to vegetation (Smith and others 2007)
- Tree growth, damage, and mortality (Bechtold 2003a,b)
- Lichen communities (McCune 2000)
- Understory vegetation structure and diversity (Schulz and others 2009)
- Down woody material (Woodall and Monleon 2008)
- Soil quality (O'Neill and others 2005c)

Soil Indicator Development

Although a comprehensive history of the development of the Montreal Criteria and Indicators process and the development of the FIA indicators of forest health is beyond the scope of this paper, some historical background will be presented to indicate how the Soil Indicator evolved. The Soil Indicator actually began as part of the U.S. Environmental Protection Agency (EPA) Environmental Monitoring and Assessment Program (EMAP) (USEPA 2009a). The purpose of EMAP is to develop the tools needed to monitor and assess the status and trend of national ecological resources at multiple spatial and temporal scales (USEPA 2009a). But beyond that, forest status and trend assessment programs are driven by MPCI concepts and framework of sustainable ecosystems (Montreal Process Working Group 2005).

Following its beginnings within EMAP, the Soil Indicator was pilot tested throughout the 1990s within the Forest Health Monitoring (FHM) program. At the time, FIA conducted forest inventories whereas FHM conducted forest health assessments. In 2000, the FHM forest health indicators transitioned from FHM to FIA. By then, many changes, improvements, and add-ons had been made to the Soil Indicator. From 2001 onward, the Soil Indicator of forest health was fully implemented as part of the FIA forest health indicators program with little change to its core measurements and protocols.

Because the forest health indicators were developed within the FHM program, a brief review of the four core areas of FHM is needed to better understand overall indicator development and implementation. Forest Health Monitoring previously consisted of four programmatic areas:

- Detection monitoring—Uses the FIA P3 plot grid consisting of one plot for every 96,000 acres. Detection monitoring is used to uncover forest health threats as they develop.
- Evaluation monitoring—This is a more spatially intensive monitoring of forest health problems uncovered by Detection Monitoring. Examples would include intensified grid special project monitoring on National Forests.
- Intensive site monitoring (ISM)—Generally, more detailed, process-oriented research at specific sites. An example includes the joint USGS-USFS Delaware River Basin project (USDA Forest Service 2009b).
- Research on monitoring techniques (ROMT)—Basically, a monitoring tool development program.

The relationship among the various monitoring programs and scales can best be described with the USFS Integrated Monitoring Framework (fig. 1). In phase 1, remote sensing is used to delineate forest from nonforest lands. Next in scale are various local management inventories. These may be done using temporary or permanent plots at various spatial scales, for example, National Forest Systems (NFS) inventory projects on individual forests.

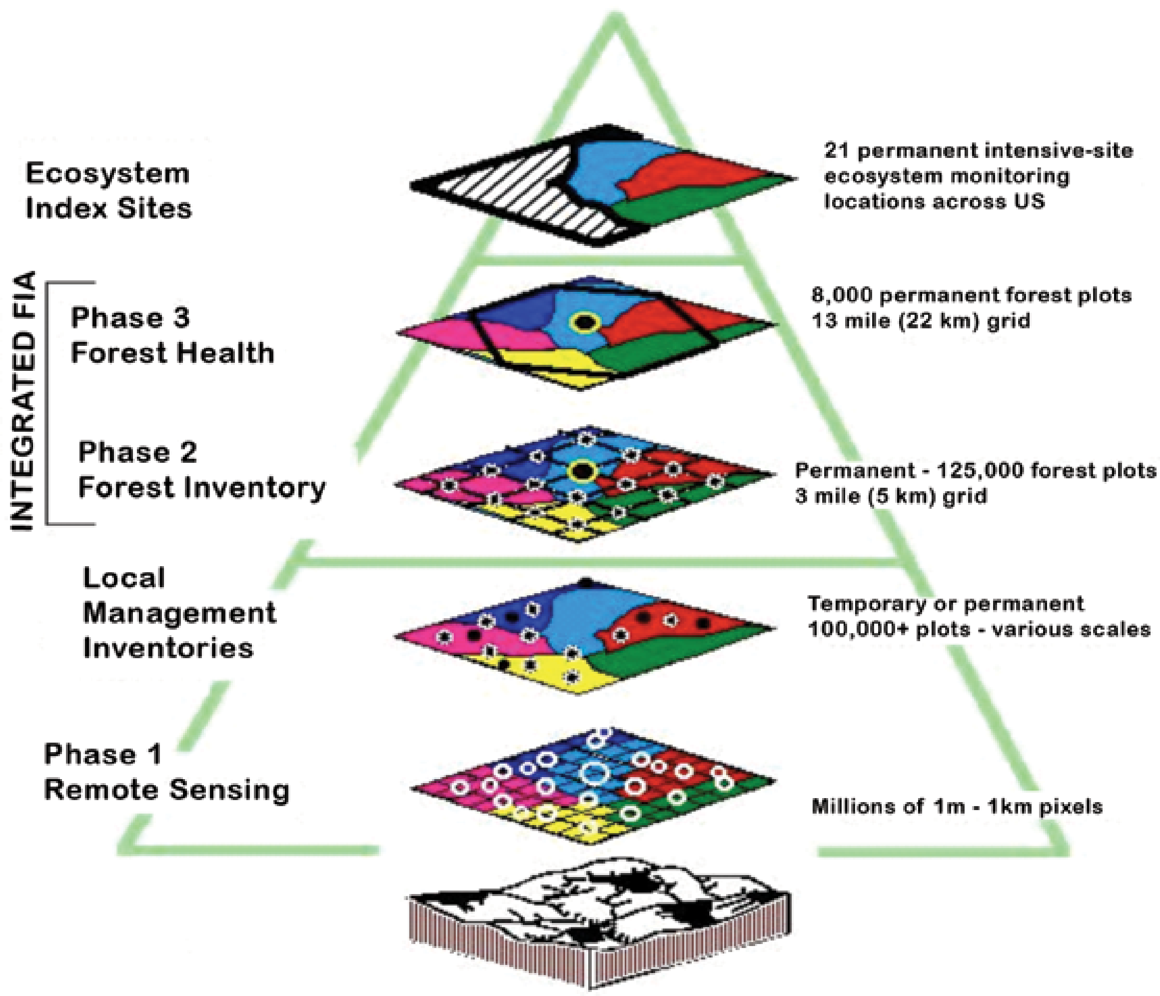


Figure 1. USFS integrated monitoring framework showing the relationship of FIA P1, P2, and P3 plot network to the forested landscape.

Field measurements in the integrated FIA program are done in two phases. Phase 2 (P2) is the annualized forest inventory and consists of a permanent plot network with approximately 125,000 forest plots on a 3-mile (5-km) grid. Phase 3 (P3) is the forest health monitoring part of the program and is a 1/16 subset of the P2 grid (about 7,800 permanent plots on a 13-mile (22-km) grid. Ecosystem index site monitoring consists of 21 permanent intensive monitoring sites across the United States.

Landscape-Scale Versus Intensive Site Monitoring

Figure 1 clearly shows the relationship among multiple spatial monitoring scales. At this point, it is worthwhile to contrast broad or landscape-scale monitoring with intensive site monitoring because the purpose and objectives of these two monitoring program are vastly different.

There are three main landscape-scale monitoring programs in the United States:

- USEPA EMAP—Develop the tools needed to monitor and assess the status and trend of national ecological resources at multiple spatial and temporal scales.
- National Resource Conservation Service (NRCS) programs:
    - National Cooperative Soil Survey (USDA NRCS 2007, 2008a)—Basically a soil mapping program.
    - National Resources Inventory (NRI) (Nusser and Goebel 1997; Nusser and others 1998; USDA NRCS 2008b)—Statistical survey of land-use and natural resource condition and trend on U.S. non-federal lands. The NRCS NRI is somewhat analogous to the Forest Service FIA program.
- U.S. Forest Service FIA (Smith 2002; USDA Forest Service 2009a)—Continuous, annualized inventory of U.S. forest resources across all public and private ownership categories. FIA collects and reports data on the status and trend of forest resources and forest health.

The principal similarity among all three programs is that they all collect data to assess condition and trend of various U.S. resources at the landscape scale using a grid-based monitoring system. Or to describe this in a simplified way, if you want to know what is going on 'out there,' you have to measure it. And 'it' needs to be measured at a sufficient spatial scale to provide a reasonably accurate snapshot of current conditions and to provide a suitable baseline to track future trends, if any.

A very different approach is used by intensive site monitoring projects. These tend to be focused on gaining a better understanding of ecosystems processes operating at a fixed number of sites representing key ecosystems or areas. They often rely on spatially and temporally intensive measurements to quantify key ecosystem processes. Findings from intensive site projects are often extrapolated elsewhere on the landscape. This works for sites with similar characteristics, but is unreliable for different areas.

The following are examples of intensive site monitoring networks:

- Experimental forests, rangelands, and watersheds (fig. 2) (Adams and others 2008; USDA Forest Service 2008);
- Long-term ecological research (LTER) sites (fig. 3) (Hobie and others 2003; U.S. Long Term Ecological Research 2007);
- Long-term soil productivity (LTSP) sites (fig. 4) (Powers and others 2005);
- Fire and fire-surrogate plots (fig. 5) (Fire Research and Management Exchange Systems 2008);
- National Ecological Observatory Network (NEON)—Continental-scale research platform for discovering and understanding impacts of climate change, land-use change, and invasive species on ecology (fig. 6) (National Ecological Observatory Network 2008); and
- Critical-Zone Exploration Network (CZEN)—Established to investigate the coupling between physical, chemical, geological, and biological processes in the critical (life-supporting) zone (Critical Zone Exploration Network 2008).

Figure 2. Map of experimental forests, rangelands, and watersheds in North America.

Figure 3. Map of long-term ecological research (LTER) sites in North America. The site names corresponding to the site abbreviations are AND = Andrews , ARC = Arctic, BES = Baltimore Ecosystem Study, BNZ = Bonanza Creek, CAP = Central Arizona – Phoenix, CCE = California Current Ecosystem, CDR = Cedar Creek, CWT = Coweeta, FCE = Florida Coastal Everglades, GCE = Georgia Coastal Ecosystems, HFR = Harvard Forest, HBR = Hubbard Brook, JRN = Jornada Basin, KBS = Kellogg Biological Station, KNZ = Konza, LUQ = Luquillo, MCM = McMurdo Dry Valleys, MCR = Moorea Coral Reef, NWT = Niwot Ridge, NTL = North Temperate Lakes, PAL = Palmer Station, PIE = Plum Island Ecosystem, SBC = Santa Barbara Coastal, SEV = Sevilleta, SGS = Shortgrass Steppe, VCR = Virginia Coastal Reserve.

Figure 4. Map of long-term soil productivity (LTSP) sites in North America.

Figure 5. Map of U.S. fire and fire surrogate plots.

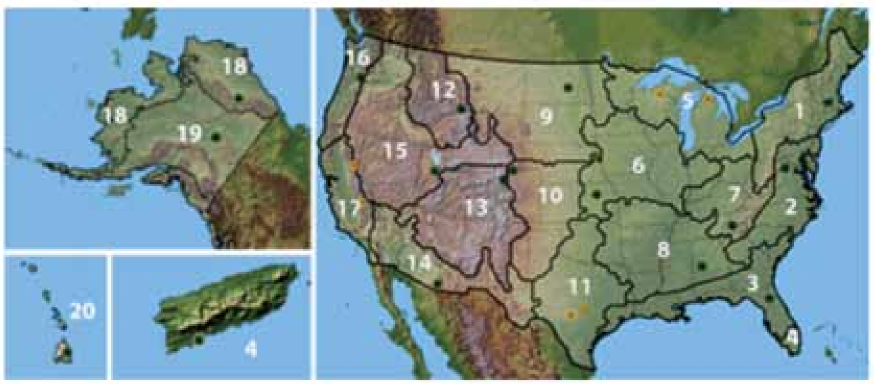


Figure 6. Map of National Ecological Observatory Network (NEON) monitoring areas. The core site areas corresponding to the numbered regions are 1 = Northeast, 2 = Mid-Atlantic, 3 = Southeast, 4 = Atlantic Neo-Tropical, 5 = Great Lakes, 6 = Prairie Peninsula, 7 = Appalachian Cumberland, 8 = Ozarks Complex, 9 = Northern Plains, 10 = Central Plains, 11 = Southern Plains, 12 = Northern Rockies, 13 = Southern Rockies, 14 = Desert Southwest, 15 = Great Basin, 16 = Pacific Northwest, 17 = Pacific Southwest, 18 = Tundra, 19 = Taiga, 20 = Pacific Tropical.

A main difference between NEON and CZEN is that NEON is more ecology oriented whereas CZEN is more geosciences oriented.

The landscape-scale and intensive site monitoring programs listed above tend to be land-based although they often include water and air measurements. There are monitoring programs run by the USEPA and U.S. Geological Survey (USGS) that are focused primarily on air and water quality assessments.

- Air quality monitoring
  - National Atmospheric Deposition Program (NADP) (National Atmospheric Deposition Program 2008)
  - Clean Air Status and Trends Network (CASTNET) (USEPA 2009b)
- Water quality monitoring
  - USEPA National Assessment Database (USEPA 2009c)
  - USGS Hydrologic Benchmark Network (HBN) (USGS 2002)
  - USGS National Stream Quality Accounting Network (NASQAN) (USGS 2009a)
  - USGS National Water Quality Assessment (NAWQA) (USGS 2009b)

One way to link landscape-scale and intensive site monitoring is to co-locate landscape-scale monitoring plots, such as FIA P3 plots, on intensive site monitoring areas. This provides a direct linkage between what would otherwise be disparate databases and allows for more reliable quantitative estimates of ecosystem states and rates of change. This approach was used for the joint USGS-USFS Delaware River Basin project.

Since this paper is an overview of the FIA Soil Indicator, it is instructive to list the key attributes of the Soil Indicator program:

- Condition and trend assessments at multiple spatial and temporal scales—detection and monitoring of soils-related forest health problems and threats;
- Integration with other forest data and with other forest health indicators;
- Standardized, unbiased, grid-based measurement and sampling design;
- A national and comprehensive scope: all U.S. forest lands are measured regardless of ownership; all ecoregions, forest types, and forest soil types are included;
- Standardized, reproducible, nationally consistent protocol;
- Standardized nationally consistent training;
- Quality Control and Quality Assurance (QC/QA) programs; and
- Standardized estimation and reporting of forest resources inventory data.

These key attributes are major strengths in that they directly overcome major weaknesses in intensive site monitoring programs. The Soil Indicator shares these attributes with other FIA program indicators.

Before turning to a detailed description of the Soil Indicator, we must also indicate that the Soil Indicator does not replace or overlap existing USDA NRCS soils programs. Specifically, the Soil Indicator is not a soil survey, is not a soil mapping program, and is not a soil characterization program, although it does characterize (measure properties of) some aspects of forest soils.

Soil Indicator and Monitoring Questions

The Soil Indicator was developed to specifically address monitoring questions posed by the Montreal Process Criteria and Indicators (MPCI): What is the current status and projected trend in the area and percent of forest land with

- Accelerated soil erosion?
- Compaction or change in soil physical properties resulting from human activities?
- Changes in the amount of moisture holding capacity, internal drainage, and rooting depth?
- Diminished soil organic matter and/or changes in other soil chemical properties?
- Contributions to the global carbon budget including absorption and release of carbon?
- Accumulations of persistent toxic substances?

Thus, in summary the FIA Soil Indicator provides data to assess (1) productivity and sustainability of forest ecosystems, (2) conservation of soil and water resources, (3) contributions of forest soils to the global carbon cycle, and (4) accumulation of persistent toxic substances.

Sampling Design

The USFS integrated monitoring framework was presented in figure 1. The statistical design of the integrated FIA program is based on a hexagonal grid or network of plots (Brand and others 2000; Bechtold and Patterson 2005). Grid density is illustrated in figure 7 using the state of Minnesota as an example. In phase 1 (P1), forest land is mapped via remote sensing using 3,000,000 national 1-m pixels. The forest map of Minnesota produced by phase I mapping is shown on the left side of figure 7. In phase 2 (P2), forest inventory data are collected on a national network of approximately 125,000 plots (3-mile grid) with each one representing 6,000 acres. P2 plot density for Minnesota is represented in the middle of figure 7. A 1/16 subset of P2 plots is used to collect forest health data. This phase 3 (P3) plot network consists of approximately 7,800 plots

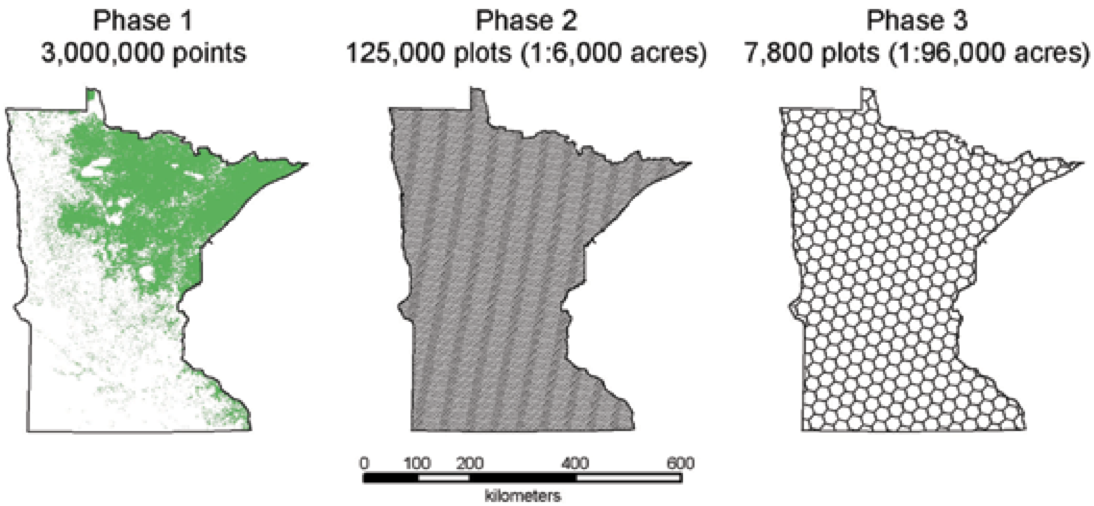


Figure 7. Map of hexagonal grid system scales using Minnesota as an example. The phase 1 (P1) grid consists of 3,000,000 points across the United States. A map of forested areas within Minnesota defined using this scale is shown on the left. The phase 2 (P2) grid consists of 125,000 plots (1 plot per 6,000 acres on a 3-mile (5-km) grid). P2 plot density for Minnesota is shown on the middle map. The phase 3 (P3) grid consists of 7,800 plots (1 plot per 96,000 acres on a 13-mile (22-km) grid). P3 plot density for Minnesota is shown on the right side map.

(13-mile grid) with each plot representing 96,000 acres. P3 plot density for Minnesota is shown on the right side of figure 7.

Figure 7 clearly shows that a hexagonal sampling design can be used at any spatial scale. Thus, sample 'hexes' can be virtually any size. The various FIA plots are assigned to the hexes. One of the requirements of the legislative authorization of the annualized FIA inventory is that plot locations are not released as public information. This is to protect landowner confidentiality. EMAP hexagons are often used to represent P3 data since they are approximately the same size. A national network of EMAP hexes containing a plot already visited for Soil Indicator measurement and sampling is shown on the U.S. map in fig. 8, but plot locations within the hexes are not disclosed.

The FIA program is a continuous annualized inventory of U.S. forest resources, but resources do not permit every plot to be assessed each year. Thus, hexes and plots within hexes are assigned to one of five panels and only one panel of plots (20% of plots) is sampled each year. In a 5-year cycle, all five panels would be visited and measured.

Each P3 plot is measured and sampled once every 10 years for Soil Indicator variables. In the eastern United States (Northern and Southern FIA regions), the Soil Indicator alternates with the Lichen Indicator over a 10-year cycle of the 5 panels of plots. In one cycle of 5 panels, each plot is sampled for soils over the 5-year cycle (one panel of plots per year). In the next 5-year cycle, each plot is sampled for lichens. Thus, after a 10-year cycle, the plots in the first panel are again sampled for Soil Indicator variables and so on. In the western United States (Interior West and Pacific West FIA regions), plots within each panel are assigned to sub-panels. In year 1, plots in sub-panel A of panel 1 are sampled. In year 2, plots in sub-panel B of panel 1 are sampled. In year 3, plots in sub-panel A of panel 2 are sampled, and so forth. Thus, it takes 10-years to visit each plot and then the process begins again. Thus, Soil Indicator data are collected on each plot in the East and West every 10 years, but the panel schedules differ among the FIA regions.

The standard FIA plot design consists of four circular subplots (24-ft radius) arranged in a triangle design with 120 ft between subplot centers (fig. 9). Forest inventory and forest health indicator measurements are made within each subplot. Surrounding each subplot is an annular plot (59-ft radius) reserved for sampling.

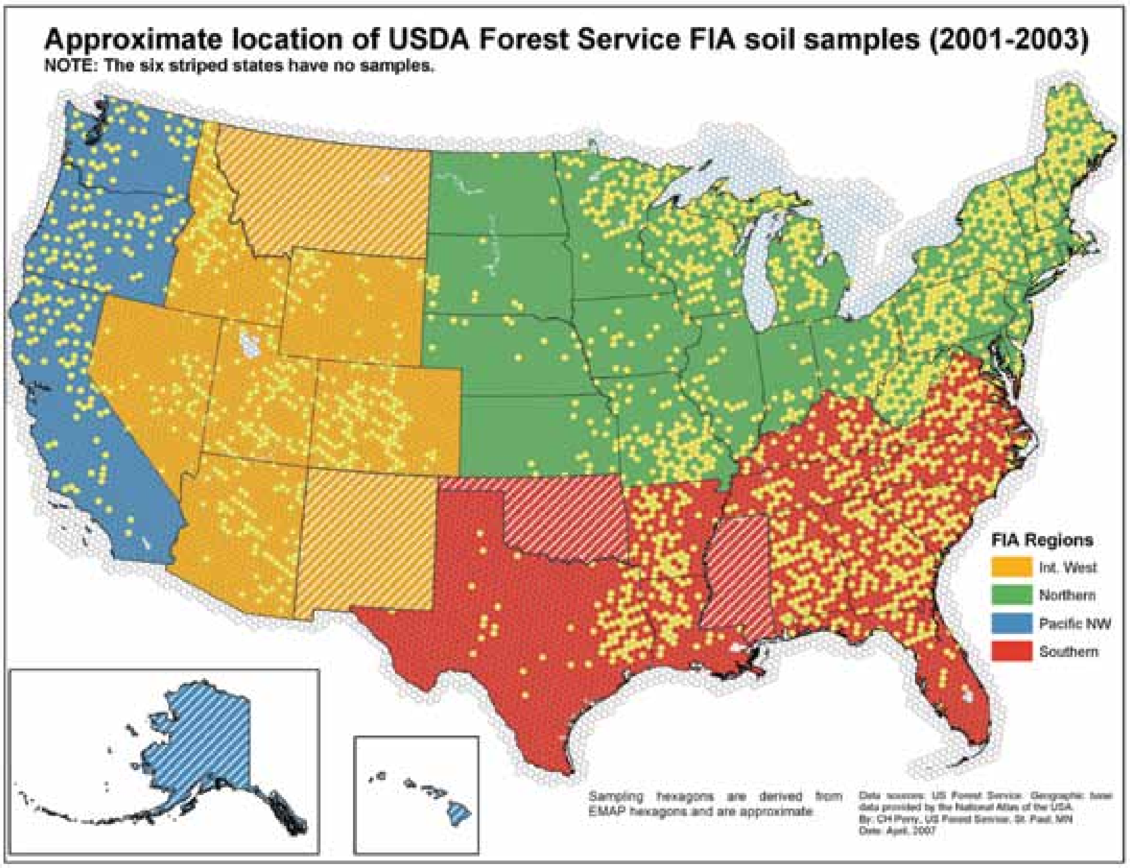
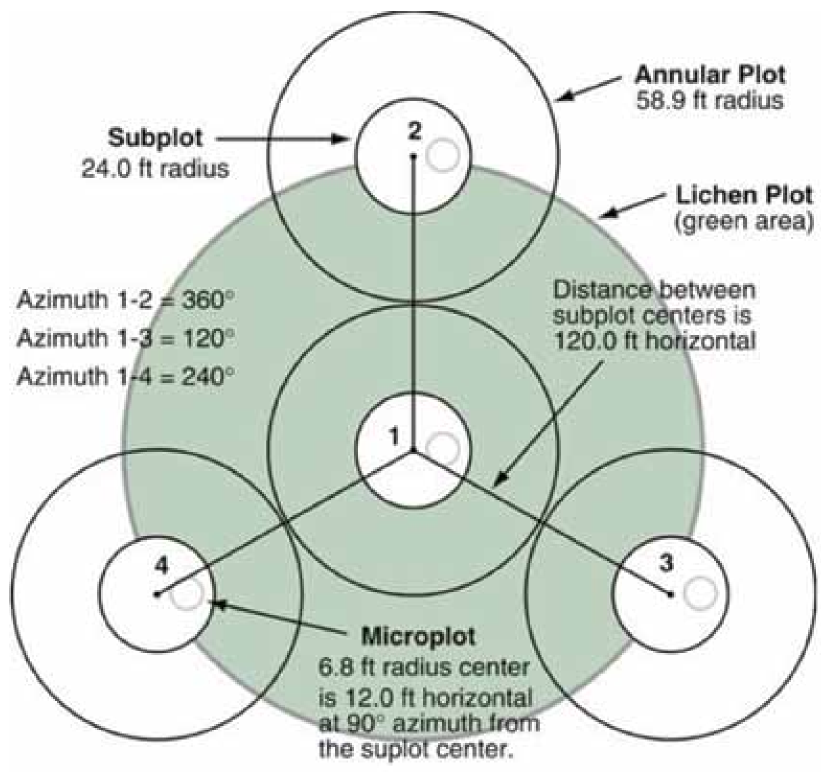


Figure 8. U.S. map of P3 plot hexagons that have been sampled for the Soil Indicator from 2000 through 2005.

Figure 9. Standard FIA plot design.



Measurement and Sampling Protocols

The FIA Soil Indicator consists of three main assessments:

1. Erosion assessment
    a. Percent of each subplot area with bare soil
2. Soil compaction assessment
    a. Percent of each subplot area with evidences of compaction
    b. Compaction type
3. Soil sampling and associated measurements
    a. Forest floor and litter thickness
    b. Forest floor sample collection
    c. Depth to restrictive layer
    d. Soil core collection for mineral or organic soils
        i. 0–10 cm
        ii. 10–20 cm
    e. Soil texture

Protocols for these measurements and soil sampling have been established and are outlined in detail in the FIA P3 field manual (USDA Forest Service 2007). A general description of the measurements and sampling is given below.

Visual estimation of the area of bare soil within each of the four subplots is expressed as percent of subplot area in 5 percent classes (table 1). Field crews are trained to identify bare soil and then to estimate the percent of plot area consisting of bare soil. Bare soil is the single most important variable in assessing erosion potential. Bare soil along with additional soil data (soil texture) and ancillary data (precipitation history from nearby weather stations, slope, and plot area) can be used to estimate soil erosion potential with the Watershed Erosion Prediction Program (WEPP) (Elliot and others 2000). Because the areal extent of bare soil on FIA plots is estimated to assess soil erosion potential, bare soil is defined in terms of particle sizes most likely to move via raindrop impact and runoff. For the FIA Soil Indicator, bare soil is defined as follows:

- Bare mineral soil consisting of fine gravel (2–5 mm), sand, silt, and clay sized particles.
- Bare organic soil; although interlocking organic fibers usually guard against organic soil erosion.
- Bedrock outcrops, rocks, and talus are excluded; rock cover often provides some measure of erosion protection in all but the most extreme storm events.

Table 1—Bare soil as a percent of subplot area data attributes for soil erosion potential assessment in the FIA P3 Soil Indicator (FIA 2008).

- Where collected: subplots 1, 2, 3, and 4.
- When collected: any portion of a subplot containing at least one accessible forested condition class.
- Field width: 2 digits
- Tolerance: ± 10 percent
- Measurement quality objective (MQO): within tolerance 75 percent of the time.

PDR code: bare soil range

00: none	25: 21-25	55: 51-55	85: 81-85
01: trace	30: 26-30	60: 56-60	90: 86-90
05: 01-05	35: 31-35	65: 61-65	95: 91-95
10: 06-10	40: 36-40	70: 66-70	99: 96-100
15: 11-15	45: 41-45	75: 71-75	
20: 16-20	50: 46-50	80: 76-80	

- Cryptobiotic crusts are excluded; these are mats of living organisms (*e.g.*, cyanobacteria and algae) covering bare soil and are usually present in arid ecosystems. They provide some measure of erosion protection against raindrop impacts.
- Basal tree area and stumps are excluded; these usually occupy a very small total area of a plot and protect against raindrop impact and runoff.

After assessing areal extent of bare soil on each subplot, field crews next look for evidences of compaction. Field crews are trained to identify several disturbances as evidences of soil compaction (table 2). They then estimate the area of compaction within each of the four subplots (percent of subplot area) in 5 percent classes (table 3). Following this, field crews identify the type of compaction (table 4). All the bare soil and compacted area and type data are entered into data recorders or are recorded on standardized data recording forms for later computer data entry.

Following bare soil and compaction estimations, forest floor and soil core samples are collected and forest floor and litter thicknesses, depth to restrictive layer (if any), and soil texture measurements associated with soil sampling are made. Soil samples are collected in the annular plots surrounding subplots 2, 3, and 4 (fig. 10). Soil sampling

Table 2—Evidence of soil disturbance related to compaction.

Visual disturbance	Evidence of compaction
Change in density	A noticeable change in density compared to nearby undisturbed soil. Most easily recognized by a difference in resistance to penetration with a soil probe assuming similar soil moisture content.
Platy structure	Coarse platy structure not evident in nearby undisturbed soil.
Loss of structure	Loss of normal soil structure found in nearby undisturbed soil (e.g., soil puddling, pulverized dust).
Ruts	Ruts at least 2 inches (5 cm) deep in mineral soil or 6 inches (15 cm) deep from undisturbed forest litter surface.
Mottling	Formation of mottles in disturbed area. Not present in nearby undisturbed soil.

Table 3—Compacted soil area (percent of subplot area) data attributes for areal extent of soil compaction assessment in the FIA P3 Soil Indicator (FIA 2008).

- Where collected: subplots 1, 2, 3, and 4.
- When collected: any portion of a subplot containing at least one accessible forested condition class.
- Field width: 2 digits
- Tolerance: ± 15 percent
- MQO: within tolerance 75 percent of the time.

PDR code: compacted area range			
00: none	25: 21-25	55: 51-55	85: 81-85
01: trace	30: 26-30	60: 56-60	90: 86-90
05: 01-05	35: 31-35	65: 61-65	95: 91-95
10: 06-10	40: 36-40	70: 66-70	99: 96-100
15: 11-15	45: 41-45	75: 71-75	
20: 16-20	50: 46-50	80: 76-80	

Table 4—Types of soil compaction in the FIA P3 Soil Indicator.

Type of compaction	Definition
Rutted trail	Ruts at least 2 inches deep in mineral soil or 6 inches deep from top of undisturbed forest litter surface.
Compacted trail	Linear compacted feature resulting from multiple passes by people, animals, or vehicles.
Compacted area	Examples include junctions of skid trails, landing areas, work areas, campsites, animal bedding areas.
Other	Explanation entered into plot notes.

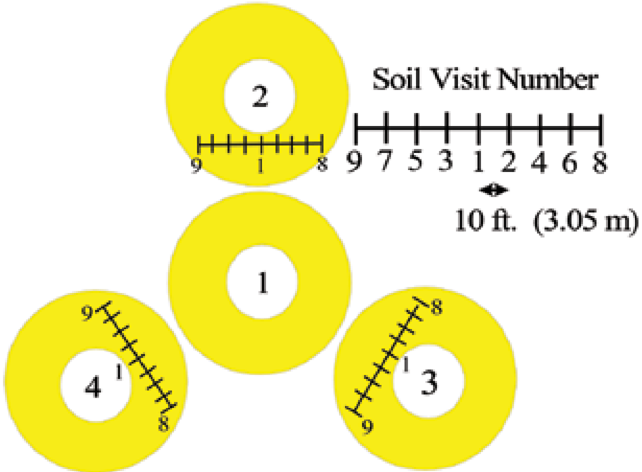


Figure 10. Location of soil sampling points along transects within annular plots surrounding subplots 2, 3, and 4. The sampling line associated with subplot 2 is located 30 ft due south (azimuth 180 deg) from the center of subplot 2. The sampling line associated with subplot 3 is located 30 ft northwest (azimuth 300 deg) from the center of subplot 3. The sampling line associated with subplot 4 is located 30 ft northeast (azimuth 60 deg) from the center of subplot 4.

transects with sampling points for each visit are located 30-ft from the centers of subplots 2, 3, and 4 as shown in figure 10. On the initial Soil Indicator visit, samples are collected at point 1 on each transect. Ten years later, on the second visit, samples are collected at point 2, which is located 10 ft from point 1. Subsequent visits at 10-year intervals are at points 3 through 9. On the next cycle, sampling begins again at point 1.

At each sample point associated with subplots 2, 3, and 4, forest floor samples are collected. Soil cores (0-10 and 10-20 cm) are collected at the sampling point associated with subplot 2 only. There are certain sampling rules governing if and where samples get collected:

- Soil samples are only collected if the soil sampling location in the annular plot is in a forested condition class regardless of the forested condition of the subplot.
- If cultural artifacts are found, soil samples are not collected.
- Certain other conditions may prevent soil sample collection (table 5).
- Field crews may collect a soil sample set within a 5-ft radius circle around the soil sampling point (fig. 10). A 5-ft radius circle does not impinge on the next soil sampling point that would be visited in 10 years, but allows for sample collection if there is an obstruction (*e.g.*, large log or rock) directly over the sample point.

Table 5—Soil sampling status codes for FIA P3 Soil Indicator.

- Where collected:
- Forest floor: Soil sampling points associated with subplots 2, 3, and 4.
- 0-10 and 10-20 cm soil cores: Soil sampling points associated with subplot 2 only.
- When collected: Soil sampling point is in a forested condition.
- Field width: 1 digit
- Tolerance: no errors
- MQO: at least 99 percent of the time.

PDR code	Soil sample status
1	Sampled
2	Not sampled: non-forest
Not sampled codes for forested condition	
3	Not sampled: too rocky
4	Not sampled: water or too boggy
5	Not sampled: access denied
6	Not sampled: too dangerous
7	Not sampled: obstruction in sampling area
8	Not sampled: broken or lost equipment
9	Not sampled: other (explanation entered in plot notes)

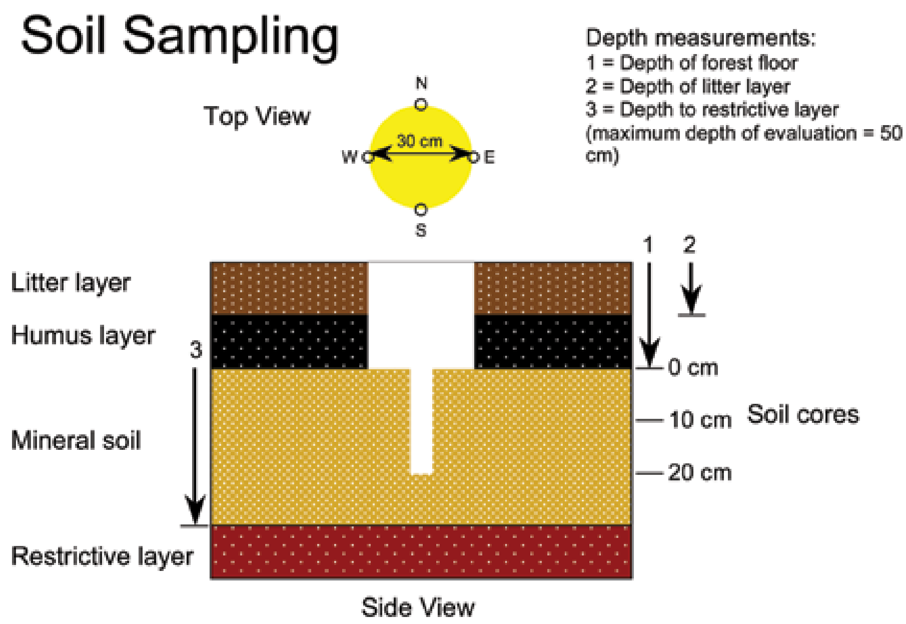


Figure 11. Cross-section diagram of forest floor and litter thickness measurements, depth to restrictive layer (if any), and forest floor and soil core sampling.

The cross-section diagram (fig. 11) shows the forest floor and litter thickness and depth to restrictive layer measurements associated with forest floor and soil core sampling. A general description of the measurement and sampling protocol is as follows:

- The entire forest floor (litter + humus) within a 30-cm diameter plot frame is collected down to the surface of the mineral soil. Woody pieces larger than 0.25-cm diameter are discarded (coarse and fine down wood are assessed as part of the down woody material indicator).
- Forest floor and litter thicknesses are measured at the north, south, east, and west compass points along the inner edge of the sample frame (fig. 11).
- A probe is used to measure depth to any restrictive layer (soil physical condition limiting root growth) within 50 cm of the mineral soil surface. Five measurements are made (center, north, south, east, west compass points) and the median of the five measurements is recorded. The maximum depth of evaluation is 50 cm.
- Two 2-inch diameter soil cores (0-10 and 10-20 cm) are collected using a coring head with two 10-cm long soil core liners attached to a slide hammer attachment. The volume of the cores is known and the soil weights (oven-dry basis) within the cores are used to calculate soil bulk density. If excessive coarse fragment content prevents soil core collection, then a hand excavation method is used to collect soil samples. Bulk density calculations are not made for manually excavated soil samples.
- The soil texture of the 0-10 and 10-20 cm mineral soil layers is determined with small samples from the sides of the coring or excavation hole.

The entire forest floor thickness and the litter layer thickness are measured as part of the sampling protocol. Field crews are trained to recognize the boundary between litter layer and humus layers:

- Litter layer—Decomposing plant parts can still be identified (*e.g.*, leaves, needles, twigs, bark, etc).
- Humus layer—Plant parts can no longer be identified because decomposition has proceeded to the point where stable humus has been formed (dark color—almost black—crumbly, organic layer).

Since the entire forest floor is sampled, field crews are taught to distinguish between the bottom of the forest floor (humus) layer and the top of the mineral soil. Sometimes the boundary is indistinct and the forest floor transitions into the underlying mineral soil. Field crews are taught to look for the following distinguishing characteristics:

- Evidence of plant parts—If they can be seen still decomposing in place, then that is still part of the forest floor.
- Texture—Crumbly (humus), or gritty (sand), silty, or clayey. The latter three are evidence that the mineral soil has been reached.
- Shiny flecks of mica or quartz—Will only help in those soils with that type of mineral soil mineralogy clearly present.
- Change in color—Humus layer is nearly black to black. Mineral soil is more brown color.
- Change in density—Humus layer is light. Mineral soil feels more dense.

Soil texture is collected primarily as a variable needed in the WEPP program for soil erosion potential assessment. For the FIA Soil Indicator, five soil texture classes estimated by feel are used: organic, loam, clay, sand, coarse sand. Organic soils are also tentatively identified in the field using texture, color, landscape setting, and vegetation characteristics. If an organic soil is being sampled, the forest floor is only the litter layer, and soil cores are collected from the underlying organic layer as with mineral soils.

Following collection, forest floor samples and soil cores are placed in sealed plastic bags and are sent to one of three FIA regional soil analysis laboratories for the north, south, and western states. The complete list of physical and chemical properties measured on the forest floor and soil cores is listed in table 6. Confirmation of organic soils is made using the percent organic C content of the soil cores. Since the entire solum is not sampled, an organic soil within the FIA Soil Indicator has an organic C content of 20 percent or greater in both sampled cores (0-10 and 10-20 cm).

Along with standardized training, quality control and quality assurance (QC/QA) are important components of measurement and sampling protocols. Quality control is the set of processes used to establish measurement quality objectives (MQOs) and to ensure quality standards are met. Quality assurance is the documentation that quality control protocols were followed. Tolerance levels and MQOs have been established for forest health indicators. Some of these Soil Indicator MQOs are listed in tables 1, 3, and 5. In addition to tolerance and MQOs, a series of interactive and non-interactive field plot checks has also been established (table 7). In addition, to provide an unbiased estimate of measurement and sampling variance, 5 percent of the plots are re-measured and re-sampled within the same field season.

Table 6—Soil physical and chemical properties measured in the FIA P3 Soil Indicator program.

Forest floor	Soil cores
Physical properties:	**Physical properties:**
Field-moist and air-dry weights	Field-moist and air-dry weights
Subsample oven-dry weight	Subsample oven-dry weight
Field-moist, residual, and total water content	Field-moist, residual, and total water content
Chemical properties:	Coarse fragments (>2 mm)
Total C (organic)	Bulk density
Total N	**Chemical properties:**
Total S (special project)	Organic, inorganic (carbonates), and Total N
Total Hg (special project)	Soil pH (water and 0.01 M $CaCl_2$)
	1 M NH_4Cl extraction:
	• Exchangeable cations (Na, K, Mg, Ca, Al)
	• Extractable metals (Mn, Fe, Ni, Cu, Zn, Cd, Pb)
	• Extractable S (SO_4-S)
	Extractable P:
	• Bray 1 (0.03 M NH_4F + 0.025 M HCl)
	• Olsen (pH 8.5, 0.5 M $NaHCO_3$)

Table 7—Field data collection QA/QC in the FIA program.

Type of QC/QA	QC/QA steps
Hot checks	Interactive—crews are present. Auditors review protocols with crew members, identify problems, suggest corrective actions, and conduct independent measurement checks.
Cold checks	Non-interactive—crews not present. Auditors conduct spot checks and do follow-up corrections.
Re-measurement and re-sampling (5 percent of plots)	Used to provide unbiased estimate of sampling variance.

The FIA regional soil laboratories also have their own separate QC/QA programs for the lab portion of the Soil Indicator. These QC/QA programs include

- Reagent and method blanks—Reagent blanks are used to establish baseline instrument calibrations. Method blanks are carried through all procedural steps of a given analysis method and are used to monitor for contamination.
- Instrument calibration standards—Used to calibrate instrument operation.
- Instrument check standards—Independent standards used to verify correct instrument operation and quantify analysis precision, bias, and accuracy. Accuracy is the sum of precision and bias measurements.
- Method check samples—Samples with 'known' or established values and tolerances based on repeat measurements among multiple laboratories and if possible, using multiple methods. These are used to check overall method repeatability and reliability.
- North American Proficiency Testing (NAPT) program—Quarterly sample exchange program administered by the Soil Science Society of America and involving more than 100 soil analysis laboratories.

Status of Forest Soils in the United States: Example of Soil Indicator Results to Date

Soil Indicator data along with that of other P3 forest health indicators plus the P2 forest inventory data are loaded into the FIA National Information Management System (NIMS). FIA also has an on-line datamart, which is the publicly accessible portion of the data known as FIADB (see http://fiatools.fs.fed.us). Various FIA analysts as well as the Forest Health Indicator Advisors and outside users access the database to analyze FIA data to assess various forest resource inventory questions.

Much of the data analysis uses post data collection stratification to derive population estimates (Scott and others 2005). For the Soil Indicator, data could be stratified by ecoregion, forest type, soil type, and major resource land area (USDA NRCS 2006). Results are often presented as shaded point maps, data distribution plots (box plots, histograms, cumulative frequency plots), and statistical summary tables (*e.g.*, means and/or medians and various measures of data variability (*e.g.*, standard deviation, coefficient of variation, standard error). Stratified results may also be presented as pixilated maps or summary tables with values reported by strata.

Once data analysis is complete, various data reporting and results interpretation outlets are available to communicate findings to science users, clients, and various publics. Following are some examples of how FIA Soil Indicator results get reported:

- National and international reports
    - MPCI Sustainable Forests reports: 2003 printed report with web-based background technical reports (O'Neill and others 2004)
    - Resource Planning Act (RPA) report (Perry and Amacher, in press)

- ◦ FHM National Technical reports: The 2001 and 2005 reports contain Soil Indicator data and interpretations (O'Neill and others 2005a; Perry and Amacher 2007a,b,c)
- ◦ Scientific literature (book chapter, journal papers, Forest Service research papers, general technical reports (GTRs), proceedings)—Examples include Perry and others 2008; O'Neill and others 2005b,c; Amacher and others 2007.

- Regional reports—none devoted to Soil Indicator yet
- State reports (resource bulletins)—Examples of state reports with Soil Indicator data include those of Minnesota (Miles and others 2007) and Virginia (Rose 2007).

Examples from recent publications showing Soil Indicator results give a snapshot of current forest soil conditions in the United States. Western forests tended to have more bare soil than eastern forests (fig. 12) because of lower overall tree canopy coverage and lesser amounts of forest floor material.

Soil compaction is not a widespread problem on forest soils of the United States. Most FIA P3 plots showed no evidence of compaction (fig. 13). Observed evidences of soil compaction tended to be found more in eastern forests than in the west (fig. 13) perhaps reflecting higher density of forest usage.

The impact of soil compaction on soil bulk density and forest productivity is complex (Powers and others 2005). Soils with bulk densities greater than 1.4 g/cm^3 tend to resist compaction. Forest productivity response to soil compaction depends on soil texture and understory vegetation. Production declined on compacted clay soils, increased on sandy soils, and was unaffected if an understory was absent (Powers and others 2005).

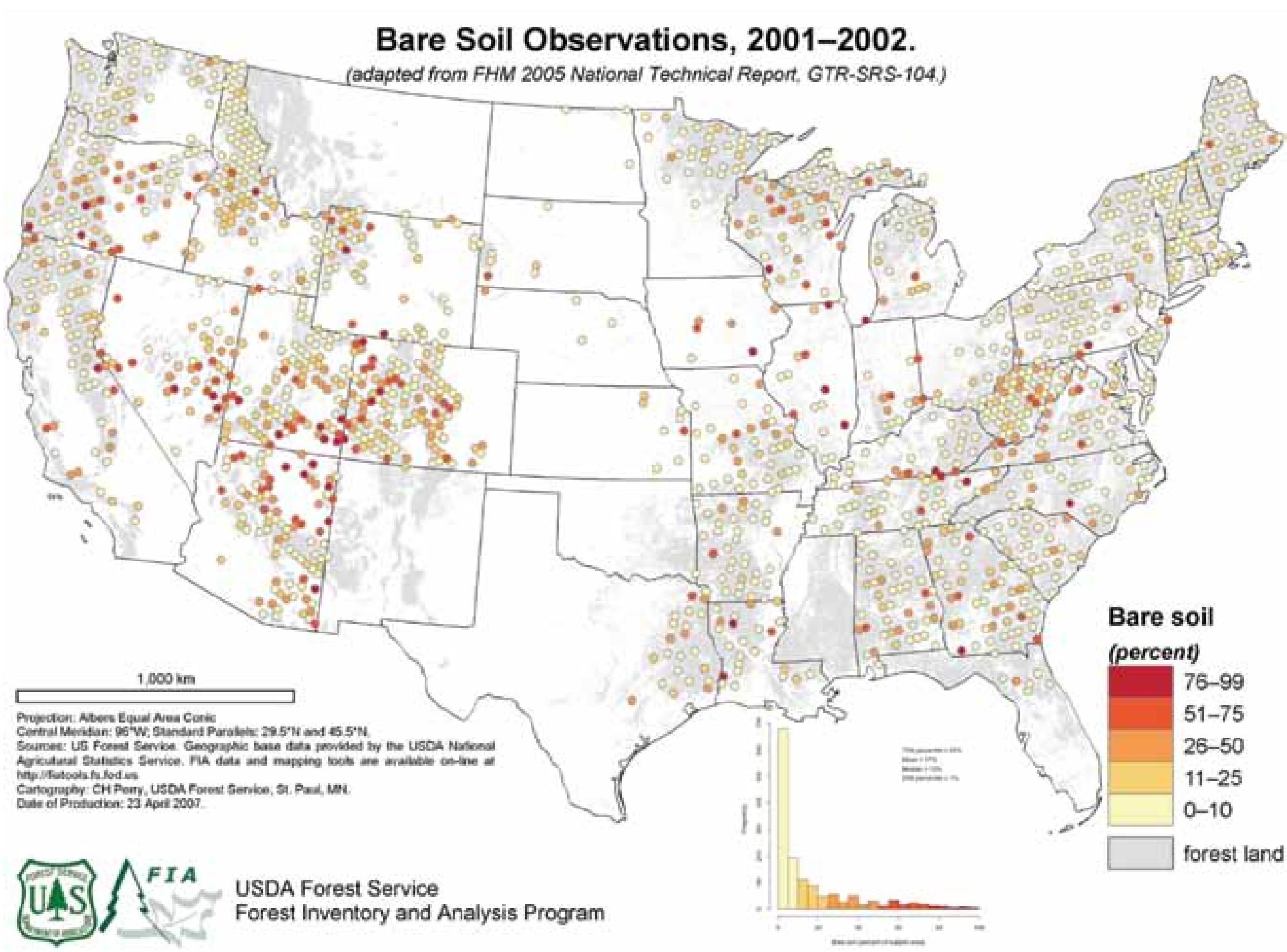


Figure 12. Spatial distribution of maximum observed percent bare soil by EMAP hexagon for FIA plots visited in 2001-2007.

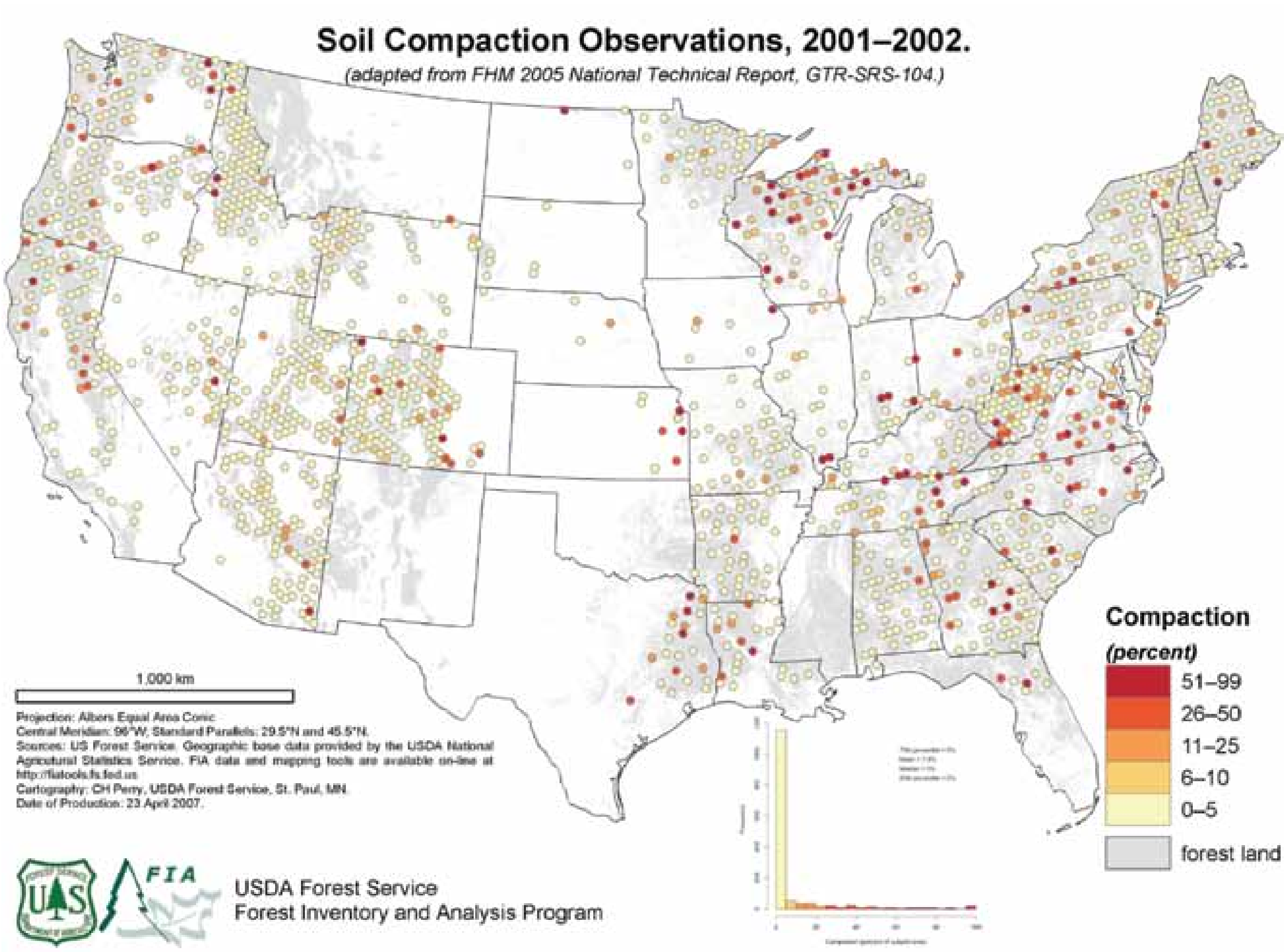


Figure 13. Spatial distribution of maximum observed percent compacted area by EMAP hexagon for FIA plots visited in 2001-2007.

Low soil nutrient and high acidity conditions may be found in forest soils throughout the United States, but strongly acid soils with low Ca and high Al levels are concentrated in the Northeast and South, primarily in the Appalachian regions (fig. 14). The most serious soils-related landscape-scale forest health threat uncovered by the FIA detection monitoring network is increasing soil acidity and associated decreases in soil Ca reserves along with potentially toxic levels of exchangeable Al. Calcium depletion and associated increases in available Al is strongly linked to atmospheric deposition (Driscoll and others 2001). Cronan and Grigal (1995) used soil solution Ca/Al molar ratios as an indicator of forest stress and indicated a near 100 percent probability of adverse impacts to forest health at a soil solution Ca/Al molar ratio of 0.2. The Ca/Al ratios presented in fig. 14 are 1M NH_4Cl exchangeable values rather than soil solution values, but exchangeable and soil solution concentrations are closely associated via exchange coefficients.

The FIA Soil Indicator has provided the first national inventory of measured C stocks in U.S. forest soils to a depth of 20 cm. Forest soils in colder wetter regions tend to have higher organic C levels (fig. 15). These latitudinal and elevational gradients in soil organic C levels are expected since organic matter decomposition rates tend to be higher under warmer and drier conditions (Schlesinger 1997). Regional organic C and total N amounts in the forest floor and 0-10 and 10-20 cm layers are summarized in fig. 16. More organic C is stored in the Northeast and Pacific States FIA regions than in the South or Interior West. The Northeast and North Central FIA regions store the most total N.

At the request of Soil Indicator analysts and users, a Soil Quality Index (SQI) was developed that integrates 19 separate measured physical and chemical properties into a

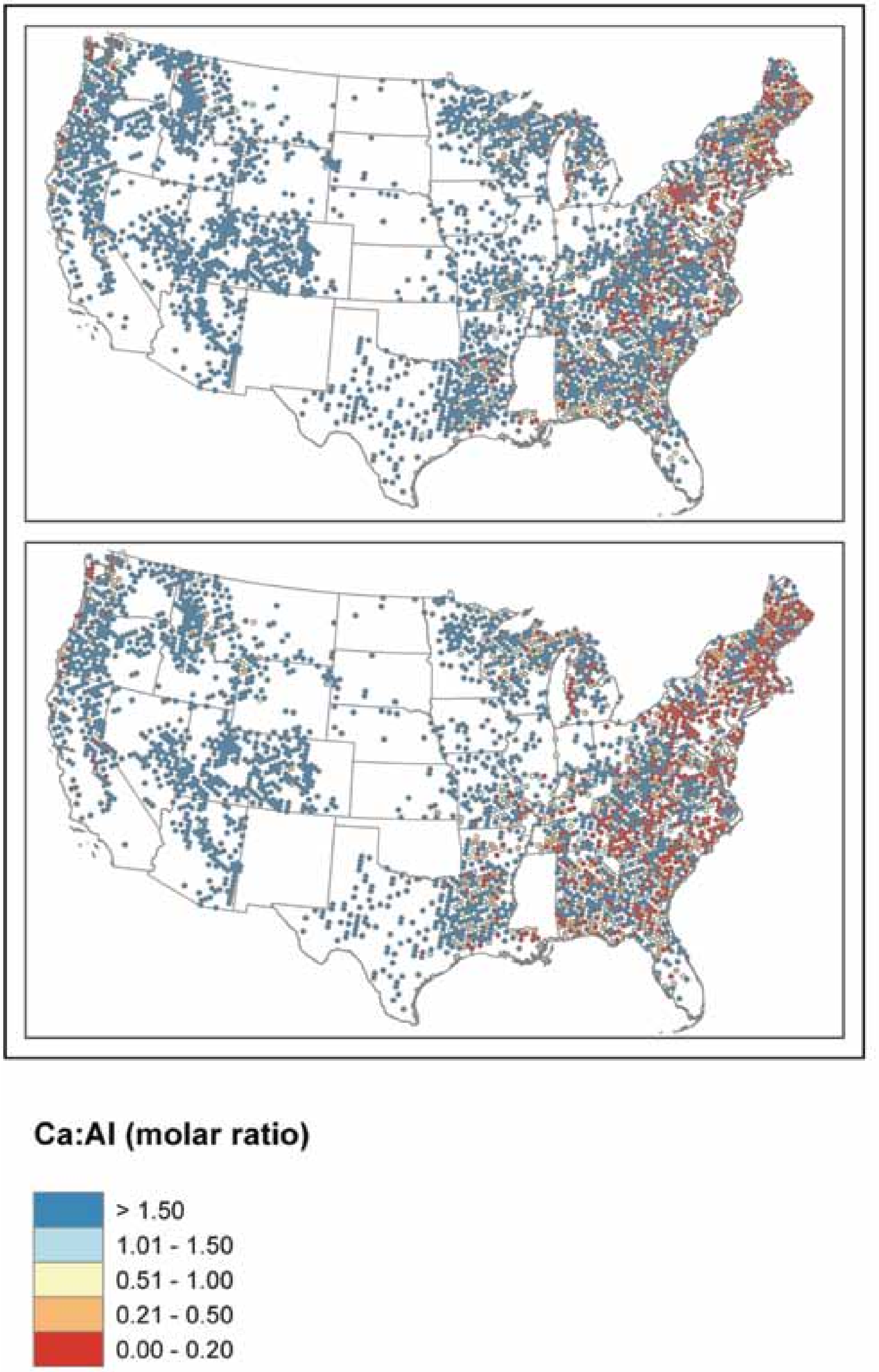


Figure 14. Spatial distribution of minimum observed exchangeable Ca/Al molar ratios by EMAP hexagon and soil depth (top: 0-10 cm; bottom: 10-20 cm) for FIA plots sampled in 2000-2007. Source: USFS FIA Soil Indicator. Geographic base data provided by the National Atlas of the U.S.A. EMAP hexagons provided by the U.S. EPA.

single index number that can be used to track soil quality condition and trend (Amacher and others 2007). Soils with lower SQI levels (< 50 %) are at increased risk of soils-related forest health decline. These soils tend to be concentrated in the Northeast and South where soils are more highly weathered and depleted of nutrients (fig. 17).

Sample Variability

Magnitude of variability for a given Soil Indicator source of variation generally increases in the order shown in figure 18. Repeat analysis usually has the least variation while variation among plots has the most. Since the FIA Soil Indicator is designed to

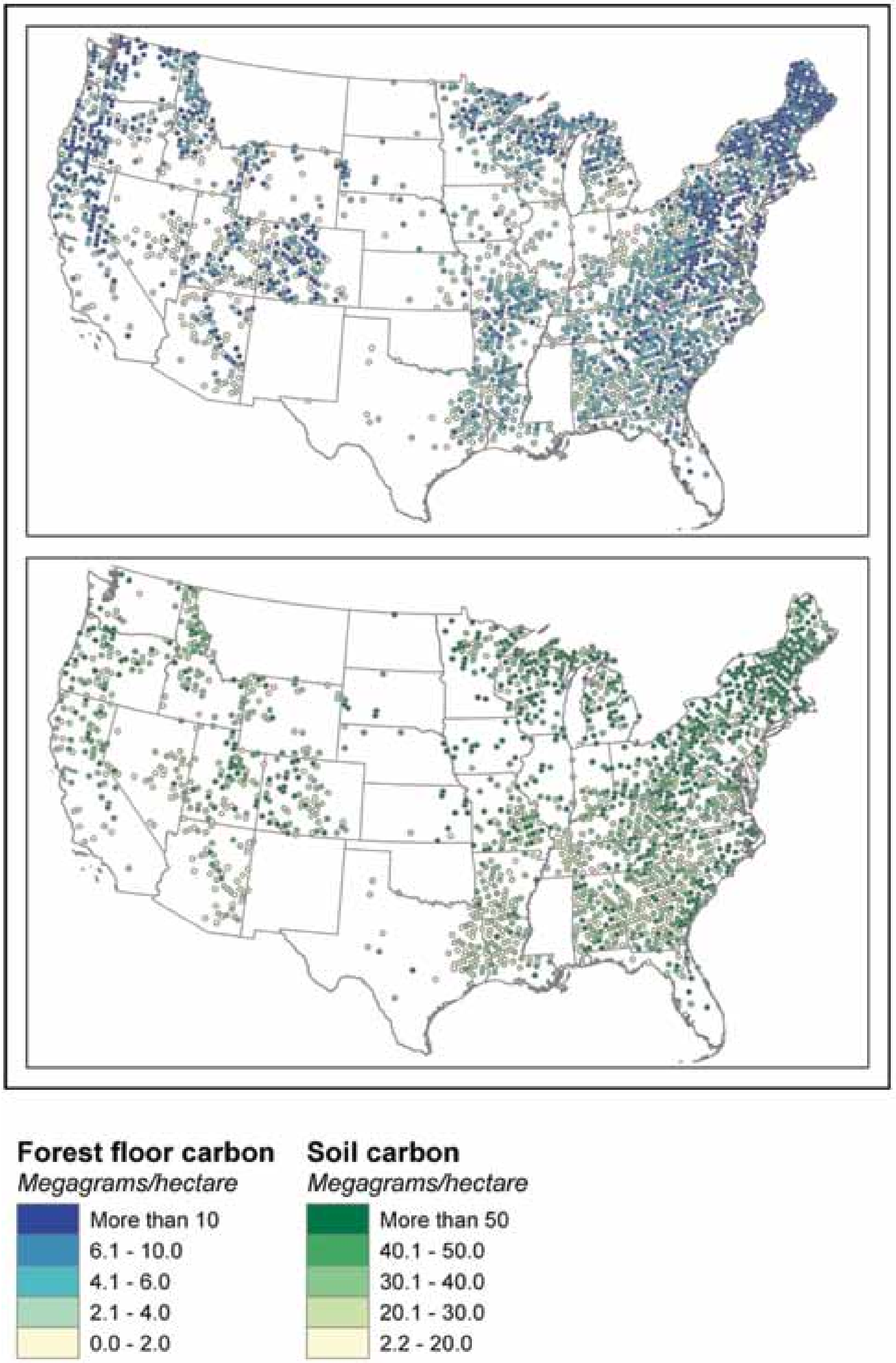


Figure 15. Spatial distribution of forest floor (top) and 0-20 cm soil (bottom) organic C by EMAP hexagon for FIA plots sampled in 2000-2004. Source: USFS FIA Soil Indicator. Geographic base data provided by the National Atlas of the U.S.A. EMAP hexagons provided by the U.S. EPA.

measure condition and trend at the landscape scale, the number of plots within a stratification layer (ecoregion, forest type, etc.) is an important factor influencing measured variance. The Soil Indicator is not designed to measure small-scale soil spatial variability. It is well recognized, based on decades of research, that soil properties are variable at multiple spatial scales (Gassner and Schnug 2006). It is also well established that closely spaced samples in time or space tend to be more closely correlated to each other. The central concept of spatial autocorrelation was first stated in Tobler's first law of geography: Everything is related to everything else, but near things are more related than distant things (ESRI 2006). Thus, landscape-scale assessments rely on spacing plots at far enough distance apart to reduce spatial correlation among samples to achieve a truer assessment of changes across the entire landscape.

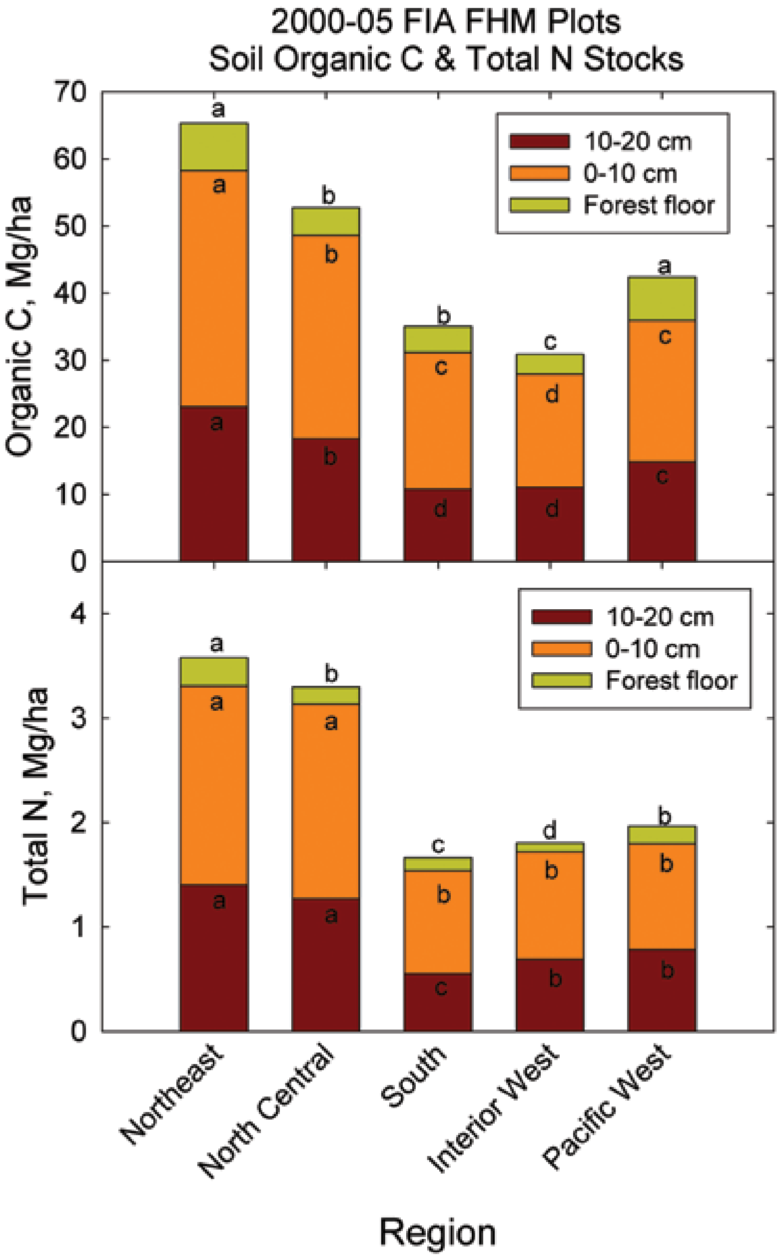


Figure 16. Regional soil organic C and total N amounts in the forest floor and 0-10 and 10-20 cm layers for FIA plots sampled in 2000-2005. Means for each layer (stacked bars) not indicated by the same letter across regions are significantly different.

Table 8—Sources of variance in the FHM soil C re-measurement study (Conkling and others 2000). Thirty plots in Georgia were measured.

Soil depth	Source of variation	Bulk density	Percent C	C stock
	Percent variance			
0–5 cm	Plots (30)	70.8 **	72.2 **	77.8 **
	Subplots (3/plot)	22.4 **	21.8 **	17.5 **
	Within subplots	6.8 ns	6.0 ns	4.7 ns
5–10 cm	Plots (30)	65.3 **	62.7 **	70.0 **
	Subplots (3/plot)	25.1 **	35.0 **	27.5 **
	Within subplots	9.5 ns	2.3 ns	2.6 ns
10–20 cm	Plots (30)	63.4 **	69.4 **	71.4 **
	Subplots (3/plot)	34.6 **	25.1 **	20.5 **
	Within subplots	2.0 ns	5.4 ns	8.1 ns

** = Significant at $p < 0.0001$, ns = not significant.

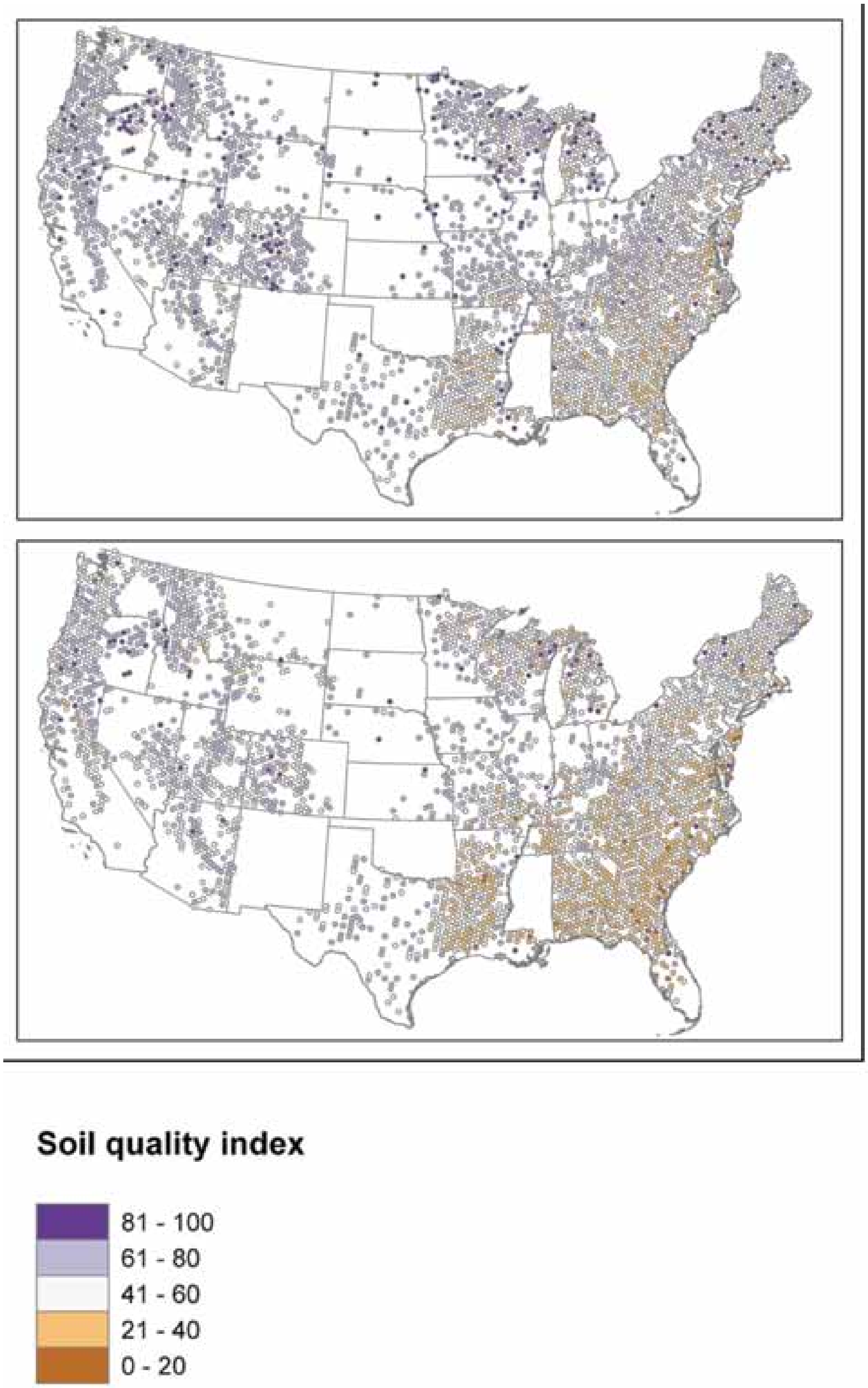


Figure 17. Spatial distribution of soil quality index (SQI) relative to the mean by EMAP hexagon and soil depth (top: 0-10 cm; bottom: 10-20 cm) for FIA plots sampled in 2000-2007. Source: USFS FIA Soil Indicator. Geographic base data provided by the National Atlas of the U.S.A. EMAP hexagons provided by the U.S. EPA.

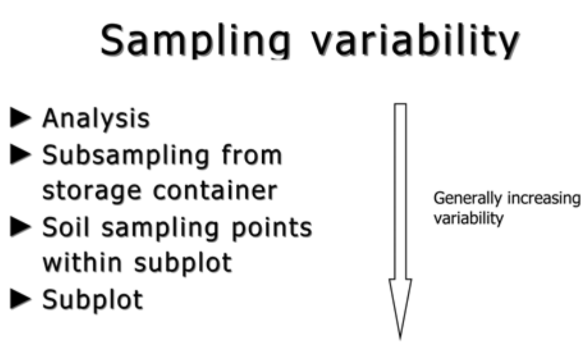


Figure 18. Sources of variation in Soil Indicator measurements arranged in order of increasing magnitude of variability.

Table 9—Median coefficients of variation (standard deviation as a percent of mean) for selected soil properties calculated from the population of FIA P3 plot re-measurement pairs.

Soil property	Number of pairs of soil cores	Median cv. (percent)
Bulk density	119	10.0
Coarse fragments	145	37.2
Organic C	368	15.3
Total N	368	14.3
Water pH	144	2.5
Effective cation exchange capacity (ECEC)	146	10.7
Extractable P (Bray 1 and Olsen)	129	22.7
	42	23.3

ECEC = sum of exchangeable cations (Na, K, Mg, Ca, Al).

The FHM C re-measurement study using 30 FIA plots in Georgia showed the magnitude of variability (percent variance) within subplots, among subplots, and among plots for three Soil Indicator variables (bulk density, percent organic C, and C stocks) at three soil depths (0-5, 5-10, and 10-20 cm) (Conkling and others 2000) (table 8). Within subplot variance was not significant compared to among subplot variance. As expected, the greatest variance was among plots. To fully capture spatial variability at the landscape scale, more plots across landscape scale strata are needed rather than more samples per plot, which only captures within-site variance.

To provide an unbiased estimate of measurement and sampling variance, 5 percent of plots are re-measured and re-sampled in the same sampling year (Hansen and others, in press). Re-sampling is done adjacent to the sample hole associated with the established sampling point for that plot visit. Thus re-sampling produces a paired set of soil samples that represents about 5 percent of the total plot population. For each pair of samples from re-sampled plots, mean, standard deviation and coefficient of variation statistics are computed. Because the magnitudes of the various soil properties display a wide range of values, expressing the standard deviation of each pair of soil samples as a percentage of the mean (coefficient of variation, cv) normalizes the standard deviations and makes for easier comparisons over the complete range of observed values and among different soil properties. The least and most variable soil properties within a sampling site can be assessed at a glance.

Median cv values for several important soil properties are shown in table 9. The numbers of pairs of soil samples are also shown. Coarse fragment content is the most spatially variable soil property within sample sites with a median cv of 37 percent. Water pH is the least spatially variable soil property with a median cv of only 2.5 percent. Table 9 provides valuable information about which soil properties tend to be the most or least spatially variable within the sampling area for a large population of re-sampled plots across multiple ecoregions, forest types, and soil types. As the database grows, we will be able to identify those areas with the most within-plot spatially variable soil properties. Within-plot sampling variability data can be used to design more efficient sampling intensification for follow-up evaluation monitoring studies.

Soil Indicator Weaknesses

Key strengths of the Soil Indicator were listed and discussed previously. However, there are some weaknesses within the program as it is presently constituted.

- This is a forest health detection monitoring program at the landscape scale. Small-scale spatial variability is not captured with the current strategic approach to sampling design. However, one of the valuable attributes of the hexagonal sampling grid is that the grid can be intensified to address specific monitoring questions: (1) spatially-intensified evaluation monitoring projects based on detection monitoring results; (2) National Forest intensified-grid measurement and sampling, (3) Intensive site monitoring (*e.g.*, Delaware River Basin study).
- The Soil Indicator is currently confined to an inventory of soil properties within the upper 20-cm of mineral or organic soil beneath the forest floor (the entire forest floor

within a plot frame is sampled). Thus, in the case of C, the total organic C inventory for the entire solum is not measured. Soil bulk density and organic C levels change with depth. In general, bulk density will increase with depth while organic C levels will decrease in mineral soils, but will remain at high levels in organic soils such as forested peat bogs. Soil depth to parent material is highly variable on the landscape. Furthermore, mineral soil profiles often grade into parent material lithology without distinct boundaries. Without an unambiguous definition of what constitutes the entire solum for sampling and inventory purposes, any soil inventory defaults to an operationally defined program based on a fixed sampling depth. The Soil Indicator program allows for deeper sampling for special projects. Although the current protocol samples the upper 20-cm of soil, manually operated soil core samplers can sample to 30-cm in all but the rockiest soils. Sampling deeper than 30 cm almost always requires a motor-driven soil core sampler. Hand augering can collect soil samples to depths of 1 m or more if coarse fragment content is low. However, hand augering precludes soil bulk density measurements because augered samples are disturbed and don't preserve the original weight/volume ratio of undisturbed soil cores.

- The Soil Indicator does not include several highly important soil property measurements as yet. For example, no measures of soil biological properties are included. Such properties as enzyme activity, microbial population activity (*e.g.*, microbial community-level physiological profiling (Biolog)), and in situ soil respiration and C and N mineralization/utilization would provide valuable additional information.

Potential Use of FIA Soil Indicator for Soil Quality Standards Monitoring

The concept of soil quality standards to maintain soil productivity and hence forest productivity following timber harvest activities is undergoing increased scrutiny. Typically, soil quality standards monitoring occurs at the project scale within various National Forests. Soil quality standards monitoring is chiefly concerned with documenting severity of soil disturbance (Neary and others 2010), whereas the FIA Soil Indicator documents the areal extent of bare soil (whether disturbance-related or not) and evidences of compaction within FIA subplot areas. It is possible to link the two approaches.

Potentially, FIA plots could be established on delineated project areas. Furthermore, FIA forest productivity and other indicator data linked to Soil Indicator data can be used to establish current and historic conditions for forest and soil types similar to proposed project areas. In addition, the soil quality standards disturbance severity protocols could be added to Soil Indicator protocols as a regional add-on for more intensified soil monitoring.

One of the Soil Indicator's greatest strengths is the collection of data across the broader landscape. The collection of Soil Indicator data in or around projects would facilitate comparisons with areas not included in the project or held by adjacent landowners. In this regard, Soil Indicator data could answer questions about the unique impact of Forest Service land management.

Summary

The Soil Indicator was developed to assess the condition and trend of forest soils throughout the United States regardless of ownership as part of a larger forest health indicators monitoring effort within FIA. It is the first comprehensive national inventory of forest soil properties using common protocols with a QC/QA program. The Soil Indicator was developed in response to Montreal Process Criteria and Indicators monitoring questions. Two key accomplishments of the Soil Indicator are the first comprehensive national inventory of organic C stocks in forest soils based on measured values and the first landscape-scale assessment of the severity of Ca depletion and associated high levels of soil Al in forest soils of the Northern and Southern Appalachians. Since current soil conditions are now well-quantified, the Soil Indicator provides the means to track changes in forest soil conditions going forward. This can lead to a refinement of the MPCI as well as refine the Soil Indicator assessment process to better measure soils-related forest health risks.

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The content of this paper reflects the views of the authors, who are responsible for the facts and accuracy of the information presented herein.