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Status and future of the forest health indicators program of the USA

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Abstract For two decades, the US Department of Agriculture, Forest Service, has been charged with implementing a nationwide field-based forest health monitoring effort. Given its extensive nature, the monitoring program has been gradually implemented across forest health indicators and inventoried states. Currently, the Forest Service's Forest Inventory and Analysis program has initiated forest health inventories in all states, and most forest health indicators are being documented in terms of sampling protocols, data management structures, and estimation procedures. Field data from most sample years and indicators are available on-line with numerous analytical examples published both internally and externally. This investment in national forest health monitoring has begun to yield dividends by allowing evaluation of state/regional forest health issues (e.g., pollution and invasive pests) and contributing substantially to national/international reporting efforts (e.g., National Report on Sustainability and US EPA Annual Greenhouse Gas Estimates). With the emerging threat of climate change, full national implementation and remeasurement of a forest health inventory should allow for more robust assessment of forest communities

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that are undergoing unprecedented changes, aiding future land management and policy decisions.

Keywords Criteria and indicators · Forest health · Forest inventory · Forest health monitoring · Forest health indicators

Introduction

The diverse forest ecosystems of the USA occupy over 300 million hectares within the world's largest economy containing over 300 million citizens all depending on essential forest ecosystem services (Woodall and Miles 2008). Given the numerous threats facing US forests (e.g., climate change, invasive species, air pollution, or urbanization), the USA has endeavored to survey indicators of forest health for over two decades. The US programs primarily responsible for conducting a survey of forest health across the USA are the State and Private (S&PF) and the Research and Development (R&D) Deputy Areas of the US Department of Agriculture's Forest Service along with cooperating individual state forestry agencies. The R&D Forest Inventory and Analysis (FIA) program administers the actual field work, data processing, data distribution, and reporting of the forest health indicators inventory; whereas the S&PF Forest Health Monitoring (FHM) program provides the overarching framework for use of FIA's forest health indicator inventory at a national scale and provides technical guidance on the development and improvement of forest health indicators. Given the complexity of a forest health monitoring program that spans a continent and addresses a diversity of forest ecosystem attributes, a synthesis of the current status, and future of the monitoring program should empower forest health specialists to fully identify and utilize program benefits.

US forest health monitoring background

The US Department of Agriculture, Forest Service, first implemented a forest health monitoring system in 1990 (Riitters and Tkacz 2004; Bechtold et al. 2007). Early efforts focused on air pollution, but the scope soon expanded to include the internationally sanctioned Montreal Process Criteria and Indicators (Montreal Process Working Group 2006). The international working group known as the Montreal Process was commissioned in 1993 to develop "Criteria and Indicators for the Conservation and Sustainable Management of Temperate and Boreal Forests" (MPCI 2009). Criteria are categories of forest values to be preserved, such as biodiversity and productive capacity; indicators are measurable aspects of these criteria. The seven criteria are: (1) conservation of biological diversity; (2) maintenance of the productive capacity of forest ecosystems; (3) maintenance of forest ecosystem health and vitality; (4) conservation and maintenance of soil and water resources; (5) maintenance of forest contributions to global carbon cycles; (6) maintenance and enhancement of long-term socio-economic benefits; and (7) the legal, institutional, and economic framework for forest conservation and sustainable management (Anonymous 1995).

Adoption of the Montreal Process with its internationally sanctioned indicators has helped the US standardize the analysis and reporting of forest health data. The US FHM system now uses a three-tiered approach by which progressively more detailed studies are conducted to evaluate forest health (USDA 2003): (1) Detection Monitoring (DM), (2) Evaluation Monitoring (EM), and (3) Intensive Site Monitoring (ISM). The national FIA inventory of forest health indicators is the most significant feature of DM, which also includes annual aerial surveys conducted by Forest Health Protection program of the Forest Service to target and map problems such as forest insect and disease outbreaks (Riitters and Tkacz 2004). Evaluation Monitoring, the second FHM tier, includes focused, short-term studies (e.g., declining crown health in local areas; Bechtold et al. 2010) to investigate the extent, severity, and potential causes of undesirable changes in forest health detected through the first tier (DM). ISM, the third tier, enhances understanding of cause and effect relationships by linking DM indicators to process-level research at long-term research sites such as calcium depletion and carbon sequestration studies (Stolte et al. 2004).

In summary, the conceptual approach to forest health monitoring in the USA includes a component to detect long-term regional changes (DM), a component to assess the practical importance and impact of observed changes (EM), and a component to conduct process-level research (ISM). DM is largely statistical and relies on multiple indicators of condition. EM focuses additional study on potentially important problems that come to our attention through DM or other sources. ISM provides a link to the other components by allowing a more rigorous evaluation of cause and effect relationships—by establishing thresholds for indicators of forest health, by investigating strategies for prevention and mitigation, and by linking to studies on the fundamental processes that shape ecosystems.

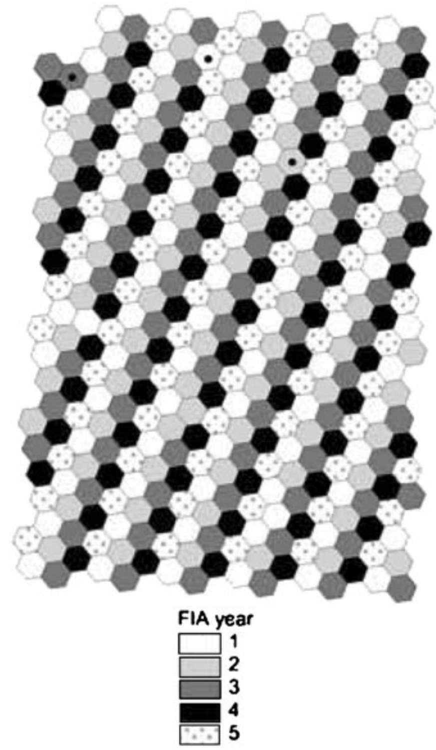

Fig. 1 The FIA sampling framework is based on a complete coverage of the US with non-overlapping 2,400-ha hexagons. The hexagons are then systematically divided into a series of panels with one panel visited every year (5-year panel displayed). Each hexagon contains one permanent fixed area plot (composed of four sub-plots), where standard forest inventory data are collected. Additional forest health indicators are measured on a 1/16th subset of these plots. (Adapted from Forest Service, Forest Inventory and Analysis Sampling Hexagon Fact Sheet. Available at: http://www.fia.fs.fed.us/library/fact-sheets/data-collections/Sampling%20and%20Plot%20Design.pdf)

Forest inventory sampling design and indicator suite

The systematic sampling of forests in space and time by FIA provides both baseline and change estimates of forest conditions. The FIA sampling framework is based on a systematic network of ground plots (Bechtold and Patterson 2005) obtained by dividing the USA into a series of 2,400-ha hexagons (Fig. 1). The hexagonal shape was selected because of its resistance to spatial distortion from the curvature of the earth. At least one permanent ground plot is randomly located inside each hexagon. Within each state, the network of hexagons is divided into five to 10 panels, where all plots in one of the panels are measured each year. Each panel represents spatially balanced coverage across the population. Panels are scheduled for measurement on a rotating basis. The result is a forest inventory that has a 5- to 10-year remeasurement cycle; annual panels can be analyzed separately or combined in various ways (e.g., use single panel after major hurricane) to strengthen the population estimates of forest attributes (e.g., forest biomass for a state). Continuous annual change estimates based on paired observations are available after the first panel is remeasured (typically 5 or 10 years in the eastern or western USA, respectively). The number of panels and sampling intensity (i.e., number of plots within each hexagon) are permitted to deviate among the FIA administrative regions (north, south, interior west, and Pacific northwest). The number of panels may be as high as 10 in regions where plot access is limited by severe winters and remote roadless terrain (e.g., Alaska) or where federal funding has not been appropriated in the past (e.g., Nevada). The sampling intensity of plots may be increased in regions that are willing to pay for the additional data.

FIA operates a multi-phase inventory based on the array of hexagon/paneling system (Bechtold and Patterson 2005). In Phase 1 (P1), land area is stratified using aerial photography or classified satellite imagery to increase the precision of estimates using stratified estimation (i.e., grouping plots within homogenous strata). Remotely sensed data may also be used to determine if plot locations have forest land cover; forest land is defined as areas at least 10% stocked with tree species, at least 0.4 ha in size, and at least 36.6 m wide (Bechtold and Patterson 2005). In Phase 2 (P2), permanent fixed-area plots are installed in each hexagon when field crews visit plot locations that have accessible forest land. Field crews collect data on more than 300 variables, including land ownership, forest type, tree species, tree size, tree condition, and other site attributes (e.g., slope, aspect, disturbance, and land use; USDA 2009). Plot intensity for P2 measurements is approximately one plot for every 2,428 ha of land (roughly 125,000 plots nationally). Briefly, the plot design for FIA inventory plots consists of four 7.2-m fixed-radius subplots spaced 36.6 m apart in a triangular arrangement; in each subplot all trees with a diameter at breast height of at least 12.7 cm are inventoried within forested conditions (Fig. 2). Within each sub-plot, a 2.07-m microplot offset 3.66 m from the subplot center is established where live tree seedlings and trees with a dbh between 2.5 and 12.7 cm are inventoried. In addition to the trees measured on these plots, data are also gathered on the condition of the area in which the trees are located (e.g., stand age class, ownership group, and tree density class).

During the third phase of FIA's multi-phase inventory (P3), forest health indicators are measured on a 1/16th subset of the entire FIA ground plot network so that each plot represents approximately 39,000 ha. The suite of P3 forest health indicators were chosen carefully to achieve a proper balance between budgetary constraints, field sampling efficiency, and the many dimensions of forest condition within the Montreal Process Criteria and Indicators framework. Those selected are tree crown condition, lichen communities, forest soils, vegetation diversity, down woody material, and ozone injury. These indicators are collected during the leaf-on to leaf-off growing season, typically late May through August (mid-September) depending upon the region. A technical specialist responsible for developing data collection protocols and analytical procedures has been assigned to each indicator. Field protocols associated with each indicator are available in the national field guide (USDA 2009). Links to additional information about these indicators are available online: http://www.fia.fs.fed.us/program-features/indicators/. A brief description of each phase 3 indicator follows below (Fig. 3).

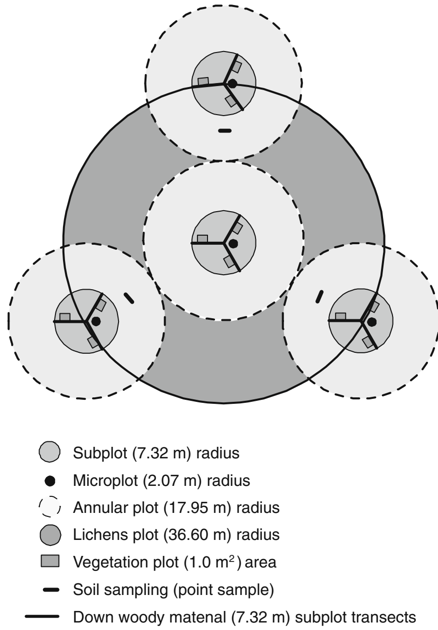

Fig. 2 FIA field plot layout for detection monitoring. (From US Forest Service, FIA Sampling and Plot Design Fact Sheet at: http://www.fia.fs.fed.us/library/fact-sheets/data-collections/Sampling%20and%20Plot%20Design.pdf)

Tree crown condition

Tree crowns are a vital indicator of tree health as they enable carbon fixation and hence sustained life. Crown measurements are recorded on all live sampled trees. Individual crown measurements on trees greater than 12.7 cm dbh include uncompacted live crown ratio, crown diameter (for some years), crown density, foliage transparency, crown dieback, crown light exposure, and canopy position. These measurements can be analyzed individually, or they can be combined to calculate crown volume or surface area. The crowns of sapling-size trees (2.5 to <12.7 cm dbh) are not developed sufficiently to assess crown diameter, crown density, foliage transparency, and crown dieback for each tree; as a result, saplings

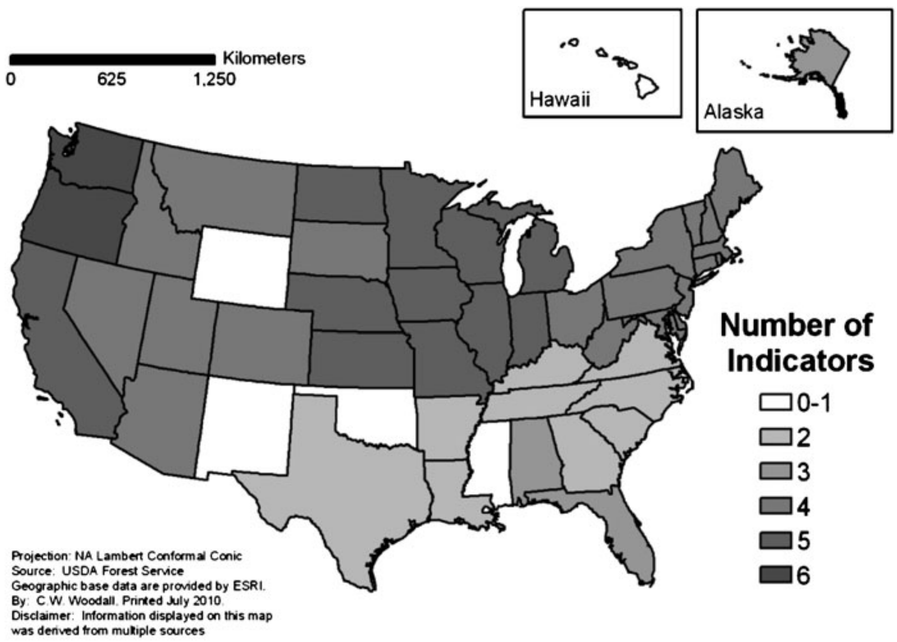

Fig. 3 Progress of forest health indicator sampling across the USA by number of indicators established in each state and data publicly available through website (http://www.fia.fs.fed.us/tools-data/), 2010. (Note: Wyoming and Hawaii annual inventories expected to begin in 2010, in Alaska only southeastern data available)

are categorized into one of three broad vigor classes based upon the amount and condition of the foliage present on the tree. The crown indicator is described in detail by Schomaker et al. (2007). Related publications and additional information about data collection protocols, training methods, and data analysis are available at http://srsfia2.fs.fed.us/crowns/ (accessed July 2009).

Lichen communities

Long-term observation of epiphytic (i.e., tree-dwelling) lichen community change indicates changes in air quality, climate, and land use. Field crews are trained to observe the presence of lichen species, to estimate the abundance of each species, and to collect specimens for identification by a specialist. Lichen community measurements are made within a 37-m radius of each plot center (∼0.38-ha area), where one field person spends up to 2 h searching for different lichen species. The lichen indicator is described in detail by Will-Wolf (2010).

Forest soils

Any environmental stressor that interferes with soil function has the potential to influence the productivity, species composition, and hydrology of forest ecosystems. The soil indicator evaluates soil physical and chemical properties. At each plot location, field crews complete ocular estimates of the percentage and type of soil compaction or erosion observed on the plot as well as the presence of restrictive layers within the top 50 cm of soil. Field crews subsequently collect five soil samples—three forest floor samples to measure organic matter and carbon content, and a mineral soil core collected at two depths: 0–10 and 10–20 cm. Samples are sent to the laboratory immediately after collection where they are stabilized by air drying and stored for future analysis. The soils indicator is described in detail by O'Neill et al. (2005). Additional information related to methods, analysis, training material, and related publications is available at http://nrs.fs.fed.us/fia/topics/soils/ (accessed October 2009).

Vegetation diversity

Changes in species diversity and composition, structural diversity, and abundance of non-native species are common concerns, as reflected in the Montreal Process Criteria and Indicators (e.g., Criterion 1, USDA 2010b). The vegetation diversity indicator is designed to evaluate the composition, abundance, and spatial arrangement of all vascular plants occurring on the plots and provide baseline data essential for assessing change. Field measurements are recorded by certified crews with prior botanical experience. Measurements include both species abundance and distribution with plants identified to the species level. Ocular estimates of total canopy cover (by species) are recorded, as well as canopy cover (by species) in different height zones (0–2, 2–5, and 5 m and above) on each of the four subplots. Plants that cannot be identified in the field are collected for later identification. To capture more detailed information about species distribution across each subplot, field crews record the species observed within three permanent 1-m^2 quadrats on each subplot. To characterize the structure created by the vascular plants across the entire P2 plot, total vegetation canopy cover is recorded in four height zones (0–0.6 m, 0.6–2, 2–5, and 5 m and above). The vegetation diversity indicator is described in detail by Schulz et al. (2009).

Down woody material

The down woody materials (DWM) indicator is designed to estimate aboveground detrital biomass in the form of coarse woody debris, fine woody debris, litter, and duff. DWM data are use to estimate volume, biomass, carbon attributes of dead, and downed woody debris that are important to emerging fire, wildlife, and climate change issues. Coarse woody debris (greater than 7.5 cm in diameter) is sampled on a series of transects across the plot totaling 87.8 m in length. Fine woody debris between 2.5 and 7.5 cm is sampled on a series of transects totaling 12.2 m in length. Fine woody debris less than 2.5 cm is sampled on a series of transects totaling 7.3 m in length. Duff and litter depth measurements are taken at 12 points on the plot. The DWM indicator is described in detail by Woodall and Monleon (2008).

Ozone injury

Ozone is a widely dispersed pollutant in the lower atmosphere that reduces tree growth, changes species composition, and predisposes trees to insect and disease attack. Because ozone causes direct foliar injury to particular forest plant species through leaf gas exchange interference, these species can be used as "bioindicators" to identify the presence and severity of local air pollution. Ozone injury is not observed directly on the P3 plot network because bioindicator species are not always present on P3 plots, and openings in the canopy are necessary to obtain useful results. Also, the measurement window for ozone sampling is narrower than the 4-month sampling season for other indicators. For these reasons, the ozone indicator is sampled on a separate biomonitoring network (Smith et al. 2007). At each biomonitoring location, field crews evaluate 30 or more individual plants from at least two bioindicator species for amount and severity of ozone injury during a 3- to 4-week window in late July through early August. The ozone indicator is described in detail by Smith et al. (2007).

Inventory data documentation, availability, and analyses

Indicator documentation

The sampling protocols, database structure, and estimation procedures have been documented for most forest health indicators (Table 1). The field sampling protocols for all indicators are detailed in one compendium field guide that is updated annually (USDA 2009). An enduring goal of the P3 program is to maintain sample protocol consistency over space and time to ensure accurate estimates of change across the entire nation. Changes to field protocols are considered only when bias has become evident, some measurement variables have been determined to be unrepeatable, or expert user groups indicate a field variable is no longer desired.

In addition to field protocol documentation, estimation, and analysis documents have been published about most indicators (Table 1). These publications outline the purpose of the indicator, sampling theory employed, sample protocols, estimation procedures, and examples of analyses. A final reference for the P3 program is database documentation (Table 1). Akin to the field methods compendium (USDA 2009), this publication

Table 1 Locations of publicly available documentation regarding the sampling, database structure, estimation procedures, and analytical core tables for the US forest health indicator inventory

Indicator	Sampling and analysis protocols[a]	Number of database tables[b,c]	Number of database fields[b,c]	Number of analytical core tables	Published core table examples[d]
Down woody materials	Woodall and Monleon (2008)	7	146	6	Woodall and Monleon (2008)
Lichen communities	Will-Wolf (2010)	6	114	3	Will-Wolf (2010)
Ozone injury	Smith et al. (2007)	5	164	1	Smith et al. (2008)
Soils	O'Neill et al. (2005)	4	116	5	O'Neill et al. (2005)
Vegetation diversity	Schulz et al. (2009)	6	153	4	Schulz (2010)
Crown condition	Schomaker et al. (2007)	1	7	7	Randolph and Moser (2009)

[a] http://www.fia.fs.fed.us/library/field-guides-methods-proc/

[b] The Forest Inventory and Analysis Database: Database Description and Users Manual Version 4.0 for Phase 3 (http://www.fia.fs.fed.us/library/database-documentation/), alternatively see Woodall et al. (2010)

[c] The Forest Inventory and Analysis Database: Database Description and Users Manual Version 4.0 for Phase 2, (http://www.fia.fs.fed.us/library/database-documentation/)

[d] http://socrates.lv-hrc.nevada.edu/fia/ab/business/Core_Tables_revised_12_19_08.xls

defines all the data tables and fields used to distribute the data to the public (Woodall et al. 2010).

Indicator data availability

An objective of the P3 program is to distribute field data as rapidly to the public as possible, but before data can be distributed, they must be verified annually through quality control procedures. Quality control procedures typically entail numerous database logic and range checks along with analysis conducted by regional and national experts (Westfall 2009). Once data are vetted they are posted to FIA's data distribution website (Tables 1 and 2). Due to the slow-changing nature of the soil condition and lichen community's indicators, in a few states they are implemented on a rotating basis whereby one indicator is measured during one measurement cycle and the other indicator is measured during the following measurement cycle. Crown condition, down woody material, ozone injury, and vegetation diversity indicators are assessed annually.

Indicator analyses

Besides actual field data, the P3 program provides summaries of indicator attributes within populations and domains of interest (e.g., coarse woody debris volume in old-growth forests of Oregon);

Table 2 Publicly available forest health indicator data by indicator, year, number of states, number field-visited forest plots, and data location

Indicator	Sample years	Number of states	Number of plots	Data location
Down woody materials	2001–present	44	19,645	1
Lichen communities	1998–present	21	2,585	1, 2
Ozone injury	1999–present	21	8,363	1, 2
Soils	1999–present	36	4,429	1, 2
Vegetation diversity	2001–present	27	2,961	1
Crown condition	2000–present	46	4,840	1, 2

For further plot status information, please see USDA (2010a). Only publicly available data on the national website are summarized, more data have been sampled and are currently being vetted before public website posting

1 Data post 2001: http://199.128.173.17/fiadb4-downloads/datamart.html, *2* Data prior 2001: http://fia.fs.fed.us/tools-data/other_data/default.asp

Table 3 Forest health issues and/or Montreal Process Criteria and Indicators (MPCI) and related indicator(s) and associated publications

Issue or MPCI	Related indicators	Associated publications
Carbon stocks	Soils and down woody materials	Perry et al. (2009), Woodall and Liknes (2008a), Woodall (2007)
Air pollution	Ozone injury, lichen communities, and crown condition	Will-Wolf and Jovan (2008), Rose and Coulston (2009), Jovan (2008), Geiser and Neitlich (2007), Hinds and Hinds (2007)
Fire hazards	Crown condition	Monleon et al. (2004)
Calcium and aluminum deposition/ depletion dynamics	Soils	USDA (2010b)
Maintenance of forest health	Crown condition, lichen communities	Applegate and Steinman (2005), McCune et al. (2007)
Invasive plant species	Vegetation diversity	Conkling (2010), Heinz Center (2008)
Insects and diseases	Crown condition	Randolph (2007)
Climate change	Down woody materials	Woodall and Liknes (2008b)

these summaries are referred to as "core tables" (Table 1). For a number of indicators, the production of core tables may satisfy many users with timely and relevant information (e.g., downed dead wood carbon stocks in the eastern USA). For other indicators, population estimates may be of less value (e.g., number of lichen species in the Pacific northwest) when addressing forest health issues. The best guide for determining directions for indicator data analysis is perusing forest health issues relevant to each indicator and sets of indicators (Table 3). Explanations and examples of all possible analyses that may be conducted with P3 data are beyond the purview of this paper; however, a few examples are presented.

Indicator estimation and analysis examples

Given the diversity of sample protocols used for every forest health indicator, a corresponding diversity of estimation and analysis procedures has been developed. Additionally, the scale of interest is critical to indicator analyses. For most indicators, the minimal scale of investigation is typically at the state or regional level. In areas where plot sample intensity has increased (i.e., from P3 to P2 plot intensity), analyses may be conducted at sub-state scales (Woodall and Nagel 2007). Analysts should couch the results of indicator analyses within the statistical power (Conkling et al. 2002) afforded by each particular indicator and associated sampling intensity. Examples of various analyses/estimation procedures have been selected that cover a diverse array of estimation/analytical procedures: population total estimates (coarse woody debris (CWD) for a domain of interest), ratio of means estimate (mean tree crown attributes per unit area), air pollution indicator analysis (ozone bioindicator), and combining indicators for a holistic examinations of a forest health concerns (ozone/lichen and soils/downed dead wood indicator combinations).

Population total estimation example: coarse woody debris

The process for estimating the attributes (e.g., biomass) of coarse woody debris in a population can be divided into three steps. The first step is to compute the total CWD attribute in each plot, corrected for plots partially outside of the population (Woodall and Monleon 2008; Section 3.1.1). In the second step, the population of interest may be stratified into relatively homogeneous strata such as forest and non-forest based on remotely sensed imagery. Next, the computed plot values are averaged to the stratum level. Finally, the averages for each stratum are combined to arrive at an estimate of the total for the population. In this example the total amount of any particular CWD attribute is the parameter of interest, regardless of species or any other attribute, so all pieces are included and the domain indicator variable is always 1.

In each plot, CWD is measured along twelve 7.32-m transects (line intersect sampling, LIS). The LIS estimator is computed for each straight-line transect and then averaged over the three transects per subplot and four subplots per plot. The LIS estimator for an attribute of interest in domain of interest d for plot i assigned to stratum h, on a per unit area basis, is:

$$y_{\text{hid}} = \frac{c\left(\pi/2\right)}{12L\overline{p}_h^{\text{CWD}}} \sum_{j=1}^{4} \sum_{m=1}^{3} \sum_{t} \frac{y_{\text{hijmt}}\delta_{\text{hijmtd}}}{l_{\text{hijmt}}} \tag{1}$$

where

- y_{hijmt} is the attribute of interest measured in piece t intersected by transect m of subplot j of plot i assigned to stratum h. A CWD piece is recorded as many times as intersected by the transect.
- l_{hijmt} (ft) is the length of piece t intersected by transect m of subplot j of plot i assigned to stratum h.
- δ_{hijmtd} domain indicator variable, which is 1 if piece t intersected by transect m of subplot j of plot i assigned to stratum h belongs to the domain of interest d and 0 otherwise.
- L (ft) length of the transect, 7.32 m
- c constant to convert to proper units

$\overline{p}_h^{\text{CWD}}$ mean proportion of stratum h observed transect lengths falling within the population. Dividing by $\overline{p}_h$ adjusts the length of the transect to account for any portion of stratum h plots falling outside the population (Bechtold and Patterson 2005). This correction factor is simply the ratio of the total length of transect segments actually observed $\left(\sum_{i=1}^{n_h}\sum_{j=1}^{4}\sum_{m=1}^{3}\sum_{k=1}^{K_{\text{hijm}}} L_{\text{hijmk}}\delta_{\text{hijmk}}\right)$ to the length that would have been observed if all plots had fallen entirely within the population ($12Ln_h$):

$$\overline{p}_h^{\text{CWD}} = \frac{1}{12Ln_h} \sum_{i=1}^{n_h} \sum_{j=1}^{4} \sum_{m=1}^{3} \sum_{k=1}^{K_{\text{hijm}}} L_{\text{hijmk}}\delta_{\text{hijmk}} \tag{2}$$

where

- L_{hijmk} (ft) is the horizontal length of the transect segment within condition class k on transect m of subplot j of plot i assigned to stratum h.
- δ_{hijmk} is an indicator variable, which is 1 if condition k on transect m of subplot j of plot i assigned to stratum h is within the boundaries of the population; 0 otherwise.
- n_h number of P3 plots in stratum h. Plots that are entirely nonsampled are excluded.
- K_{hijm} is number of conditions intersected by transect m of subplot j of plot i assigned to stratum h.

The attribute of interest in equation 3.1, y_{hijmt}, could be any attribute measured or calculated in each piece (e.g., volume of CWD; Woodall and Monleon 2008, Table 3.1).

Population mean estimation example: tree crown attributes

In addition to estimates of population totals for a domain of interest (e.g., total CWD carbon stocks for US forest land), forest health specialists are often interested in estimates of mean tree attributes such as crown health. Ratio-of-means (ROM) estimators (Cochran 1977) are the preferred estimators used to calculate FIA inventory attributes on a per unit area basis. The crown indicator data do not need to be combined for microplot and subplot trees. Except for sapling crown vigor (which is only recorded for microplot saplings), other crown indicators are recorded only for subplot trees. Ignoring P1 stratification for the sake of simplicity (i.e., by computing estimates on the basis of simple random sampling), only the most basic ROM estimator is needed to calculate the means of crown indicators:

$$\hat{R} = \frac{\sum_{i=1}^{n} y_i}{\sum_{i=1}^{n} x_i} \tag{3}$$

where

y_i the variable of interest on plot i
x_i an auxiliary variable on plot i that is correlated with y_i and
n total number of plots in the population of interest (including plots with no observations of interest).

The variance is:

$$\hat{V}\left(\hat{R}\right) = \frac{1}{n\,(n-1)\left(\sum_{i=1}^{n} x_i \Big/ n\right)^2} \times \left(\sum_{i=1}^{n} y_i^2 + \hat{R}^2 \sum_{i=1}^{n} x_i^2 - 2\hat{R} \sum_{i=1}^{n} y_i\, x_i\right) \quad (4)$$

When calculating a mean tree attribute with Eqs. 3 and 4, y_i is defined as the sum of the tree attribute of interest for the trees of interest in the population of interest on plot i, and x_i is defined as the number of trees of interest in the population of interest on plot i. So, if the attribute of interest is crown density and the trees of interest are all trees in the population, then

y_i the sum of all crown densities sampled in the population of interest on plot i and
x_i the number of trees sampled in the population of interest on plot i.

Note that in cases where plot i has no trees of interest, or no trees sampled at all (e.g., nonforest) then y_i and x_i are both zero for that plot, but that plot still contributes to n.

Calculation of mean crown values permits hypothesis testing to determine whether any statistically significant differences exist among samples drawn from different populations, or from different periods in time.

Ozone injury assessment example

Chemical reactions of volatile organic compounds and nitrogen oxides driven by sunlight interfere with the normal breakdown of tropospheric ozone, which in turn causes a buildup of pollutant levels of ozone in the lower atmosphere (Manning 2005). Plants are injured by ozone during normal gas exchange when ozone enters leaves through the stomates. Ozone can cause foliar injury and reduce photosynthetic activity, which can result in reduced tree growth and predispose trees to secondary stressors such as insects and pathogens (Coulston et al. 2003). It should be noted that while growth reductions have been documented based on chamber studies (for examples, see Chappelka and Samuelson 1998; Skarby et al. 1998; Bytnerowicz et al. 2004), extrapolating chamber experiments to the landscape level is problematic. Additionally, ozone inventory locations are not coupled with the FIA P2 locations (i.e., different plot networks), which can confound and complicate some modeling efforts. For these reasons, analysis of the ozone bioindicator data is typically performed in an ecological risk assessment framework.

The goal of an ecological risk assessment is to evaluate the likelihood of an adverse ecological event occurring as a result of exposure to stressors (Mazaika et al. 1995). In the case of the ozone bioindicator, the risk of forest tree injury is based on interpolated information collected at ozone biomonitoring sites (Coulston et al. 2003; Smith et al. 2007). Examples of regional and national risk assessments can be found in Coulston et al. (2004), Ambrose and Conkling (2007), Campbell et al. (2007), and Rose and Coulston (2009). The goal of risk assessments is to identify candidate areas for subsequent investigation during the evaluation monitoring phase of the FHM program. Skelly et al. (2003) provide an example of an evaluation monitoring project that was conceptualized based on the regional risk analysis performed by Coulston et al. (2003). For more information, readers are directed to the Ozone Biomonitoring Users' Guide (Smith et al. 2008).

Lichen and ozone cross indicator analysis example

Will-Wolf and Jovan (2008) explored whether estimated air pollution risk to forests (as indicated by lichen and ozone indexes) correlates with forest health (as indicated by condition of tree crowns and recent tree mortality) in the Greater Sierra Nevada (GSN) region of California (Jovan and McCune 2006) and a multi-state region in New England (NE). Lichen communities are sensitive to regional air pollutants, thus regional-specific risk indices should be developed for proper evaluation of lichen species diversity. The ozone-interpolated biotic index (IBI), derived from indicator data, is based on severity of damage to leaves of ozone-sensitive vascular plants. A lichen pollution risk index is region specific, while the IBI is comparable across the entire country. The GSN lichen pollution risk index primarily reflects lichen community response to neutral/alkaline agricultural nitrogen pollution in the region (Jovan 2008). For the NE region, the best provisional lichen pollution risk index reflects response to acidic urban/industrial pollution (combined SO_x and NO_x; Will-Wolf, unpublished data). Maps based on National Atmospheric Deposition Program data (Will-Wolf and Jovan 2008) suggest that wet deposition of all air pollutants is much higher in the NE than the GSN region. Dry deposition predominates in the GSN (Fenn et al. 2003) and, as an inherently less predictable process, it is not reliably depicted in nationwide mapping products.

Linkage of any tree stress index to air quality risk indicators is likely to be robust where air pollution is stronger and any potential interaction of pollution with other environmental stressors on trees would be easier to detect. Species-based standards for identifying stressed trees will be much easier to calculate for the western USA than for the eastern USA due to fewer tree species in the west. It is expected that only in a few areas is air pollution strong enough to be the primary stressor affecting tree health (Will-Wolf and Jovan 2008). The possibility does exist that in much broader areas low to moderate air pollution interacts with other stressors by, for instance, reducing tolerance to other more obvious stressors affecting tree health or slowing recovery from other episodic stressors.

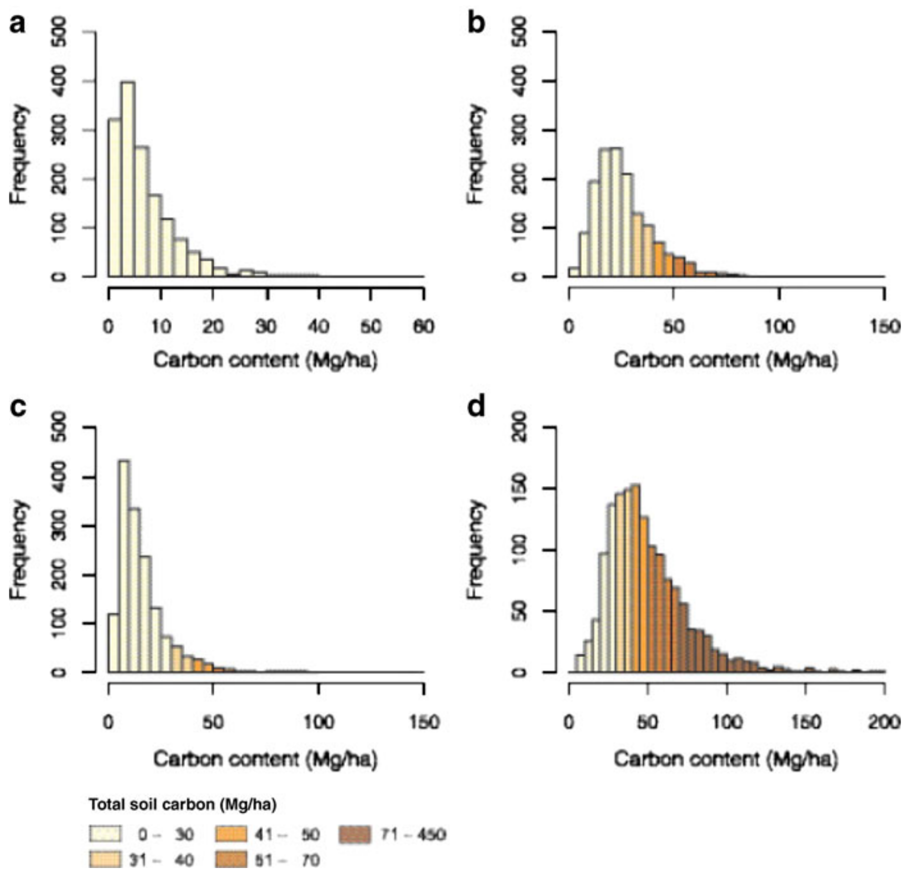

Fig. 4 Frequency (number of phase three soil plots) of classes of soil carbon content by soil layer (2001–2003): **a** forest floor, **b** mineral soil 0–10 cm, **c** mineral soil 10–20 cm, **d** sum of all layers sampled

Downed dead wood and soil carbon cross-indicator analysis example

Depending upon the estimate, soils contribute upwards of 50% of the total carbon stock in US forests (Turner et al. 1995; Smith and Heath 2008), and mean soil carbon content varies across ecosystems (Turner et al. 1995; Amundson 2001). Early analyses of the soil quality indicator documented the variations in soil carbon content through soil profiles (Fig. 4; Perry and Amacher 2007). Mean carbon contents spanned an order of magnitude, 7.11 Mg ha^{-1} in the forest floor, 27.41 Mg ha^{-1} in the top 10 cm of mineral soil,

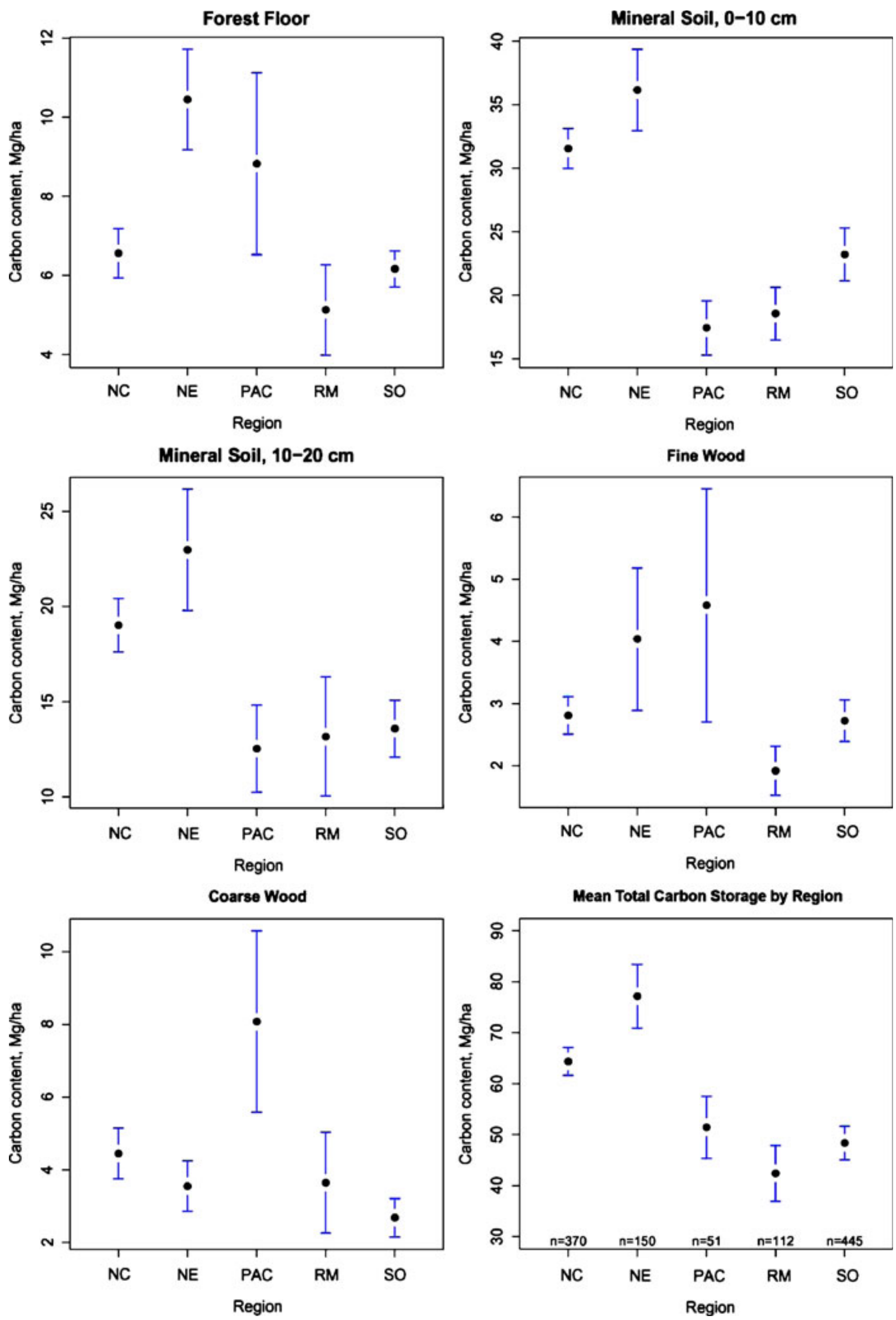

Fig. 5 Mean forest land carbon content (Mg/ha) and associated standard errors by region (*NC* north central, *NE* northeastern, *PAC* Pacific coast, *RM* rocky mountain, *SO* southeast) across the USA and by forest soil/dead wood component (forest floor, mineral soil 0–10 cm, mineral soil 10–20 cm, fine wood, coarse wood, and total soil/dead wood), 2001–2003 (Table 1). Locations of publicly available documentation regarding the sampling, database structure, estimation procedures, and analytical core tables for the US forest health indicator inventory

and 17.02 Mg ha^{-1} in the 10–20 cm layer of mineral soil (Perry and Amacher 2007). Analyses of down woody material conducted at the same time found up to 10.45 Mg ha^{-1} of carbon in CWD and 4.06 Mg ha^{-1} in fine woody debris (Woodall et al. 2008). This being said, one significant attribute of the forest health indicators is the fact that the P3 suite of indicators is measured on the same set of plots (with the only exception being the ozone bioindicator network), facilitating cross-indicator analysis.

The soil and DWM indicators represent a unique opportunity to jointly document a significant and highly variable carbon stock as well as monitor changes in it. In this cross-indicator analysis, inventory plots had to meet several criteria for inclusion (Perry et al. 2009). First, plots with CWD carbon greater than 56.5 Mg ha^{-1} were excluded from the dataset as outliers. Second, plots missing any of the three stocks (down wood, forest floor, and mineral soil) were excluded. It is important to note that forests on organic soils (peatlands) were not included in this analysis. Additional research is underway to improve the inventory and reporting of forested organic soil carbon stocks.

Mineral soils were found to store more carbon than either the down wood or forest floor stocks (Fig. 5). In fact, carbon in dead wood stocks is a minor component of the total carbon pool in forested landscapes.

This type of cross-indicator analysis demonstrates the strengths of an inventory approach to carbon monitoring: (1) statistical power associated with the inventory design, (2) integration with estimates of tree carbon stocks, (3) annual remeasurement on the more transitory stocks (down wood), and (4) national consistency (Perry et al. 2009).

Current status

As of 2010, at least one indicator has been established in every state (Fig. 3). Typically, forest health indicators were implemented in individual states as FIA's annual forest inventory was deployed after 2000. However, there are exceptions to this general rule. For example, the vegetation diversity indicator was still under development when some regions initiated annual inventory; this indicator requires field crews with specialized botanical skills and several regions have opted to delay full implementation.

At the state level, indicator data have been used to address forest health concerns in comprehensive state forest resource reports as mandated by the US congress. The first state forest resource report (South Carolina) based on the FIA annualized system (Connor et al. 2004) incorporated the suite of indicators alongside traditional forest inventory metrics (e.g., sawtimber volume and mortality). Subsequently, indicator data have been assimilated into standard inventory reports in all regions of the country, e.g., Oswalt et al. (2009) in the southeast, McWilliams et al. (2005) in the northeast, Woodall et al. (2005) in the north central, Barrett and Christensen (2010), in the west. More robust forest health monitoring has been facilitated in national forests and states that have adopted the indicator suite at a higher sampling intensity than the national intensity (for examples, see Huebner et al. 2009; Morin et al. 2009).

Forest health indicator analyses have also been incorporated into numerous national/international efforts. At the national level, forest health indicator analyses have been reported in annual FHM national technical reports since 2001 (Ambrose and Conkling 2007, 2009; Conkling 2010; Conkling et al. 2005; Coulston et al. 2005a, b, c; Potter and Conkling 2010). In addition to the national reports directly sponsored by the FHM program, indicator data and results are often included in other important national reporting efforts. Some noteworthy reports in this category include (1) the Forest Service 2003 and 2010 National Reports on Sustainable Forests (USDA 2004, 2010b); (2) the Heinz Center's State of the Nation's Ecosystems (available at http://www.heinzctr.org/ecosystems/report.html); (3) the EPA's US/Canada Air Quality Agreement Progress Reports (available at http://www.epa.gov/airmarkets/progsregs/usca/index.htm); and (4) empirical validation of some of the official US National Greenhouse Gas stocks compiled by the US Forest Service and EPA (Smith and Heath 2008) and reported to the United Nations (for example, see Woodall et al. 2008).

Indicator data are addressing forest health concerns at increasing levels of detail in national sustainability reports. In the 2003 National Report on Sustainable US Forests (based on Montreal Process Criteria and Indicators, USDA 2004), only half the states in the USA had soils indicator data to address Indicator 21 (area and percent change of forest land with significantly diminished soil organic matter and/or changes in other soil chemical properties). In the latest version of this national sustainability report (USDA 2010b), the soils indicator provides data coverage for all but three of the coterminous states. Without the FIA indicator data, several Montreal Process indicators can only be addressed using modeled or simulated estimates. With the establishment of the P3 inventory in all 50 states, it will be possible to address numerous indicators using empirical information (e.g., downed dead carbon stock estimates based on P3 measurements as opposed to models, Woodall et al. 2008). Simulation-based carbon flux estimates of soil organic carbon or dead wood stocks may not fully reflect the impacts of climate change or stochastic disturbance events. Even so, emerging indicator-based carbon flux estimates suggest that the statistical power resulting from the current P3 sample intensity may be adequate only to detect considerable fluxes at the national scale (Woodall 2010).

Future

A major goal of the US' forest health monitoring effort is full implementation with remeasurement in all 50 states, thus enabling robust forest health assessments nationwide. The P3 sampling intensity may be increased either through congressional appropriation or through partnerships with states or national forests. Increases in sampling intensity need not be facilitated solely by the federal government. Features of the P3 program (sampling designs and data management/estimation systems) have already been adopted by some state agencies to assess forest health at smaller scales with higher sample intensities than FIA's P3 program (Westfall and Scott 2009; Morin et al. 2009). Working from a set of common forest health indicators, sample protocols, and database structures has facilitated the creation of a consistent forest health inventory across spatial scales in some areas of the USA with investment from numerous partners.

Increasing the precision and accuracy of greenhouse gas inventories has been an emerging issue (Heath et al. 2010) for the USA. Given the 10- to 20-year remeasurement cycle (i.e., 5- to 10-year measurement cycles times two) of the forest health monitoring program, the complete empirical assessment of soil and dead wood annual carbon fluxes may be available by 2020 or shortly thereafter for almost every state in the nation (with the possible exception of interior Alaska due to budget constraints). Without FIA's indicator program, a number of the Montreal Process indicators could be addressed only by using modeled or simulated estimates, as opposed to the empirical design-based estimates provided by FIA's inventory. The same paradigm applies to national efforts to estimate forest carbon pools and fluxes. It is hoped that a number of carbon stock estimates can progress from being simulation based to empirically based (for dead wood example, see Woodall et al. 2008). Purely simulation-based carbon flux estimates of soil organic carbon or dead wood stocks may not fully reflect the impacts of climate change or stochastic disturbance/management events. Emerging indicator-based carbon flux estimates suggest that the statistical power resulting from the current sample intensity may be adequate only to detect considerable fluxes at the national scale (Woodall 2010). National assessments of carbon and many other forest attributes should be more fully enabled in the years ahead as the indicator program approaches complete implementation.

Despite the rather static list of indicators surveyed by the monitoring program, the circumstance of climate change may necessitate the incorporation of additional indicators or variables to existing protocols as new forest health threats emerge. For example, the National Phenological Network (NPN 2010) monitors the seasonal timing of cyclical life events of a number of species with broad range distributions. Many species respond to physical and seasonal climatic conditions that are difficult or expensive to measure directly. Observations of dates of leaf emergence, leaf expansion, flowering, and fruiting can provide clues to the impacts of changing climatic conditions. Recording observations of phenological states for a select number of species, even though the observation occurs only once every 5 to 10 years may aid climate change research. FIA continuously reviews its inventory protocols and has an established process by which current variables are modified or removed and new variables are added. This flexibility is a critical component of successful forest health monitoring.

The efforts invested in a nationwide forest health monitoring program will not be fully realized until colleagues working at a variety of spatial scales and in a variety of sub-disciplines are able to utilize a fully implemented indicator program (i.e., all 50 states). With the emerging threat of climate change and possible increased use of forest resources (e.g., biomass harvest for energy and carbon offsets), the P2 and P3 forest inventory program will allow for more robust quantification and description of forest communities that are undergoing unprecedented changes. Hence, a fully functional national-scale forest monitoring program serves not only to ensure forest sustainability, but also the sustainability of public well-being (e.g., clean air and water) and economies (e.g., biomass for energy) into the future.

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