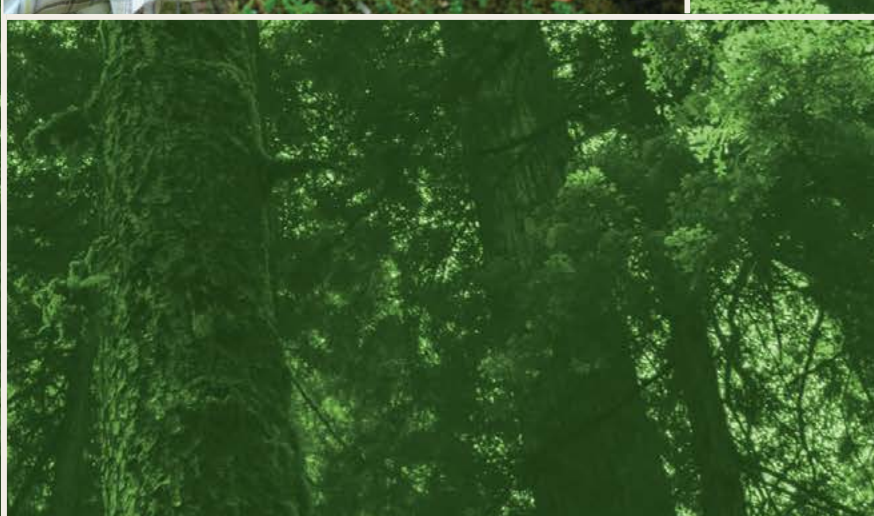
USDA
United States Department of Agriculture

Forest Ecosystem Health Indicators



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CONTRIBUTING AUTHORS

KaDonna C. Randolph	Research Mathematical Statistician	Southern Research Station Forest Inventory and Analysis Knoxville, TN 37919
Randall S. Morin	Research Forester	Northern Research Station Forest Inventory and Analysis Newtown Square, PA 19073
Kerry Dooley	Forester	Southern Research Station Forest Inventory and Analysis Knoxville, TN 37919
Mark D. Nelson	Research Forester	Northern Research Station Forest Inventory and Analysis St. Paul, MN 55108
Sarah Jovan	Research Ecologist	Pacific Northwest Research Station Portland, OR 97205
Christopher W. Woodall	Research Forester	Northern Research Station Forest Inventory and Analysis Durham, NH 03824
Bethany K. Schulz	Emeritus Scientist Research Ecologist	Pacific Northwest Research Station Forest Inventory and Analysis Anchorage, AK 99501
Charles H. Perry	Research Soil Scientist	Northern Research Station Forest Inventory and Analysis St. Paul, MN 55108
Cassandra M. Kurtz	Forester	Northern Research Station Forest Inventory and Analysis St. Paul, MN 55108
Sonja N. Oswalt	Forest Resource Analyst	Southern Research Station Forest Inventory and Analysis Knoxville, TN 37919
William H. McWilliams	Research Forester	Northern Research Station Forest Inventory and Analysis Newtown Square, PA 19073 (No longer with the Northern Research Station)
Rachel Riemann	Research Forester/Geographer	Northern Research Station Forest Inventory and Analysis Troy, NY 12180

Randall S. Morin, Compiler

USDA Forest Service
Northern Research Station
11 Campus Boulevard
Newtown Square, PA 19073

Randall.S.Morin@USDA.gov

Beaver damage.
(Photo by Sjana Schanning, USDA Forest Service)

CONTENTS

ONLINE STORY MAP:

https://usfs.maps.arcgis.com/apps/MapJournal/index.html?appid=a434a8d7b3d447c8a747efb4fd22d742#

INTRODUCTION

The U.S. Department of Agriculture (USDA), Forest Service, **Forest Inventory and Analysis (FIA)** Program is the Nation's continuous forest census. Since 1930, we have collected, analyzed, and reported information on the status and trends of America's forests: how much forest exists, where it exists, who owns it, and how it is changing — growing, dying, being harvested, or converted to and from forest land uses. In response to widening customer interests, the FIA developed a program that was implemented in the same manner on all U.S. forest lands. This included sampling an extended suite of forest health indicators. Many of these indicators were developed and initially measured by the Forest Health Monitoring (FHM) Program in the 1990s. In 1999, they were transferred to FIA and now are a subset of the FIA inventory.

Originally, the health indicators were sampled on 1 of every 16 standard FIA plots, but this design faced budget and logistical constraints. In 2012, FIA redesigned the health program as a flexible system with spatial and temporal intensities that are adaptable to meet budgetary constraints, client needs, and regional issues. A minimum national set of protocols are "core" to the forest/ecosystem health indicator program. These health indicators are collected at intensities ranging from a minimum of approximately 7 percent up to 25 percent of the standard plot grid. In addition, the Vegetation Profile and Down Woody Materials indicators are sampled on all plots in the Western United States. The FIA indicators discussed in this publication are:

- Crown Condition *(KaDonna C. Randolph)*
- Tree Damage *(Randall S. Morin and Kerry Dooley)*
- Tree Mortality and Standing Dead Trees *(Randall S. Morin and Mark D. Nelson)*
- Lichen Communities *(Sarah Jovan)* (adjunct inventory conducted by National Forest Systems in some regions; retired as a national core indicator)
- Down Woody Materials *(Christopher W. Woodall)*
- Vegetation Profile *(Bethany K. Schulz)*
- Soil Quality *(Charles H. Perry)*
- Nonnative Invasive Plants *(Cassandra M. Kurtz and Sonja N. Oswalt)*
- Regeneration and Browse Impact *(William H. McWilliams)*
- Fragmentation and Landscape Context *(Rachel Riemann)*

The Ozone Injury indicator was retired around 2010, but data from 1994 to 2010 are available in the FIA database. Sampling and estimation procedures are documented in Smith et al. (2007).

The purpose of this publication is to describe these health indicators by providing:

- Background information about how and why the indicator was developed
- Examples of the data, products, and publications available
- The direction of future research and development

CLIENTS AND PRODUCTS

The FIA Program has a diverse and growing set of customers who are interested not only in reports and analyses produced by FIA but also in using the FIA data. Congress and State legislators have long used FIA information as a basis for formulating sound forest policy. State forestry and other agencies depend on FIA monitoring for long-term decision making and policy formulation. Forest industry, nongovernmental organizations, and a wide range of private consultants use FIA information for management decisions and planning.

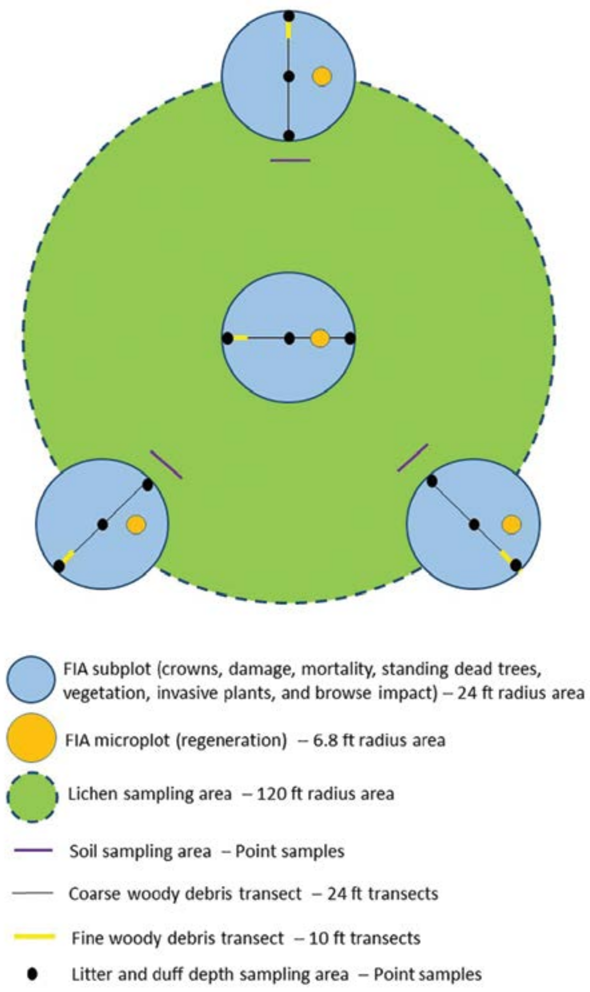

Figure 1. Forest Inventory and Analysis Program plot design for forest health indicators.

Government and academic researchers use FIA data as a basis for detecting science needs and directing scarce funds to priority research. Land managers at all levels rely on FIA data for a strategic look at forest resources and as a basis for strategic-scale forest planning. These users have expressed interest in a broader suite of FIA measures that includes indicators of forest health. Information about a diverse array of forest health attributes, beyond trees, serve as indicators of complex forest ecosystem processes across the United States.

FIA also contributes data and analyses to a variety of national and global assessments, including many of the Criteria and Indicators of Sustainability for reporting under the Montreal Process. FIA data are key for producing the reports required by the Resource Planning Act (RPA) and are increasingly being used to support regional resource assessments that are a basis for forest planning.

Scientists and policymakers employ FIA data about forest soils, down woody materials, and tree biomass to estimate carbon budgets and to model the potential for carbon sequestration under different management scenarios. The fire management community identifies areas at highest risk of catastrophic fire and opportunities for preventive treatments using the forest structure, understory vegetation, and down woody debris data. Land managers, equipped with data on understory vegetation, track invasive species, assess regeneration security, and quantify the impacts of browsing. This fills critical information gaps for restoring healthy young forest habitat that sets the trajectory for future forests following disturbance. Forest health specialists rely on information about tree condition to quantify the occurrence and impacts of abiotic and biotic forest disturbances. Surveys of lichen communities in some regions of the United States are used to provide information on human health, air quality, climate, and biodiversity. Indicators of forest fragmentation and urbanization help policymakers understand trends in the spatial distribution of forest land and proximity of forest land to urban development.

CROWN CONDITION

KaDonna C. Randolph ▪ Research Mathematical Statistician ▪ Southern Research Station

BACKGROUND

The crown condition indicator describes the amount, condition, and distribution of foliage, branches, and growing tips of trees. In addition to being aesthetically pleasing, tree crowns provide shade, temperature and wind moderation, and food and habitat for many organisms. They also mitigate erosion by intercepting rainfall and provide a source of fuel for wildfires. Healthy, full crowns suggest carbon is being stored, the tree is growing, and there are no serious impacts from pathogens, air pollutants, or insects. When FIA first implemented the indicator, five components of crown condition were assessed: live crown ratio, crown density, foliage transparency, crown dieback, and crown diameter. Schomaker et al. (2007) thoroughly describe the methods used to assess crown condition. Because live crown ratio and crown dieback have proven to be the most broadly applicable components, currently these are the only crown variables collected as part of the core program.

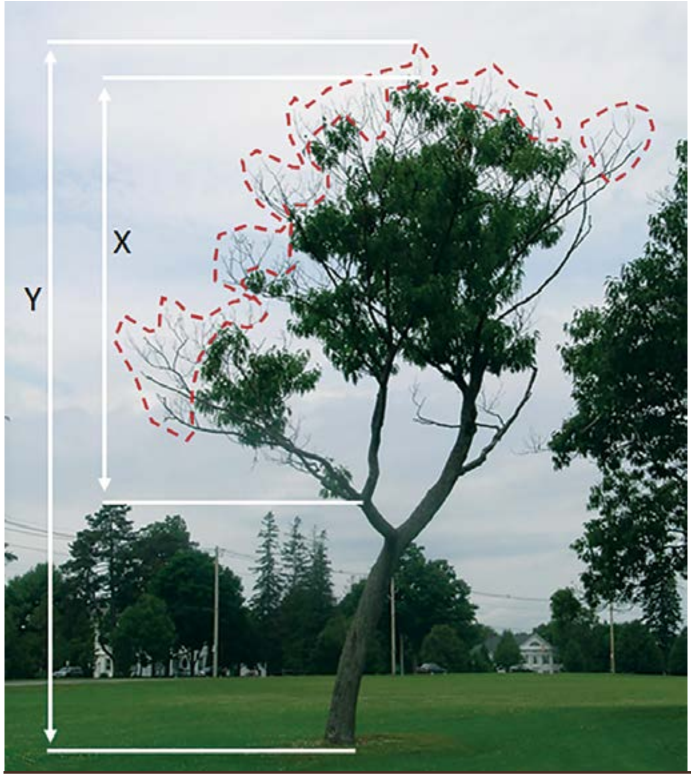

Figure 2. Live crown ratio is the length of the tree with branches (X) divided by the total tree length (Y). Crown dieback is the death of sun-exposed twigs in the upper and outermost parts of the crown (areas within the dashed lines). (Photo by KaDonna C. Randolph, USDA Forest Service)

PRODUCTS AND PUBLICATIONS

Tree crowns reflect the effects of forest stressors such as insects, pathogens, and too much or too little water. As such, the crown condition indicator provides a good general indicator of tree health and can be related to tree growth and survivorship. Crown assessments can also be used to describe forest characteristics such as potential fire risk and wildlife habitat. FIA summarizes crown condition data approximately every 5 years at the State, regional, and national levels. In addition, independent researchers conducting individual studies employ the crown condition assessment methods implemented by FIA.

Examples of published studies that utilize FIA crown condition data or the indicator assessment methods include:

- Predicting tree mortality in the Eastern United States (Morin et al. 2012)
- Assessing eastern hemlock vulnerability to hemlock woolly adelgid in West Virginia and Pennsylvania (Fajvan and Wood 2010)
- Evaluating oak decline and mortality in the Ozark Highlands (Crosby et al. 2012)
- Assessing the risk of crown fire hazard in Washington (Campbell et al. 2010)

RESEARCH AND DEVELOPMENT

Previous studies have established expected crown conditions for typically healthy trees in forested settings. Continued assessment of tree crowns under shifting climatic patterns will reveal if the distribution of crown conditions is also shifting. Future studies may consider how climate-related

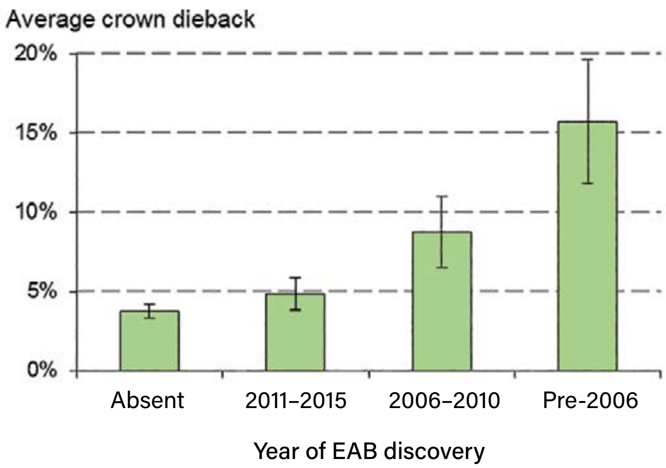

Figure 3. Average crown dieback by duration of emerald ash borer (EAB) infestation for ash trees assessed in the Eastern United States during 2011–2015. Bars around the average represent one standard error. Adapted from Randolph (2018). (Data source: Forest Inventory and Analysis Program)

changes in crown condition, if they do occur, affect tree vitality, forest structure, and other characteristics of interest, e.g., wildfire fuels. As FIA expands to collect data on trees in urban areas, assessments of crown condition will be an integral part of accounting the economic and environmental benefits of trees and understanding the interactions between natural environments and human health.

TREE DAMAGE

Randall S. Morin ▪ Research Forester ▪ Northern Research Station and
Kerry Dooley ▪ Forester ▪ Southern Research Station

BACKGROUND

The tree damage indicator identifies the presence and type of damages from various causes. This indicator is collected on all forested portions of all field-measured plots and is taken at the individual live tree level, as opposed to plot or stand level. This allows for earlier identification of forest health problems, as collection will happen before tree mortality or stand-level effects are reached.

Previous FIA surveys collected information on damages various ways, but a new national methodology implemented in 2013 provided a means of gathering specific data on types of damage. On each tree, up to 3 damages may be selected from 24 categories derived from a list used by Forest Service forest health programs. Examples include "boring insects," "root/butt diseases," "wild animals," and "unknown damage." Combined with data from FIA and other programs, this indicator can contribute to detailed estimations of forest health issues.

PRODUCTS AND PUBLICATIONS

Collection of this data set is nearing completion nationally, and therefore new analyses for national products are anticipated. Some products that used past iterations of damage or closely related data give an indication of how these new data will be used:

- Assessment of damage from catastrophic weather events (Nelson and Moser 2007, Randolph 2015)
- Presence, severity, and hazard reports of regional pest activity in association with ancillary data sets (Lockman, Bush, and Barber 2016, Morin et al. 2016)
- Tree damage chapters in 5-year State reports (Meneguzzo et al. 2018, Lister et al. 2018)

As data sets are completed, they will become part of standard 5-year reports at the State and national levels.

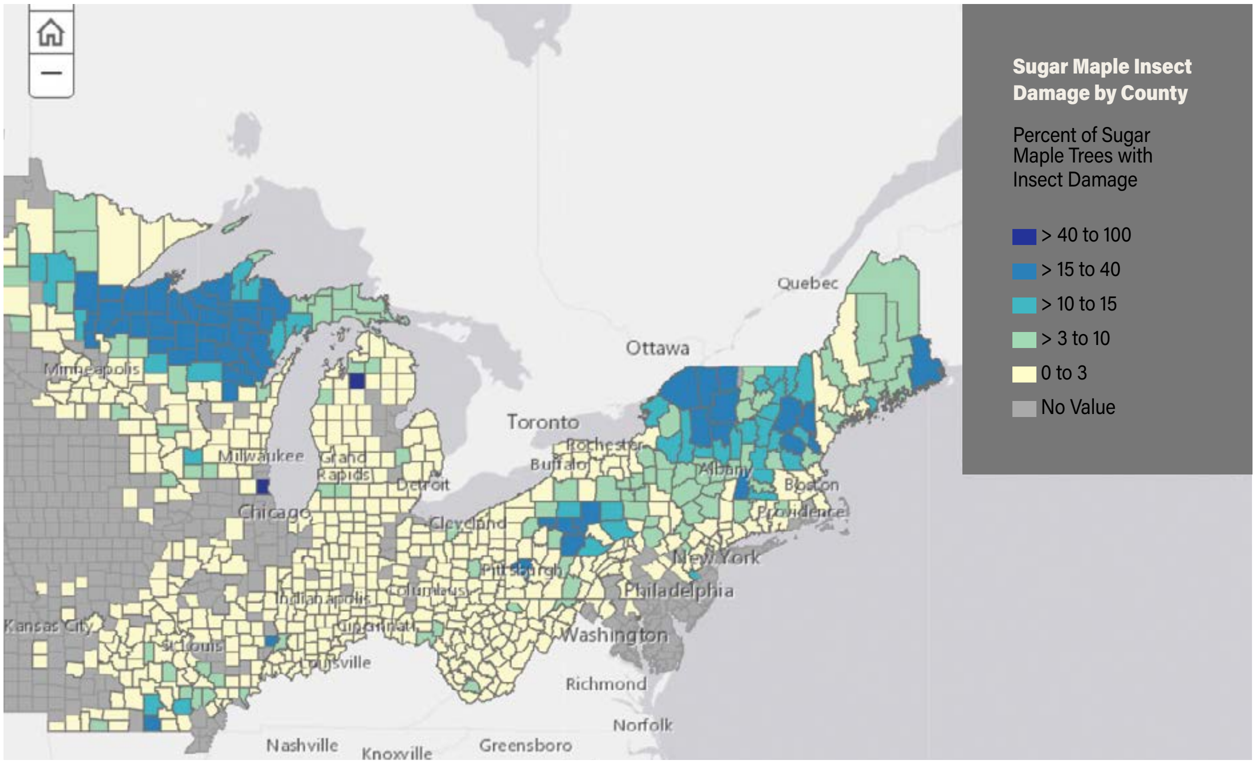

Figure 4. Map of the percentage of sugar maple trees with observed insect damage by county for States in the Northern United States, 2013 (Morin et al. 2016; story map version).

RESEARCH AND DEVELOPMENT

Tree damage data are available from across the country, and the national data from the updated protocols will be completed in several years. Future work will focus on testing the repeatability of the damage protocols and integrating analysis and tools with other ancillary data sets. For example, tree damage data from FIA can help to quantify the impacts of disturbances such as invasive forest pests or extreme weather events.

Figure 5. Nectria fruiting bodies on American beech. (Photo courtesy of Elizabeth Morin)

TREE MORTALITY AND STANDING DEAD TREES

Randall S. Morin ▪ Research Forester ▪ Northern Research Station and
Mark D. Nelson ▪ Research Forester ▪ Northern Research Station

BACKGROUND

The tree mortality indicator shows the number, size, and volume of trees that have died since the previous measurement on an FIA plot. Those trees also remain part of the inventory as dead trees until they are no longer standing. Standing dead trees are also sampled on newly installed FIA plots. Mortality and dead trees provide information on whether changes in abiotic or biotic stressors or stand development are creating conditions less favorable for tree growth and survival. Since the implementation of the annual inventory in 1999, the amount of remeasurement data available for tree mortality estimation has increased substantially.

Mortality is an essential part of all healthy forest ecosystems. It contributes to ecosystem functioning and diversity by creating dead material for nutrient recycling, producing openings that result in mosaics of species and ages, and providing habitat for wildlife. Mortality may also reduce productivity of forests being managed for wood production and increase risk of wildfire. Changes in the rates and amounts of mortality require close scrutiny to identify whether or not those variations indicate the presence of a forest health issue. Analyses of affected species, their ages, disturbance history in the area, and the cause of mortality offer essential information for land managers and policymakers.

PRODUCTS AND PUBLICATIONS

The tree mortality indicator quantifies a key ecological process in forests and can be used to estimate a variety of important metrics. For

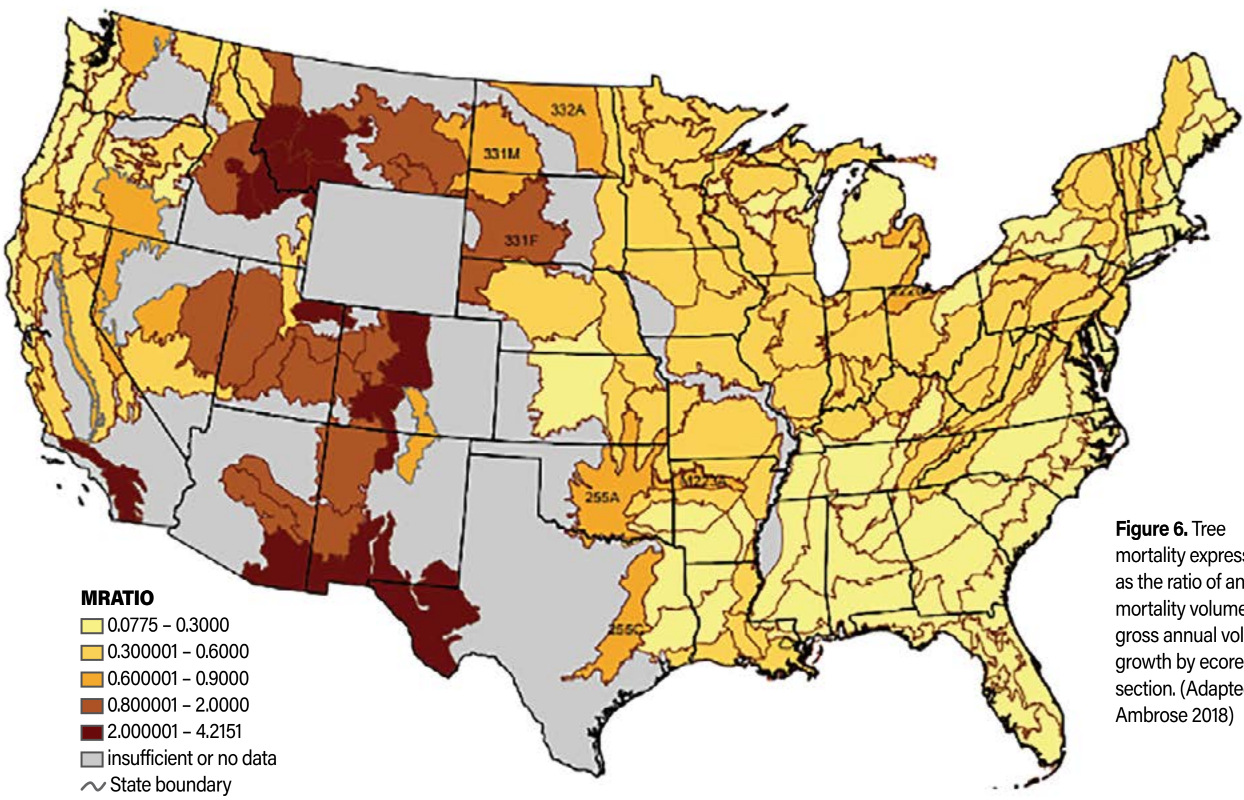

Figure 6. Tree mortality expressed as the ratio of annual mortality volume to gross annual volume growth by ecoregion section. (Adapted from Ambrose 2018)

Figure 7. Hemlock woolly adelgid-related hemlock mortality in Great Smoky Mountains National Park. (Photo by Songlin Fei, Purdue University)

example, tree mortality can provide information about the impacts of biotic and abiotic disturbances, habitat characteristics for wildlife species that depend on dead trees, fuel loading and fire risk, carbon cycling patterns, and sustainability. FIA data provide standardized outputs at the national level in RPA and FHM reports and at the State level in 5-year reports to quantify the status and trends in tree mortality and standing dead trees. Some examples of published studies that utilize the tree mortality indicator include:

- Climate and weather impact assessments (Shaw et al. 2005)
- Contribution of standing dead trees and tree mortality to carbon stocks and dynamics (Woodall et al. 2015, Domke et al. 2013, Fei et al. 2019)
- Quantification of native and invasive pest impacts (Thompson 2017, Morin and Liebhold 2015)
- Assessments of fire effects and risk (Shaw et al. 2017, Whittier and Gray 2016)

RESEARCH AND DEVELOPMENT

Remeasurement data in the FIA database allows mortality and standing dead trees to be estimated across the country. Integrating these findings with other data sources enables researchers to quantify the impacts of landscape-level disturbances that cause mortality. Most research on mortality and standing dead trees focuses on working with partners to use these data for contemporary forest health issues and to develop online tools for analysis and reporting. For example, FIA and Forest Health Monitoring survey data have been integrated to assess insect and disease impacts to characterize wildlife habitat for species dependent on snags and den trees.

LICHEN COMMUNITIES

Sarah Jovan ▪ Research Ecologist ▪ Pacific Northwest Research Station

BACKGROUND

The national lichen community indicator, begun in 1992, is the most extensive and detailed lichen-monitoring program in the world, generating more than 5,500 standardized surveys of epiphytic (tree-dwelling) lichen communities across the United States. Federal land managers and researchers use these surveys to provide information on air quality, climate, biodiversity, and lichen floristics in forests. A related ground layer indicator, developed in 2014, focuses on ground-dwelling lichens and moss, providing landscape-scale estimates of cover, biomass, carbon, and nitrogen in functional groups (e.g., peat moss, wildlife forage lichens, nitrogen-fixers). Moss and lichen mats, abundant or dominant in some forests, play well-known ecological roles in hydrology, carbon storage, wildlife migration patterns, and soil stabilization and chemistry. Lacking roots, lichens and moss derive all nutrition and water from the atmosphere. This makes them highly sensitive to air pollutants, climate changes, and shifts in habitat conditions that affect light, microclimate, and nutrient availability. Currently, FIA samples this indicator only in the Pacific Northwest, but the program is poised to implement this indicator nationally when and if funding becomes available.

PRODUCTS AND PUBLICATIONS

The two Indicators have been used in more than 75 products. The most commonly used metrics include:

- Air quality: The use of lichen communities as "canaries in the coal mine" for air quality studies dates back to 1866. Clients use the Community

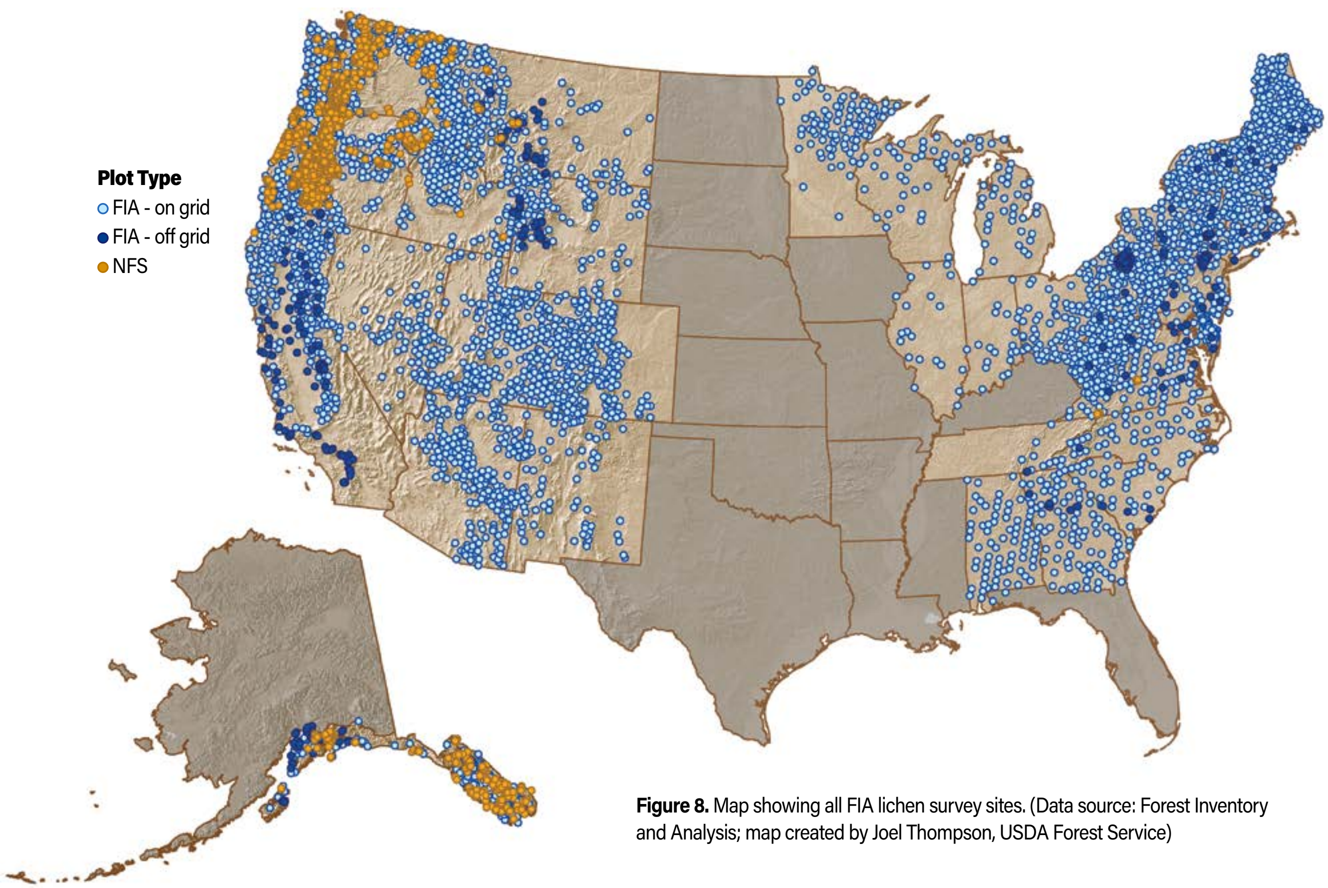

Figure 8. Map showing all FIA lichen survey sites. (Data source: Forest Inventory and Analysis; map created by Joel Thompson, USDA Forest Service)

Figure 9. *Evernia prunastri* (antlered perfume lichen) growing in clean air (left – photo by Richard Droker) and polluted air (right – photo by Sarah Jovan, USDA Forest Service). The convoluted thallus on the right is called a "pollution morph."

Indicator to inform air quality policy (e.g., EPA Integrated Science Assessments 2008, 2017), provide managers with empirical guidelines for air-quality monitoring in protected areas (i.e., "Critical Loads"; Fenn et al. 2008, 2010; Pardo et al. 2011), and supplement widely spaced instrument monitoring networks at a variety of spatial scales (e.g., Jovan and McCune 2005, Will-Wolf et al. 2015).

- Climate: The community indicator can be employed to model species' climate tolerances (Smith et al. 2017) and to delineate "bellwether" zones where climate change is expected to have particularly severe effects (Root et al. 2014). These, then, provide the building blocks for simple, repeatable metrics for tracking climate change.
- Carbon: The ground layer indicator accounts for a carbon pool not otherwise measured in the forest inventory. Lichen and moss ground mats can be more than 11.8 in (30 cm) thick and, under the right conditions, sit atop extensive carbon deposits (i.e., peat; Smith et al. 2015).

RESEARCH AND DEVELOPMENT

Three research arcs are underway to expand the scope or foundation for indicator applications.

- **A pilot for the lichen elemental indicator**, a very low-cost tool for monitoring air quality on the FIA grid by measuring the amounts of pollutants accumulating inside lichens, was recently completed.
- **A 14-month calibration study** underway in Portland, OR, compares heavy metals in moss to levels measured in air and precipitation. This study provides the foundation for the lichen elemental indicator, as well as guiding pilot work using that technique for fine-scaled pollution mapping in urban areas.
- Differentiating climate change effects on lichens from other possible drivers is tricky. **Ongoing experimental work to inform lichen-climate metrics** includes tracking lichens in climate-warming enclosures (Spruce and Peatland Responses Under Changing Environments study) and using cameras to track lichen growth and recruitment in relation to weather patterns (Epiphytic Lichen Observation Network study).

DOWN WOODY MATERIALS

Christopher W. Woodall ▪ Research Forester ▪ Northern Research Station

BACKGROUND

The down woody materials (DWM) indicator estimates the amount and condition of dead and downed woody material across all U.S. forests. Down woody materials can be delineated as detrital components of forest ecosystems, including fallen twigs and small branches (fine woody debris) and fallen tree stems and large branches (coarse woody debris). Fine woody debris is less than 3 inches in diameter at the point of intersection with a sampling transects; coarse woody debris is 3 inches or larger.

Fine woody debris is further divided into three size classes that align with fire behavior model inputs. In addition to size, the species and decay class of coarse woody debris is measured for the purpose of biomass and carbon estimation.

As coarse woody debris can sometimes be assembled into piles during harvest operations, there are sampling protocols for residue piles. The depth of duff and litter is sampled at the end of each sampling transect as an indicator of surface fuel loadings. Duff is highly decomposed forest biomass to the point of being indistinguishable as to its origin. In contrast, litter can be identified as leaf material or fractured woody material not included in the fine woody debris population. Down woody material was sampled across most States from 2002 to 2011. Measurements (and remeasurements) continued in 2012 using updated sample protocols across all States at a greater sampling intensity.

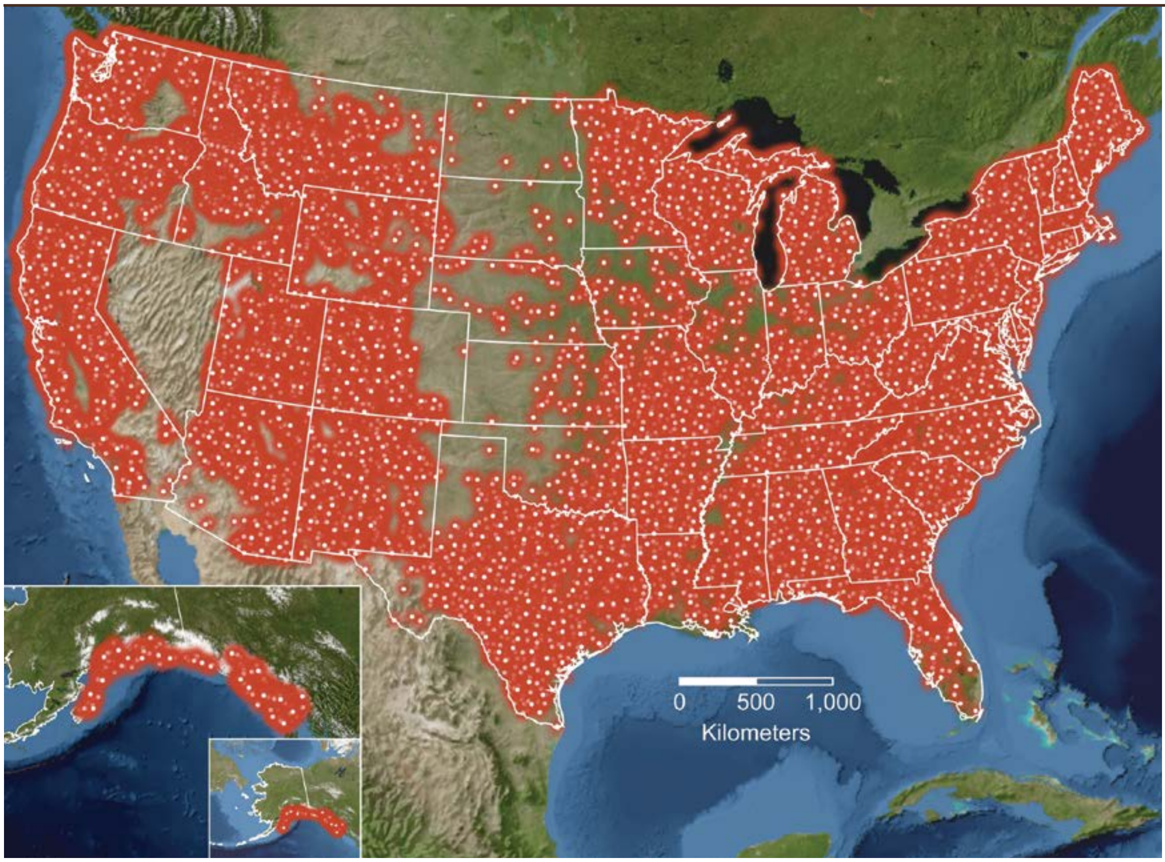

Figure 10. Locations of down woody material inventory plots, 2012–2016, are aligned with the distribution of forest across the United States. (Map by Dale Gormanson)

PRODUCTS AND PUBLICATIONS

The quantity and condition of DWM is emerging as a major factor governing forest ecosystem processes such as carbon cycling, fire behavior, and tree regeneration. Downed dead wood plays a central role in many forest ecosystem functions, including wildlife habitat, biodiversity of deadwood-dependent organisms, tree regeneration, wildfire risk and behavior, nutrient cycles, and carbon stocks and cycling. Downed woody material data are used to inform National Greenhouse Gas Inventories and, when coupled with live tree inventory data, they provide a robust quantification of forest changes over time. As global change is projected to increase the frequency and intensity of natural disturbances that cause tree mortality and hence create DWM (e.g., invasive pests, droughts, windstorms, wildfires), we can expect expanded interest and use of DWM data sets to address wildfire risks, forest sustainability, and carbon estimation and modeling.

Some examples of published studies using the DWM indicator include:

- National analysis of dead wood biomass and volume (Woodall et al. 2013)
- Carbon stocks and flux associated with downed and dead wood (Woodall et al. 2008, Domke et al. 2013, Woodall et al. 2015)
- Models of dead wood residence time in forest ecosystems (Russell et al. 2013, Russell et al. 2014)
- Relationships between live and downed dead tree attributes (Woodall and Westfall 2009, Garbarino et al. 2015)
- Fuel loading and fire hazard assessments (Woodall and Nagel 2007)

RESEARCH AND DEVELOPMENT

Refinements of the DWM indicator continue, with focus on improving the estimation procedures associated with deriving biomass and carbon attributes from dead wood transect sampling (e.g., Harmon et al. 2013), along with assessing sources of uncertainty (Campbell et al., in press). Given the DWM indicator refinements implemented in 2012 to gain a greater sample intensity across the Nation, work continues on documenting the changes to the sampling and estimation procedures and associated databases for the public (Woodall et al., in review). Prior work incorporating the DWM indicator data into the National Greenhouse Inventory focused on calibrating past models to align with DWM indicator carbon estimates. Current research is exploring ways to adapt soil carbon modeling techniques (Domke et al. 2017) to the DWM indicator. Emerging work is focused on the creation of low-cost fuel moisture sensors that may be deployed at a low sample intensity to inform real-time assessments of fire hazards across the national network of DWM plots.

Figure 11. Snail on a downed log. (Photo by Christopher W. Woodall, USDA Forest Service)

VEGETATION PROFILE

Bethany K. Schulz ▪ Emeritus Scientist Research Ecologist ▪ Pacific Northwest Research Station

BACKGROUND

The Vegetation Profile assesses all vascular vegetation to record the arrangement of trees, shrubs, forbs, and grasses. Additional levels of detail provide information about the most abundant species in each growth habit; up to four species of large grasses, forbs, shrubs, small trees (trees less than 5 inches in diameter) and large trees, if they are present with a canopy cover of at least 3 percent of the subplot area (Western United States only). This is a simplified version of the earlier Vegetation Structure and Diversity Indicator, which made a complete census of all vascular plant species present on a small subset of all FIA plots. The Vegetation Profile, with species information, is collected on all standard inventory plots in the western regions. However, in the eastern regions, only a rapid assessment is performed and sampling is restricted to a small proportion of plots (approximately 18 percent).

The total of all vegetation growth is important when considering the health and range of ecological services provided by forests. The structure of vegetation can indicate suitability for wildlife habitat, the components of fuels in wildfire situations, or potential competition for reforestation efforts. Information on the most abundant species can further define the quality, presence of forage species, species that will spread or suppress fire, known tree seedling competitors, and identify serious infestations of invasive plant species. Structure and species information better describe the vegetation community with more detail than tree data alone. This helps us understand the distribution and diversity of the forest communities inventoried over time.

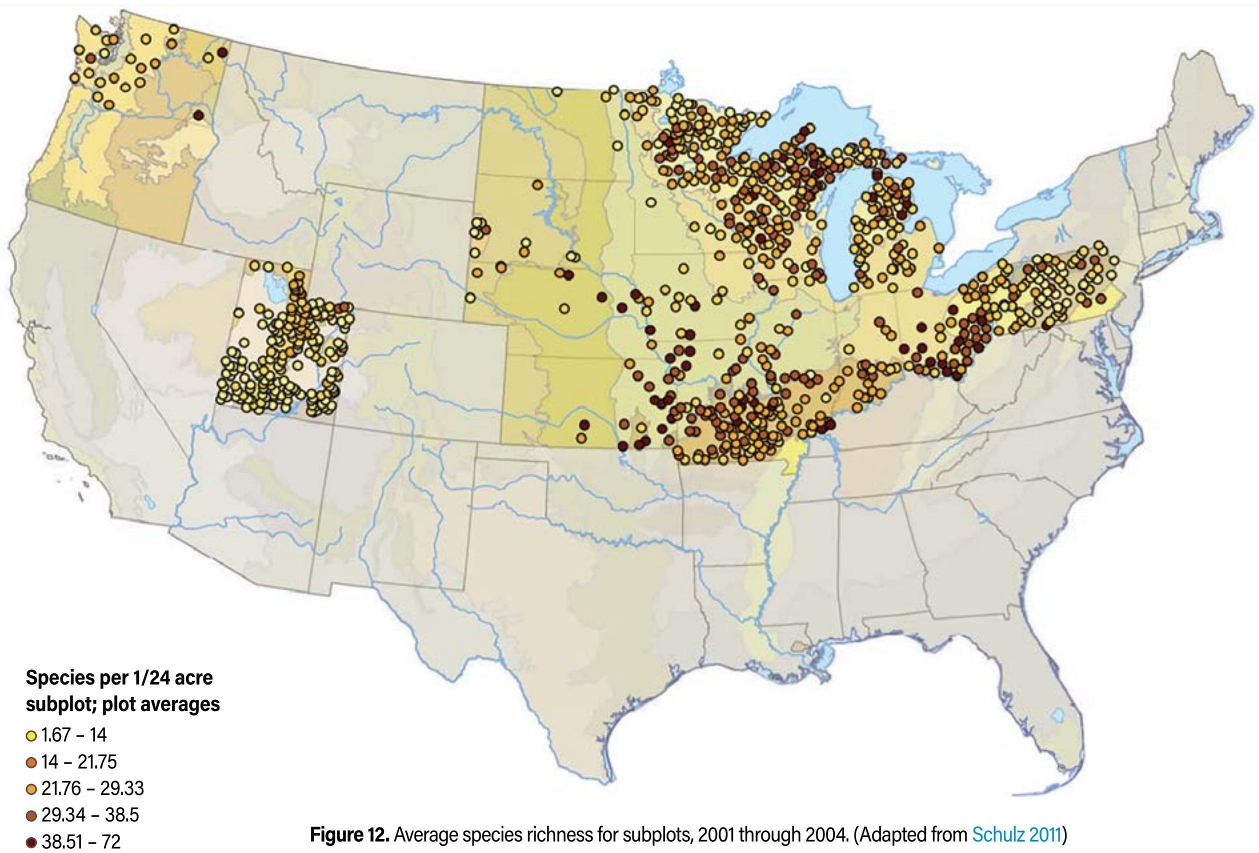

Figure 12. Average species richness for subplots, 2001 through 2004. (Adapted from Schulz 2011)

Figure 13. An FIA field crew member navigates the dense understory on Kuiu Island in southeast Alaska. Devil's club (*Oplopanax horridus*) is the dominant vegetation in the foreground. (Photo by Gerard Dean, USDA Forest Service)

PRODUCTS AND PUBLICATIONS

Vegetation structure and composition data quantify key components in forests and can be used to assess vegetation diversity in terms of native and nonnative species richness and distribution, physical arrangement of growth habit canopy cover, and dominant species by forest type. To date, products include:

- Describing how to collect and analyze vegetation indicator data (Schulz et al. 2009, Schulz 2016)
- Describing vegetation diversity (Schulz 2011)
- Quantifying distribution of introduced species (Schulz and Gray 2013)
- Quantifying biomass contributions of understory species (Russell et al. 2014)
- Assessing impacts of air pollutants on forest understory diversity (Simkin et al. 2016, Clark et al. 2019)
- Resource reports (Barrett and Christensen 2011, Pattison et al. 2018)

RESEARCH AND DEVELOPMENT

Vegetation often reflects impacts of biotic and abiotic disturbances, habitat characteristics for many wildlife species, fuel loading and fire risk, and carbon cycling patterns. The more detailed Vegetation Indicator data are still in demand for research into patterns of species richness and species distribution (Simkin et al. 2016, Clark et al. 2019). The current Vegetation Profile is a slight modification of what western regions have collected in the past: most abundant species and cover by growth habit on all plots. As new plot data are acquired with remeasurement, assessments of changes in species dominance and growth habit structure will be possible. These data are also being incorporated with other FIA data into revisions of national programs including LANDFIRE's modeling efforts and the National Vegetation Classification. Research to improve estimations of biomass contributions of non-tally tree growth forms is ongoing.

Additionally, options for collecting more detailed species information with the Vegetation Profile (e.g., full species census on one subplot) have been tested and used in Alaska (Pattison et al. 2018). This option allows for assessments of species richness.

SOIL QUALITY

Charles H. Perry ▪ Research Soil Scientist ▪ Northern Research Station

BACKGROUND

Soils are the foundation of the forest ecosystem, and they are nonrenewable over the course of management timescales. The Soil Quality indicator seeks to document changes in relevant physical and chemical characteristics of forest soils. Physical characteristics impact the growth and distribution of trees by influencing the ability of roots to access nutrients and water. Important characteristics monitored by FIA include bulk density, soil texture, forest floor thickness, depth to any restrictive horizons, and compaction. The forest floor and the top 8 inches of soil are sampled in the field for laboratory analyses because soil nutrients reflect the relative fertility of the soil as well as the legacy of some human impacts (e.g., acid deposition). The Soil Quality indicator assesses soil pH; carbon, nitrogen and phosphorus content; and extractable levels of major cations (sodium, potassium, calcium, magnesium, and aluminum) and sulfur along with several micronutrients. Soils evolve rather slowly, so this indicator features "on" and "off" measurement cycles to maximize the opportunity to detect change within a constrained budget.

PRODUCTS AND PUBLICATIONS

The soil's physical and chemical properties may be influenced by natural and anthropogenic processes as well as management actions, so

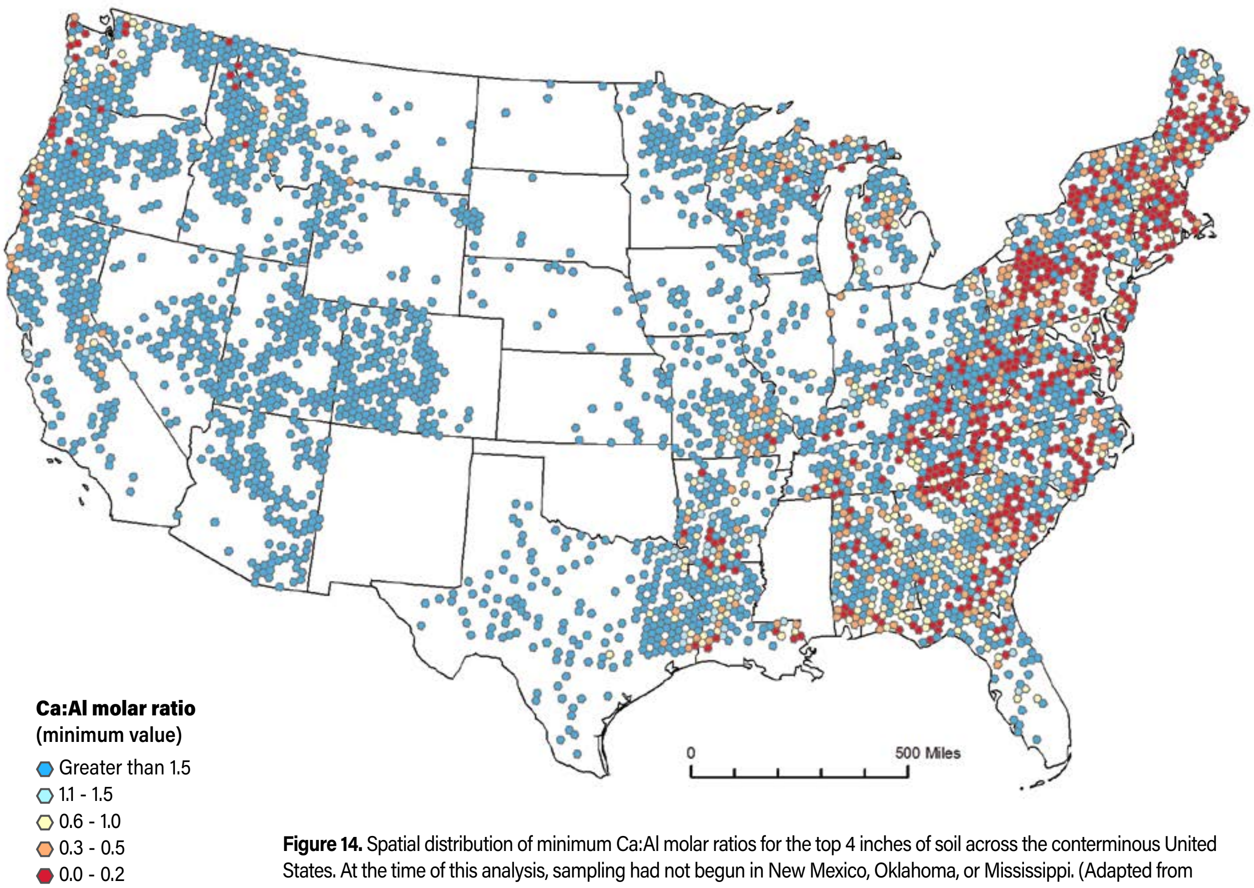

Figure 14. Spatial distribution of minimum Ca:Al molar ratios for the top 4 inches of soil across the conterminous United States. At the time of this analysis, sampling had not begun in New Mexico, Oklahoma, or Mississippi. (Adapted from Perry and Amacher 2012)

Figure 15. Soil core from a Forest Inventory and Analysis Program plot. (Photo by Charles H. Perry, USDA Forest Service)

continued monitoring is vital to understanding forest health and productivity. The first round of remeasurement is currently underway, so this update reflects products and publications based on one round of sampling. Change detection will be an important feature of the indicator in the near future.

The FIA program has published many analyses documenting soil conditions at the State level. These studies document how different forests occupy different niches in the landscape. We also have published regional- and national-scale analyses, including several focused on the legacy of acid deposition. Simply put, acid deposition leaches mobile cations from the soil, shifting the balance from calcium to aluminum. This negatively impacts tree health because trees use calcium (but not aluminum) in root and leaf development as well as in the construction of cell walls.

RESEARCH AND DEVELOPMENT

Soils are but one part of an increasingly complete database of physical and biological components, and current research focuses on converting plot-level information into continuous map services that are easier to distribute and more accessible for analysis by partners. Given the importance of carbon, much of the current work concentrates on soil carbon stocks. The resulting maps reflect our understanding of soil-forming processes, using predictors such as air temperature and precipitation, the ratio of precipitation to potential evapotranspiration, elevation, forest-type group, and surface geology. These novel products are finding application in the National Greenhouse Gas Inventory and will serve as the foundation of future guidance on best practices for inventory compilation. You can access this geospatial data through agency and open data portals.

INVASIVE PLANT SPECIES

Cassandra M. Kurtz ▪ Forester ▪ Northern Research Station and
Sonja N. Oswalt ▪ Forest Resource Analyst ▪ Southern Research Station

BACKGROUND

The Invasive Plant Species (IPS) indicator assesses the percentage of cover and presence of select IPS on a subset of FIA plots. The plants monitored vary by region and are determined based on their identification as IPS of regional concern on forested landscapes. The data collected provide information about IPS presence and spread as well as changing growing conditions. IPS can affect ecosystem health by displacing native plants and altering wildfire risk, nutrient availability, and habitat suitability. IPS data help land managers and policymakers track the spread, abundance, and risk of these species in forests.

PRODUCTS AND PUBLICATIONS

The IPS indicator has been used in various site-level analyses as well as for early detection. In most areas of the country, only a subset of forested plots is sampled for IPS, so coarse sampling may lead to high standard errors—a factor to keep in mind when assessing results. Combining IPS data with other plot data allow for the study of their relationships with trees, saplings, regeneration, and other site characteristics. Annual and cyclical State reports often include the results of IPS sampling.

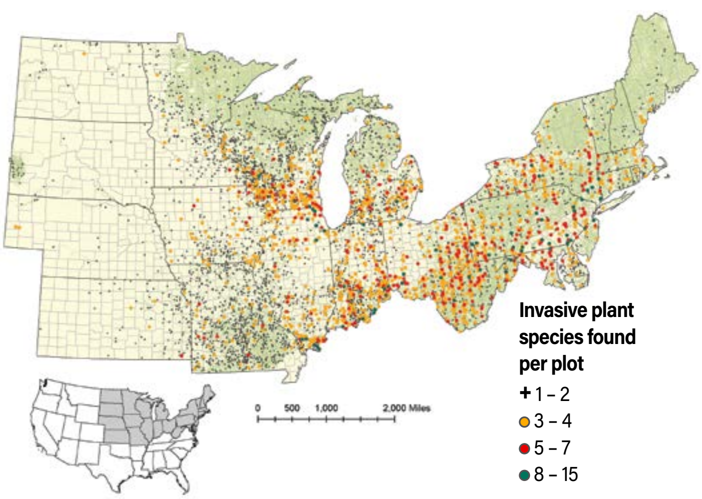

Figure 16. Number of invasive plant species (IPS) observed per plot on Forest Inventory and Analysis IPS plots (2005–2010). Depicted plot locations are approximate (Kurtz 2013).

Figure 17. Showy foliage and flowers of the invasive plant saltcedar, which is native to Eurasia. Within the United States, this tree is most commonly observed in the West, an arid region where it has heavily impacted water supply and displaced many species (Kurtz 2013). (Photo by Cassandra M. Kurtz, USDA Forest Service)

Additional regional, national, and scientific articles containing IPS results are available in print and online. Some examples of published studies that utilize the IPS indicator include:

- National and regional patterns of forest plant invasions (Oswalt et al. 2015, Oswalt and Oswalt 2011, Kurtz 2013)
- Quantification of factors related to the spread and distribution of invasive plant species (Riitters et al. 2017, Guo et al. 2017, Jo et al. 2017)

RESEARCH AND DEVELOPMENT

IPS data are currently available for all 50 States. This relatively new availability has allowed for broad-scale IPS analyses. However, the inherent and necessary variability of the species monitored and other regional differences make comparisons of species at national scales challenging. Nevertheless, studies exploring the change in presence and spread of IPS continue to grow, informing our understanding of climatic influences, urban interfaces, long-term impacts, and more. Ways to further explore the IPS data include regional studies, online data dashboards, and interactive story maps.

REGENERATION AND BROWSE IMPACT

William H. McWilliams ▪ Research Forester ▪ Northern Research Station

BACKGROUND

The maturation of Midwest and Northeast U.S. forests has led to an imbalance in age class structure, as young forest habitat has become rare. Stressors like white-tailed deer, invasive plants, climate variability, other limiting factors and their impacts on young tree seedlings have made regeneration of forests difficult. Young forest characteristics set the trajectory for composition, structure, and function over the life of a forest. This means that values the public has come to expect from healthy young forest are largely missing, and novel approaches will be needed to restore healthy young forest under stress to replace older forests as stand-initiation events occur, e.g., mortality or harvest.

Increased concern about regeneration caused the Northern Research Station (NRS) FIA, in 2012, to implement a suite of Regeneration Indicator (RI) measurements on Phase 3 plots. The RI tracks all established seedlings down to 2-inches tall and plot-level browse impacts. The approach was adapted from protocols from a quarter-century study of regeneration in Pennsylvania (McWilliams et al. 2016). FIA currently samples this indicator only in the Northern United States, but the program is poised to implement the indicator nationally when and if funding becomes available.

PRODUCTS AND PUBLICATIONS

RI science products address a range of information gaps related to restoring sustainable forests across the Midwest and Northeast United States. Examples include:

Subcontinental-scale visualization of browse impacts (McWilliams et al. 2018).

- Technique for estimating regeneration security for NRS-FIA region (Vickers et al. 2018, in review).
- Regeneration Status chapters for NRS-FIA 5-year State reports (e.g., Albright et al. 2017).
- Assisting forest and deer agencies in balancing habitat in Pennsylvania (McWilliams et al. 2017).

RESEARCH AND DEVELOPMENT

The RI fills a critical information gap for policymakers and managers working to regenerate

Figure 18. White-tailed deer herd. (Photo from Adobe Stock Images)

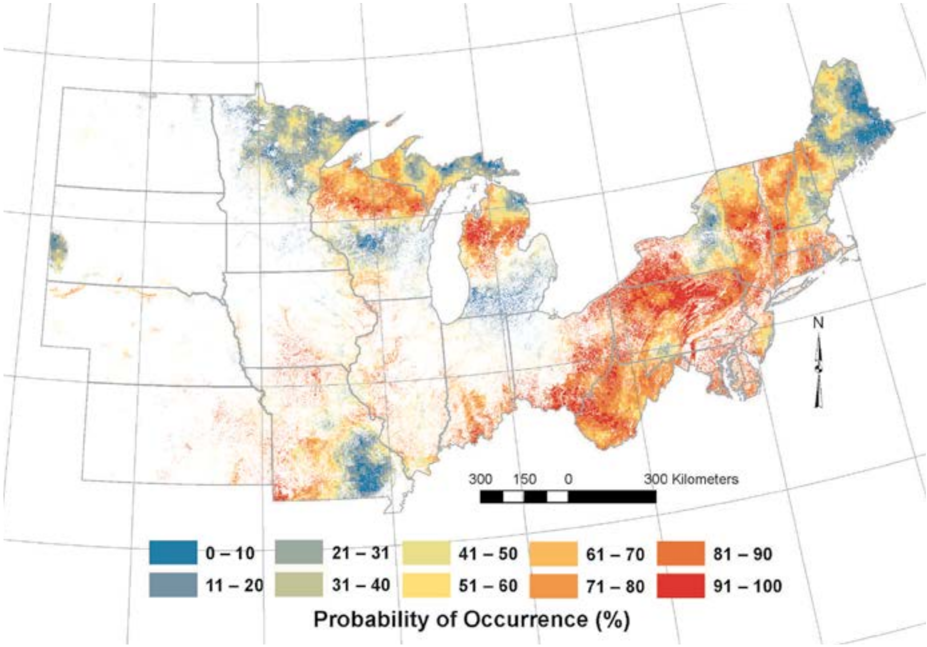

Figure 19. Probability of occurrence for moderate or high ungulate browse impacts on forest land, Midwest and Northeast United States, 2017. (Adapted from McWilliams et al. 2018)

desirable native species to sustain future forest values and provide healthy young forest habitat to support wildlife that depend on young forest. Research is needed to develop analytics that evaluate regeneration security and to identify problem areas where more intensive management may be required. These fundamental data provide a platform for conducting geospatial analyses using related geodatabases—e.g., fragmentation, population, or land use—to answer larger, more complex questions.

Natural research extensions are:

- Implementing a public estimation portal for core analytical products
- Building trend estimates and analyses as remeasured samples become available
- Comparing understory-overstory tree abundance/composition for taxonomic groups and ecoregions
- Developing advance regeneration security statistics.
- Capturing the value of geospatial analytics, visualization, and data.
- Broadening the scope of regeneration security estimation algorithms, e.g., coppice and plantation management.

FRAGMENTATION, URBANIZATION, AND LANDSCAPE CONTEXT

Rachel N. Riemann ▪ Research Forester/Geographer ▪ Northern Research Station

BACKGROUND

Forest fragmentation, urbanization, and habitat loss are associated with diminished regional biodiversity and are recognized as a major threat to animal populations worldwide, particularly for species that require interior forest conditions for all or part of their life cycle, and for those that are wide ranging, slow moving, and/or slow reproducing. Changes in the size of remaining forest patches, in their level of connectivity to other large patches, in the amount of general forest cover surrounding each patch, and in the amount of forest-nonforest edge directly affect the amount and quality of interior forest conditions. The same factors also affect forest ecosystem function and resilience, its ability to protect the quality and quantity of surface and ground water resources, its ability to supply forest products, and the ease with which nonnative, invasive, or generalist species can gain a foothold and spread throughout the landscape.

Indicators of forest fragmentation, landscape context, and urbanization describe the spatial distribution of forest land, the spatial context in which the forest land occurs, and the proximity of forest land to human populations and urban development. FIA/FHM use remotely sensed landscape data to develop forest fragmentation indicators that describe the spatial distribution of forest land itself—including spatial integrity index (forest patch size, degree of forest connectivity, local forest density), amount of interior or core forest, and the amount and type of forest edge. Landscape context indicators, such as landscape pattern type, describe the local land cover around forest land and the proportion that is natural, agricultural, or associated with urban development. Urbanization indicators describe the forest's proximity to different types of urban development, such as roads or local densities of houses or human populations.

PRODUCTS AND PUBLICATIONS

The suite of landscape pattern metrics quantifies aspects of fragmentation and urbanization known to have an effect on forest ecosystems, their management, or on their ability to provide ecosystem services.

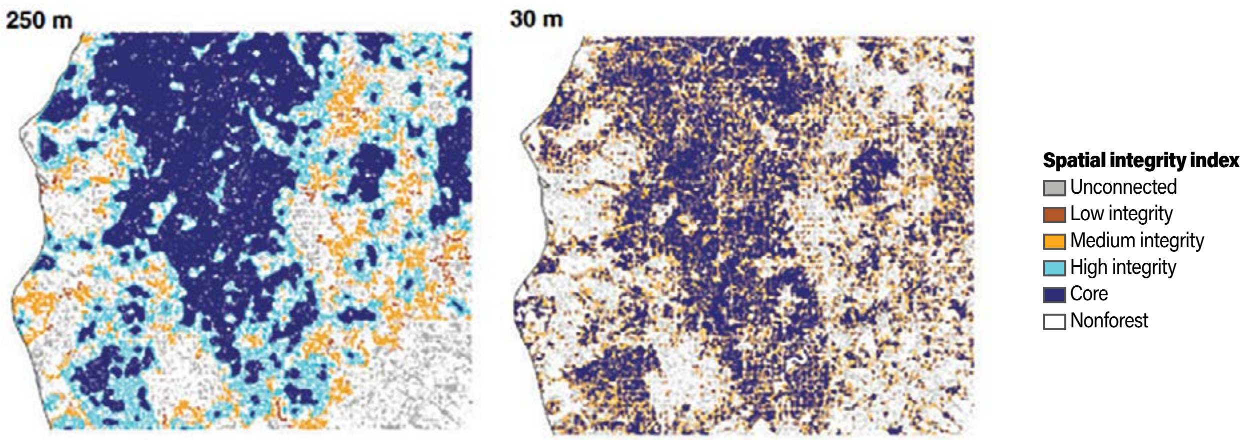

Figure 20. Spatial integrity index of forest land at the 250- and 30-meter scale in a region north of Grand Rapids, MI. (Adapted from Pugh et al. 2017)

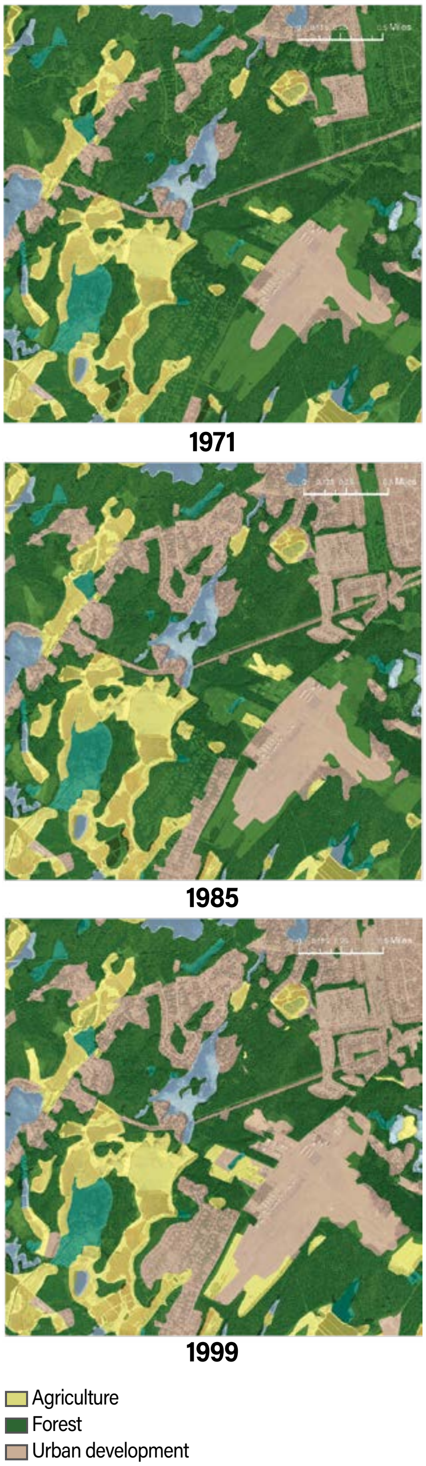

Figure 21. Forest becoming increasingly fragmented and urbanized over time in southeastern Massachusetts. (Created from the MassGIS land cover dataset - https://docs.digital.mass.gov/dataset/massgis-data-land-use-1951-1999)

Some examples of published studies that utilize these indicators include:

- FIA State 5-year reports (e.g., recent reports—Pugh et al. 2017, Crocker et al. 2017, Albright et al. 2017)
- Vermont's forest fragmentation report to its State legislature (Vermont Department of Forests, Parks and Recreation 2015)
- Effects of forest fragmentation and urbanization on stream conditions (Riemann et al. 2004, Riva-Murray et al. 2010)
- Trends of forest interior conditions in the United States (Riitters and Wickham 2012) and distance from forest to roads (Riitters and Wickham 2003)

Some examples of datasets that we plan to make publicly available:

- Fragmentation metrics such as forest density, forest connectivity, and forest patch size
- Forest by Wildland Urban Interface (WUI) house density class
- Road density
- Forest edges
- Forest density
- Neighborhood density of each nonforest land cover type

RESEARCH AND DEVELOPMENT

All of the above landscape pattern metrics will continue to be updated as new landscape data sets and census data become available, and data sets will be archived and made available to the public. Work will continue with partners and user communities to further fine-tune the data offered and increase integration with issues, questions, and applications. Effort will be focused on data delivery, developing data tools to ensure that the data will be easily updated over time, and integrating the data sets into online tools for analysis, reporting, and storytelling.

SUMMARY

FIA began implementing a nationwide, field-based forest ecosystem health indicator monitoring effort in the 1990s, and it currently collects forest health measures in 47 States. The suite of FIA forest health indicators delivers critical information about complex forest ecosystem processes across the United States. The program continues to deliver reports and analyses that contribute to critical national and global assessments, but, increasingly, a new and diverse set of customers are demanding access to the data for their own analyses and integration of tools and systems to improve forest health science and develop new indicators of forest ecosystem health.

After nearly 2 decades of collecting, analyzing, and reporting on forest health, FIA has updated its sampling techniques with flexible spatial and temporal intensities for these indicators, in response to fluctuating budgets. This also allows the program to improve field operation efficiency, address emerging user demands, and adjust to evolving forest health science.

The enhanced Phase 2 sampling scheme can change in response to budgetary fluctuations (i.e., flexibility) without compromising long-term analytical capabilities. Although the enhanced indicator protocols collect less detailed information on each sampled plot, substantially more plots are sampled, increasing the statistical power of future forest health analyses and improving the reliability of estimates in important national assessments. For example, since 2012, the number of samples in the DWM indicator has increased to a nearly 7-times sample, while crown condition and vegetation diversity has increased to approximately a 4-times sample. These changes represent a continuation of efforts to address current budget realities and adapt for the future while continuing to meet customer and partner needs.

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REFERENCES

Albright, T.A.; Butler, B.J.; Crocker, S.J.; Kurtz, C.M.; Lister, T.W.; McWilliams, W.H.; Miles, P.D.; Morin, R.S.; Nelson, M.D.; Riemann, R.; Smith, J.E.; Woodall, C.W. 2018. Ohio Forests 2016. Resour. Bull. NRS-118. Newtown Square, PA: U.S. Department of Agriculture, Forest Service, Northern Research Station. 114 p.

Albright, T.A.; McWilliams, W.H.; Widmann, R.H.; Butler, B.J.; Crocker, S.J.; Kurtz, C.M.; Lehman, S.; Lister, T.W.; Miles, P.D.; Morin, R.S.; Riemann, R.; Smith, J.E. 2017. Pennsylvania forests 2014. Resour. Bull. NRS-111. Newtown Square, PA: U.S. Department of Agriculture, Forest Service, Northern Research Station. 140 p.

Ambrose, M.J. 2018. Tree mortality. In: Potter, Kevin M.; Conkling, Barbara L., eds. 2018. Forest health monitoring: national status, trends, and analysis 2017. Gen. Tech. Rep. SRS-233. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southern Research Station. Pages: 85-98. Chapter 5.

Barrett, T.M.; Christensen, G.A., tech. eds. 2011. Forests of southeast and south-central Alaska, 2004–2008: five-year forest inventory and analysis report. Gen. Tech. Rep. PNW-GTR-835. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 156 p.

Campbell, S.; Waddell, K.; Gray, A. 2010. Washington's forest resources, 2002–2006: five-year Forest Inventory and Analysis report. Gen. Tech. Rep. PNW-GTR-800. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 189 p.

Clark, C.M., Allen, E.B.; Bowman, W.D.; Benlap, J.; Brooks, M.L; Collins, S.L.; Geiser, L.H.; Gilliam, F.S.; Jovan, S.E.; Pardo, L.H.; Schulz, B.K.; Simkin, S.M; Stevens, C.J.; Suding, K.N.; Throop, H.L.; Waller, D.M. 2019. Potential vulnerability of 348 herbaceous species to atmospheric deposition of nitrogen and sulfur in the U.S. Nature Plants. 5(7): 697-705.

Crocker, S.J.; Butler, B.J.; Kurtz, C.M.; McWilliams, W.H.; Miles, P.D.; Morin, R.S.; Nelson, M.D.; Riemann, R.I.; Smith, J.E.; Westfall, J.A.; Woodall, C.W. 2017. Illinois forests 2015. Resour. Bull. NRS-113. Newtown Square, PA: U.S. Department of Agriculture, Forest Service, Northern Research Station. 82 p.

Crosby, M.K.; Fan, Z.; Spetich, M.A.; Leininger, T.D. 2012. Remote sensing of forest health indicators for assessing change in forest health. In: Merry, K.; Bettinger, P.; Lowe, T.; Nibbelink, N.; Siry, J., eds. Proceedings of the 8th southern forestry and natural resources GIS conference. Athens, GA. Warnell School of Forestry and Natural Resources, University of Georgia.

Domke, G.M.; Woodall, C.W.; Walters, B.F.; Smith, J.E. 2013. From models to measurements: comparing downed dead wood carbon stock estimates in the U.S. forest inventory. PLoS ONE. 8(3): e59949.

Domke, G.M.; Perry, C.H.; Walters, B.F.; Nave, L.E.; Woodall, C.W.; Swanston, C.W. 2017. Toward inventory-based estimates of soil organic carbon in forests of the United States. Ecological Applications. 27(4): 1223-1235.

Fajvan, M.A.; Bohall Wood, P. 2010. Maintenance of Eastern hemlock forests: factors associated with hemlock vulnerability to hemlock woolly adelgid. In: Rentch, James S.; Schuler, Thomas M., eds. 2010. Proceedings from the conference on the ecology and management of high-elevation forests in the central and southern Appalachian Mountains. Gen. Tech. Rep. NRS-P-64. Newtown Square, PA: U.S. Department of Agriculture, Forest Service, Northern Research Station: 31-38.

Fei, S.; Morin, R.S.; Oswalt, C.M.; Liebhold, A.M. 2019. Biomass losses resulting from insect and disease invasions in U.S. forests. Proceedings of the National Academy of Sciences: 201820601. 6 p.

Fenn, M.E.; Jovan, S.; Yuan, F.; Geiser, L.; Meixner, T.; Gimeno, B.S. 2008. Empirical and simulated critical loads for nitrogen deposition in California mixed conifer forests. Environmental Pollution. 155: 492-511.

Fenn, M.E.; Allen, E.B.; Weiss, S.B.; Jovan, S.; Geiser, L.H.; Tonnesen, G.S.; Johnson, R.F.; Rao, L.E.; Gimeno, B.S.; Yuan, F.; Meixner, T.; Bytnerowicz, A. 2010. Nitrogen critical loads and management alternatives for N-impacted ecosystems in California. Journal of Environmental Management. 91: 2404-2423.

Garbarino, M.; Marzano, R.; Shaw, J. D.; Long, J. N. 2015. Environmental drivers of deadwood dynamics in woodlands and forests. Ecosphere. 6(3): Article 30.

Guo, Q.; Iannone III, B.V.; Nunez-Mir, G.C.; Potter, K.M.; Oswalt, C.M.; Fei, S. 2017. Species pool, human population, and global versus regional invasion patterns. Landscape Ecology. 32(2): 229-238.

Harmon, M.E.; Fasth, B.; Woodall, C.W.; Sexton, J. 2013. Carbon concentration of standing and downed woody detritus: effects of tree taxa, decay class, position, and tissue type. Forest Ecology and Management. 291: 259-267.

Jo, I.; Potter, K.M.; Domke, G.M.; Fei, S. 2018. Dominant forest tree mycorrhizal type mediates understory plant invasions. Ecology Letters. 21: 217-224.

Jovan, S.; McCune, B. 2005. Air-quality bioindication in the greater central valley of California, with epiphytic macrolichen communities. Ecological Applications. 15(5): 1712-1726.

Kurtz, C.M. 2013. An assessment of invasive plant species monitored by the Northern Research Station Forest Inventory and Analysis Program, 2005 through 2010. Gen. Tech. Rep. NRS-109. Newtown Square, PA: U.S. Department of Agriculture, Forest Service, Northern Research Station. 70 p.

Lister, T.W.; Butler, B.J.; Crocker, S.J.; Kurtz, C.M.; Lister, A.J.; Luppold, W.G.; McWilliams, W.H.; Miles, P.D.; Morin, R.S.; Nelson, M.D.; Piva, R.J.; Riemann, R.I.; Smith, J.E.; Westfall, J.A.; Widmann, R.H.; Woodall, C.W. 2017. Delaware forests 2013. Resour. Bull. NRS-115. Newtown Square, PA: U.S. Department of Agriculture, Forest Service, Northern Research Station. 104 p.

Lockman, B.; Bush, R.; Barber, J. 2016. Assessing root disease presence, severity and hazard in northern Idaho and western Montana using Forest Inventory and Analysis (FIA) plots and the USFS Northern Region VMap Database. Report No. 16-07. Missoula, MT: U.S. Department of Agriculture, Forest Service, Northern Region, State and Private Forestry, Forest Health Protection. 26 p.

McWilliams, W.H.; Westfall, J.A.; Brose, P.H.; Lehman, S.L.; Morin, R.S.; Ristau, T.E.; Royo, A.A.; Stout, S.L. 2017. After 25 years, what does the Pennsylvania Regeneration Study tell us about oak/hickory forests under stress? In: Kabrick, J.M.; Dey, D.C.; Knapp, B.O.; Larsen, D.R.; Shifley, S.R.; Stelzer, H.E., eds. Proceedings of the 20th central hardwood forest conference. Gen. Tech. Rep. NRS-P-167. Newtown Square, PA: U.S. Department of Agriculture, Forest Service, Northern Research Station: 280-290.

McWilliams, W.H.; Westfall, J.A.; Brose, P.H.; Dey, D.C.; D'Amato, A.W.; Dickinson, Y.L.; Fajvan, M.Ann; Kenefic, L.S.; Kern, C.C.; Laustsen, K.M.; Lehman, S.L.; Morin, R.S.; Ristau, T.E.; Royo, A.A.; Stoltman, A.M.; Stout, S.L. 2018. Subcontinental-scale patterns of large-ungulate herbivory and synoptic review of restoration management implications for midwestern and northeastern forests. Gen. Tech. Rep. NRS-182. Newtown Square, PA: U.S. Department of Agriculture, Forest Service, Northern Research Station. 24 p.

Meneguzzo, D.M.; Haugen, D.E.; Walters, B.F.; Butler, B.J.; Crocker, S.J.; Kurtz, C.M.; Morin, R.S.; Nelson, M.D.; Piva, R.J.; Smith, J.E. 2018. Northern Great Plains forests 2015. Resour. Bull. NRS-116. Newtown Square, PA: U.S. Department of Agriculture, Forest Service, Northern Research Station. 108 p.

Morin, R.S.; Liebhold, A.M. 2015. Invasions by two non-native insects alter regional forest species composition and successional trajectories. Forest Ecology and Management. 341: 67-74.

Morin, R.S.; Randolph, K.C.; Steinman, J. 2015. Mortality rates associated with crown health for Eastern forest tree species. Environmental Monitoring and Assessment. 187(3): 87.

Morin, R.S.; Pugh, S.A.; Steinman, J. 2016. Mapping the occurrence of tree damage in the forests of the Northern United States. Gen. Tech. Rep. NRS-GTR-162. Newtown Square, PA: U.S. Department of Agriculture, Forest Service, Northern Research Station. 19 p.

Nelson, M.D.; Moser, W. K. 2007. Integrating remote sensing and forest inventory data for assessing forest blowdown in the boundary waters canoe area wilderness. In: Greer, J.D., ed. New remote sensing technologies for resource managers; proceedings of the eleventh Forest Service remote sensing applications conference. American Society for Photogrammetry and Remote Sensing. 8 p.

Oswalt, S.N.; Oswalt, C.M. 2011. The extent of selected nonnative invasive plants on southern forest lands. In: Fei, Songlin; Lhotka, John M.; Stringer, Jeffrey W.; Gottschalk, Kurt W.; Miller, Gary W., eds. Proceedings, 17th central hardwood forest conference. Gen. Tech. Rep. NRS-P-78. Newtown Square, PA: U.S. Department of Agriculture, Forest Service, Northern Research Station: 447-459.

Oswalt, C.M.; Fei, S.; Guo, Q.; Iannone III, B.V.; Oswalt, S.N.; Pijanowski, B.C.; Potter, K.M. 2015. A subcontinental view of forest plant invasions. NeoBiota. 24: 49-54.

Pardo, L.H.; Robin-Abbott, M.J.; Driscoll, C.T., eds. 2011. Assessment of nitrogen deposition effects and empirical critical loads of nitrogen for ecoregions of the United States. Gen. Tech. Rep. NRS-80. Newtown Square, PA: U.S. Department of Agriculture, Forest Service, Northern Research Station. 291 p.

Pattison, R.; Andersen, H.; Gray, A.; Schulz, B.; Smith, R.J.; Jovan, S., tech. coords. 2018. Forests of the Tanana Valley State Forest and Tetlin National Wildlife Refuge, Alaska: results of the 2014 pilot inventory. Gen. Tech. Rep. PNW-GTR-967. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 80 p.

Perry, C.H.; Amacher, M.C. 2012. Patterns of soil calcium and aluminum across the conterminous United States. In: Potter, K. M.; Conkling, B. L., eds. Forest Health Monitoring: 2008 National Technical Report. GTR-SRS-158. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southern Research Station: 119-130. Chapter 9.

Pugh, S.A.; Heym, D.C.; Butler, B.J.; Haugen, D.E.; Kurtz, C.M.; McWilliams, W.H.; Miles, P.D.; Morin, R.S.; Nelson, M.D.; Riemann, R.I.; Smith, J.E.; Westfall, J.A.; Woodall, C.W. 2017. Michigan forests 2014. Resour. Bull. NRS-110. Newtown Square, PA: U.S. Department of Agriculture, Forest Service, Northern Research Station. 154 p.

Randolph, K.C. 2015. Benefits and limitations of using standard Forest Inventory and Analysis data to describe the extent of a catastrophic weather event. e-Res. Pap. SRS-55. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southern Research Station. 10 p.

Randolph, K.C. 2018. Crown Condition. In: Potter, Kevin M.; Conkling, Barbara L., eds. 2018. Forest health monitoring: national status, trends, and analysis 2017. Gen. Tech. Rep. SRS-233. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southern Research Station. Chapter 7.

Riemann, R.; Murry-Riva, K.; Murdoch, P. 2004. Effects of forest fragmentation and urbanization on stream conditions—the development of relevant landscape parameters and source datasets for effective monitoring. In: Proceedings, Society of American Foresters 2003 national convention. Bethesda, MD: Society of American Foresters: 234-235.

Riitters, K.H.; Wickham, J.D. 2003. How far to the nearest road? Frontiers in Ecology and the Environment 2003. 1(3): 125–129.

Riitters, K.H.; Wickham, J.D. 2012. Decline of forest interior conditions in the conterminous United States. Scientific Reports. 2(653): 1-4.

Riitters, K.; Potter, K.; Iannone, B.V.; Oswalt, C.; Fei, S.; Guo, Q 2017. Landscape correlates of forest plant invasions: a high-resolution analysis across the Eastern United States. Diversity and Distributions. 24: 274-284.

Root, H.T.; McCune, B.; Jovan, S. 2014. Lichen communities and species indicate climate thresholds in southeast and south-central Alaska, USA. The Bryologist. 117(3): 241-252.

Russell, M.B.; Woodall, C.W.; Fraver, S.; D'Amato, A.W. 2013. Estimates of downed woody debris decay class transitions for forests across the Eastern United States. Ecological Modelling. 251: 22-31.

Russell, M.B.; D'Amato, A.W.; Schulz, B.K.; Woodall, C.W.; Domke, G.M.; Bradford, J.B. 2014. Quantifying understory vegetation in the U.S. Lake States: a proposed framework to inform regional forest carbon stocks. Forestry. 87: 629-638.

Russell, M.B.; Woodall, C.W.; Fraver, S.; D'Amato, A.W.; Domke, G.M.; Skog, K.E. 2014. Residence times and decay rates of downed woody debris biomass/carbon in Eastern U.S. forests. Ecosystems. 17(5): 765-777.

Schomaker, M.E.; Zarnoch, S.J.; Bechtold, W.A.; Latelle, D.J.; Burkman, W.G.; Cox, S.M. 2007. Crown-condition classification: a guide to data collection and analysis. Gen. Tech. Rep. SRS-102. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southern Research Station. 78 p.

Schulz, B.K.; Bechtold, W.A.; Zarnoch, S.J. 2009. Sampling and estimation procedures for the vegetation diversity and structure indicator. Gen. Tech. Rep. PNW-GTR-781. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 53 p.

Schulz, B. 2011. Vegetation diversity. In: Conkling, Barbara L., ed. 2011. Forest health monitoring: 2007 national technical report. Gen. Tech. Rep. SRS-147. Asheville, NC: U.S. Department of Agriculture Forest Service, Southern Research Station: 65-96.

Schulz, B.K.; Gray, A.N. 2013. The new flora of the northeastern USA: quantifying introduced plant species occupancy in forest ecosystems. Environmental Monitoring Assessment. 185: 3931-3957.

Schulz, B. 2017. Changes in vegetation indicator plots: small sample reveals significant trends. In: Potter, Kevin M.; Conkling, Barbara L., eds. 2017. Forest health monitoring: national status, trends, and analysis 2016. Gen. Tech. Rep. SRS-222. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southern Research Station. 195 p. Chapter 6.

Shaw, J.D.; Steed, B.E.; DeBlander, L.T. 2005. Forest Inventory and Analysis (FIA) annual inventory answers the question: What is happening to pinyon-juniper woodlands? Journal of Forestry. 103(6): 280-285.

Shaw, J.D.; Goeking, S.A.; Menlove, J.; Werstak, C.E., Jr. 2017. Assessment of fire effects based on Forest Inventory and Analysis data and a long-term fire mapping data set. Journal of Forestry. 115(4): 258-269.

Simkin, S.M; Allen, E.B.; Bowman, W.D.; Clark, C.M.; Benlap, J.; Brooks, M.L; Cade, B.S.; Collins, S.L.; Geiser, L.H.; Gilliam, F.S.; Jovan, S.E.; Pardo, L.H.; Schulz, B.K.; Stevens, C.J.; Suding, K.N.; Throop, H.L.; Waller, D.M. 2016. Conditional vulnerability of plant diversity to atmospheric nitrogen deposition across the United States. Proceedings of the National Academy of Sciences. 113(15): 4086–4091.

Smith, G.C.; Smith, W.D.; Coulston, J.W. 2007. Ozone bioindicator sampling and estimation. Gen. Tech. Rep. NRS-20. Newtown Square, PA: U.S. Department of Agriculture, Forest Service, Northern Research Station. 34 p.

Smith, R.J.; Jovan, S.; McCune, B. 2015. Evaluating carbon stores at the earth-atmosphere interface: moss and lichen mats of subarctic Alaska. In: Stanton, Sharon M.; Christensen, Glenn A., comps. 2015. Pushing boundaries: new directions in inventory techniques and applications: Forest Inventory and Analysis (FIA) symposium 2015. Gen. Tech. Rep. PNW-GTR-931. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. p 55.

Smith, R.J.; Jovan, S.; McCune, B. 2017. Lichen communities as climate indicators in the U.S. Pacific States. Gen. Tech. Rep. PNW-GTR-952. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 44 p.

Thompson, M.T. 2017. Assessing the impact of a mountain pine beetle infestation on stand structure of lodgepole pine forests in Colorado using the Forest Inventory and Analysis annual forest inventory. Journal of Forestry. 115: 270-275.

Vermont Department of Forests, Parks, and Recreation. 2015 Vermont Forest Fragmentation Report. 54 p. https://fpr.vermont.gov/sites/fpr/files/About_the_Department/News/Library/FOREST%20FRAGMENTATION_FINAL_rev06-03-15.pdf

Whittier, T.R.; Gray, A.N. 2016. Tree mortality based fire severity classification for forest inventories: a Pacific Northwest national forests example. Forest Ecology and Management. 359: 199-209.

Will-Wolf, S.; Jovan, S.; Neitlich, P.; Peck, J.E.; Rosentreter, R. 2015. Lichen-based indices to quantify responses to climate and air pollution across northeastern U.S.A. The Bryologist. 118(1): 59-82.

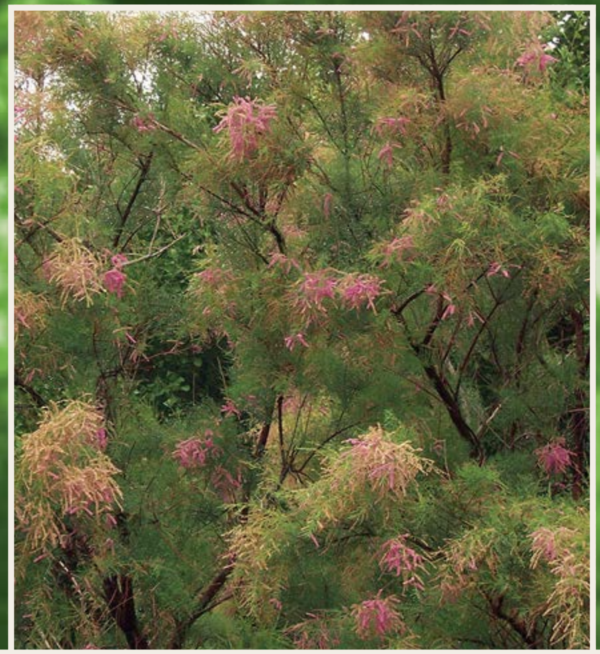
Woodall, C.W.; Nagel, L.M. 2007. Downed woody fuel loading dynamics of a large-scale blowdown in northern Minnesota, U.S.A. Forest Ecology and Management. 247: 194-199.

Woodall, C.W.; Heath, L.S.; Smith, J.E. 2008. National inventories of down and dead woody material forest carbon stocks in the United States: challenges and opportunities. Forest Ecology and Management. 256: 221-228.

Woodall, C.W.; Westfall, J.A. 2009. Relationships between the stocking levels of live trees and dead tree attributes in forests of the United States. Forest Ecology and Management. 258: 2602-2608.

Woodall, C.W.; Walters, B.F.; Oswalt, S.N.; Domke, G.M.; Toney, C.; Gray, A.N. 2013. Biomass and carbon attributes of downed woody materials in forests of the United States. Forest Ecology and Management. 305: 48-59.

Woodall, C.W.; Russell, M.B.; Walters, B.F.; D'Amato, A.W.; Fraver, S.; Domke, G.M. 2015. Net carbon flux of dead wood in forests of the Eastern U.S. Oecologia. 177: 861-874.



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Cover photo: View of massive redwood trees in Jedediah Smith Redwoods State Park, CA. (Photo by Nate Hovee)