Forest Health Monitoring 2003 National Technical Report

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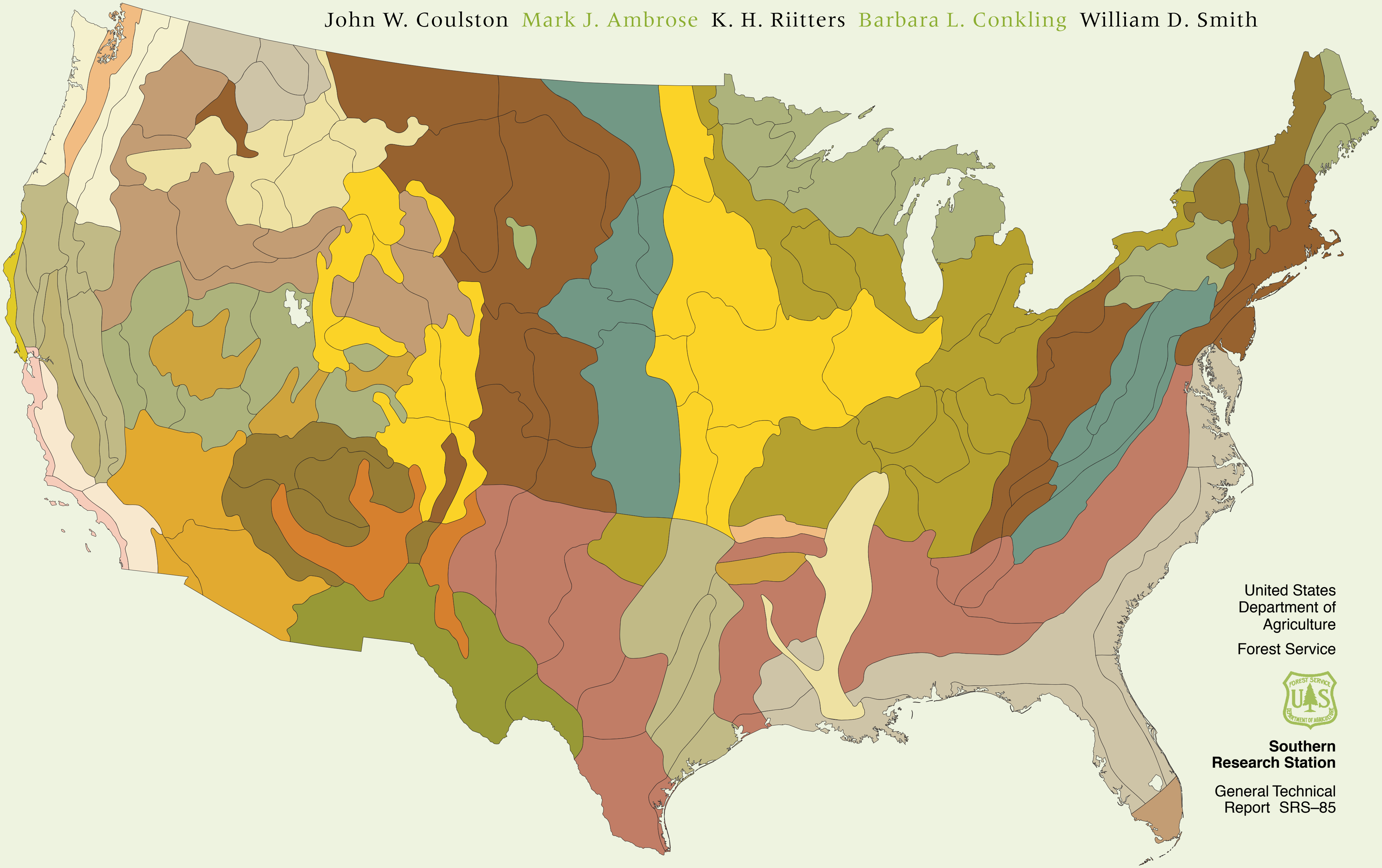

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Front cover map: Bailey's ecoregion provinces and ecoregion sections for the conterminous United States (Bailey 1995).

Back cover map: Forestland (green) backdrop derived from Advanced Very High Resolution Radiometer satellite imagery (Zhu and Evans 1994).

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Abstract

The Forest Health Monitoring Program's annual national reports present results from forest health data analyses focusing on a national perspective. The Criteria and Indicators for the Conservation and Sustainable Management of Temperate and Boreal Forests are used as a reporting framework. This report has five main sections. The first contains introductory material. The next three sections, "Landscape Structure," "Abiotic and Biotic Factors," and "Forest Conditions," contain results of data analyses. Some of the indicators discussed use data collected from ground plots. These include ozone bioindicator plants; changes in trees (crown condition, mortality, and stand age); and soils (forest floor depth). Other indicators or indicator groups use data about insects and diseases, and remotely sensed or ground-based data about distance to roads, forest edge, interior forest, drought, fire, and air pollution (sulfates, nitrates, and ozone). Identifying patterns and observing possible relationships is an important part of national level analysis and reporting. The fifth section "Integrated Look at Forest Health Indicators" presents results of analyses designed to evaluate whether or not individual indicators or linear combinations of indicators discriminate between crowns in poor condition and crowns not in poor condition.

Keywords: Assessment, bioindicators, criteria and indicators, fragmentation, monitoring, mortality.

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Executive Summary

This report is one of a series of Forest Health Monitoring (FHM) Program annual national technical reports. The annual reports are designed to present results from forest health data analyses from a national perspective. The reporting framework used is the Criteria and Indicators for the Conservation and Sustainable Management of Temperate and Boreal Forests (Anon. 1995a).

This report has five main sections: (1) introduction, (2 through 4) annual information about status and change for selected indicators, and (5) integrated analyses of indicators.

USDA Forest Service (Forest Service) data sources were: FHM ground plots (1990 through 1999), Forest Inventory and Analysis (FIA) annual surveys (2000 to 2001), Forest Health Protection (FHP) aerial surveys (1996 through 2001), and Fire Science Laboratory—fire current condition class. Other data sources are National Oceanic and Atmospheric Administration (NOAA)—Palmer Drought Severity Index (1895 through 2002); National Atmospheric Deposition Program (NADP) (1994 through 2001); and U.S. Geological Survey, Earth Resources Observations Systems (EROS) (circa 1992).

Landscape Structure

Distance to roads—The potential for road impacts on forests is significant because one-fifth of the total forestland area of the conterminous United States is within about 125 m of the nearest road, and the proportion increases rapidly with distance such that four-fifths of total forestland area is within 1 km of a road (Riitters and Wickham 2003). A comparison of road influence zones (defined as the area within 42 m, 127 m, and 1061 m of the nearest road) among ecoregions is presented. The highest values were found for ecoregions dominated by extensive urban areas, such as the Boston-Washington and Los Angeles-San Diego metroplex regions. With some exceptions, values in the East were higher than in the West, reflecting the higher overall road density in the East.

Forest edge—Our objective was to characterize ecoregion sections in terms of the lengths of different types of forest edges that they contain. Nationwide, there were about 31.4 million km of forest-nonforest edge, about equally split between forest-anthropogenic edge (forest edge with urban or agricultural landcover types) and forest-seminatural edge (forest edge with water, wetland, barren, grassland, or shrubland). Generally, the largest amount of forest-nonforest edge is contained in eastern ecoregion sections, and in western ecoregion sections that are mostly forested. Most anthropogenic edge is located in the East. Many western ecoregion sections with high human populations, such as the Los Angeles Basin, Denver, and Salt Lake City, did not have large amounts of anthropogenic edge.

Interior forest—Interior forest was measured at two scales by considering a forested location to be interior if a surrounding square window was at least 90 percent forested; window sizes of 7.29 and 5314.41 ha defined the two measurement scales. Values were expressed as the percentage of all forest that is interior within an analysis unit, helping to account for different amounts of forest among analysis units [analysis units were defined by a grid of 5625-ha (7.5 km by 7.5 km) squares]. Ecoregion sections with a relatively high percentage of interior forest at the 7.29-ha scale also had a relatively high percentage at the 5314.41-ha scale. However, while about half of the forest was considered interior at the 7.29-ha scale, much less forest meets that criterion at the larger scale.

One way to interpret the importance of the results is in terms of habitat for obligate interior forest species. For example, ecoregion sections with a high percentage of interior forest at the smaller scale (7.29 ha) might be expected to contain significant amounts of habitat capable of supporting species with relatively small home range sizes. Some examples of ecoregion sections with 80 to 100 percent interior forest are found in Province M212—Adirondack—New England Mixed Forest—Coniferous Forest—Alpine Meadow in the Northeastern and Northcentral United States; Province 212—Lauretian Mixed Forest; Section M221C—Northern Cumberland Mountains in the Northeast; Section 221H—Northern Cumberland Plateau in Kentucky, Tennessee, and northern Alabama; Section 231G—Arkansas Valley in Arkansas and eastern Oklahoma; Section 212L—Northern Superior Uplands in northeastern Minnesota; and Section M242A—Oregon and Washington Coast Ranges.

Ecoregion sections with a relatively high percentage of interior forest at the larger scale might be expected to contain more habitat for species with relatively large home range scales. For example, sections with 80 to 90 percent interior forest were Sections M212D—Adirondack Highlands and M221C—Northern Cumberland Mountains.

Abiotic and Biotic Factors

Drought—Deviation from historic drought occurrence (drought deviation) represents the deviation of drought occurrence in the current 20-year period from historic averages. Several ecoregion sections in the Eastern United States had a drought deviation of > 12 months (12 months of drought over a 20-year period in addition to that expected based on the historical average): M221D—Blue Ridge Mountains, 232A—Middle Atlantic Coastal Plain, 232G—Florida Coastal Lowlands (Eastern), 221C—Upper Atlantic Coastal Plain, and 212A—Aroostook Hills and Lowlands in northern Maine. Section M221D—Blue Ridge Mountains was the most droughty with a drought deviation of 33 months. Many areas in the Northeastern, Southern, and Northcentral United States experienced less drought than expected.

The most droughty areas in the West included parts of Province M261—Sierran Steppe—Mixed Forest—Coniferous Forest—Alpine Meadow in California and Province M262—California Coastal Range Open Woodland—Shrub—Coniferous Forest—Meadow; Section 263A—Northern California Coast; parts of Province M331—Southern Rocky Mountains Steppe—Open Woodland—Coniferous Forest—Alpine Meadow and Province M332—Middle Rocky Mountains Steppe—Coniferous Forest—Alpine Meadow; and Section M242C—Eastern Cascades. The most droughty ecoregion section was Section M262B—Southern California Mountains and Valleys with a drought deviation of 60 months.

In 2002, much of the Western United States experienced 9 to 12 months of drought. The fewest months of drought were experienced west of the Cascade Mountains in Washington and Oregon. Several ecoregion sections in the East experienced 6 to 9 months of drought: M221D—Blue Ridge Mountains, 231A—Southern Appalachian Piedmont, 232A—Middle Atlantic Coastal Plain, 232C—Atlantic Coastal Flatlands, and 221C—Upper Atlantic Coastal Plain. Three to six months of drought occurred all along the Eastern United States.

Fire—Areal extent of wildfire from 1938 through 2002 is presented in the full report. A marked reduction in areal extent occurred between 1938 and 1957, with a relative leveling off from 1957 to the present. The three most recent years of data show some fluctuation: 2000 (approximately 34 100 km^2), 2001 (approximately 14 400 km^2), and 2002 (approximately 28 100 km^2).

Using current condition class data for the conterminous United States, 38.7 percent of forested land was classified as condition class 1 (minor deviation from conditions compatible with historic fire regimes), 37.5 percent was classified as condition class 2 (moderate deviation), and 23.8 percent was classified as condition class 3 (major deviation). Several areas classified as having forest in condition class 3 were Section 212M—Northern Minnesota and Ontario in northern Minnesota (approximately 80 percent of the forested area); Section 212G—Northern Unglaciated Allegheny Plateau in Pennsylvania and New York (approximately 75 percent); Section 212F—Northern Glaciated Allegheny Plateau in New York and Pennsylvania (70 percent); Section 212K—Western Superior in Minnesota and Wisconsin (65 percent); and in the West, Sections M334A—Black Hills in South Dakota, M333D—Bitterroot Mountains in Idaho and Montana; and 331J—Northern Rio Grande Basin in New Mexico and Colorado (all 50 percent or more).

Air pollution—The spatial trends in average annual wet sulfate and inorganic nitrogen deposition from 1994 through 2001 were similar. Nine ecoregion sections, all in the Eastern United States, had average annual wet sulfate deposition exceeding the 95th percentile—four sections in Province 221—Eastern Broadleaf Forest (Oceanic), which includes parts of Pennsylvania, Ohio, West Virginia, Virginia, Kentucky, North and South Carolina, and Georgia; Section M212E—Catskill Mountains; Section M221B—Allegheny Mountains; Section 212G—Northern Unglaciated Allegheny Plateau in Pennsylvania, and Section 222H—Central Till Plains, Beech-Maple in Indiana and Ohio. Nine ecoregion sections also exceeded the 95th percentile for average wet deposition of inorganic nitrogen—four sections in Province 222—Eastern Broadleaf Forest (Continental); Section 251D—Central Till Plains; Section 221F—Western Glaciated Allegheny Plateau in New York, Pennsylvania, and Ohio; Section 221E—Southern Unglaciated Allegheny Plateau in Pennsylvania, Ohio, West Virginia, and Kentucky; Section 212G—Northern Unglaciated Allegheny Plateau in Pennsylvania and New York; and Section M212E—Catskill Mountains.

The ozone bioindicator used a biosite index based on the number of species evaluated, the number of plants of each species evaluated, the proportion of injured leaves on each plant, and the average severity of injury of each plant. Ozone-induced foliar injury to bioindicator plants occurred more frequently in the Eastern United States from 1997 through 2001. Section 222G—Central Till Plains, Oak-Hickory in southern Illinois and Indiana was in the highest risk category (ozone biosite index of 25 or greater). Sections 232A—Middle Atlantic Coastal Plain and 212G—Northern Unglaciated Allegheny Plateau, both classified in the moderate risk category (biosite index of 15.0 to 25.0) are in areas determined to have sensitive tree species and relatively high incidence of ozone-induced foliar injury to bioindicator plants. Section M262B—Southern California Mountains and Valleys and Section M261F—Sierra Nevada Foothills were classified in the low risk category (biosite index of 5.0 to 15.0), which indicates visible injury to highly sensitive species. However, most ecoregion sections in the Northcentral and Western United States had an average biosite index of < 5.0, indicating little or no injury recorded on bioindicator plants.

Insects and diseases—In the Northeast FHM region, the most intense mortality-causing activity was recorded in parts of Sections M221B—Allegheny Mountains and M221A—Northern Ridge and Valley in West Virginia. The most intense defoliation-causing agent activity was in Section M221A—Northern Ridge and Valley.

In the South FHM region, the relative exposure analysis highlights southern pine beetle activity because it is the predominant mortality-causing agent recorded. More than twice the expected exposure was observed in parts of Section 232B—Coastal Plains and Flatwoods, Lower; Section M221D—Blue Ridge Mountains; and large sections of Province 221—Eastern Broadleaf Forest (Oceanic) and Province 231—Southeastern Mixed Forest. The most intense defoliation-causing agent activity was in Section 232E—Louisiana Coast Prairies and Marshes and the southern extent of the Mississippi Alluvial Basin sections.

In the North Central FHM region, triple the expected exposure rates to mortality-causing agents were found in areas of Section M334A—

Black Hills and scattered areas of the Great Lakes States. Activity by defoliation-causing agents was widespread in the southern extent of Province 222—Eastern Broadleaf Forest (Continental) and portions of Sections 212L—Northern Superior Uplands and Section 212M—Northern Minnesota and Ontario.

In the Interior West FHM region, the most intense activity of mortality-causing agents was in Sections M333D—Bitterroot Mountains in Idaho and Montana, M331I—Northern Parks and Ranges in Colorado and Wyoming, and M331H—North-Central Highlands and Rocky Mountain in Colorado and Wyoming. The most intense activity of defoliation-causing agents was in Sections M331F—Southern Parks and Rocky Mountain Ranges and M331G—South-Central Highlands in Colorado and New Mexico.

In the West Coast FHM region, forested portions of Sections M333A—Okanogan Highlands in northern Washington and M242C—Eastern Cascades were exposed to more than triple the expected amounts of both mortality- and defoliation-causing insects and diseases.

Forest Condition

Crown condition—To evaluate each tree, a composite foliage index [the adjusted ZB-index (Ambrose 2004)] was calculated using foliar transparency and crown dieback. This index, in theory, represents the amount by which the foliage of the tree is reduced relative to an ideal, fully foliated tree having the same crown diameter, live crown ratio, and crown density. A tree crown was considered poor if its adjusted ZB-index was ≥ 0.25, or if the tree was a softwood and had dieback of ≥ 10 percent. The most recent data available for each State were used in the crown analyses. In most of the ecoregion sections for which status could be estimated, 10 percent or less of the basal area was associated with poor crowns. Areas with the highest percentage of basal area associated with poor crowns in the East were Sections 212A—Aroostook Hills and Lowlands and 212C—Fundy Coastal and Interior in eastern Maine. The areas with highest percentages in the West were Sections M331A—Yellowstone Highlands; M331B—Bighorn Mountains; M331J—Wind River Mountain; 342F—Central Basin and Hills; 342G—Green River Basin in Wyoming; and 313A—Grand Canyon in southwestern Colorado, southern Utah, and northern Arizona.

Annual change in percent of plot basal area represented by trees classified as having poor crowns was also estimated. In most areas, the percent of basal area with poor crowns was remaining constant or decreasing over the period for which data were available. The percentage of basal area with poor crowns increased at the fastest rate in Sections 221B—Hudson Valley, 222I—Erie and Ontario Lake Plain, and 342A—Bighorn Basin. Areas shown as having the highest rate of reduction in basal area associated with poor crowns were Section 212L—Northern Superior Uplands in northeastern Minnesota; Sections 251D—Central Till Plains and 222G—Central Till Plains, Oak-Hickory in Illinois and western Indiana; Section M332F—Challis Volcanics in Idaho; Section M341B—Tavaputs Plateau in Colorado and Utah; and Section 342B—Northwestern Basin and Range in southern Oregon and Idaho and northern Nevada. These results should be interpreted in the context of other available ecoregion section information such as tree mortality.

Tree mortality—Mortality was expressed using two analyses: (1) the ratio of annual mortality volume to gross volume growth (MRATIO), where a value > 1 indicates that mortality exceeds growth, and live standing volume is decreasing; and (2) the ratio of average dead tree diameter to average live tree diameter (DDLD). Using data through 2001, relatively high MRATIO values (> 0.6) were found in the following western ecoregion sections: M242C—Eastern Cascades in central Washington and Oregon, M333A—Okanogan Highlands in northern Idaho and eastern Washington, M332A—Idaho Batholith in central Idaho, M331A—Yellowstone Highlands, and M331J—Wind River Mountain in northwestern Wyoming. Many of the plots in these regions that experienced mortality also had high DDLD ratios, indicating that larger trees died on those plots. In the East, Section 231C—Southern Cumberland Plateau in northern Alabama and Georgia was the only section to have an MRATIO > 0.6.

Several ecoregion sections in the North Central region also showed high MRATIOs: Section 212L—Northern Superior Uplands in eastern Minnesota and Sections 222D—Interior Low Plateau, Shawnee Hills and 222H—Central Till Plains, Beech-Maple in Indiana and southern

Illinois. However, only data through 1999 from the North Central FIA region were available for this analysis, so these results are the same as those presented in the "Forest Health Monitoring 2002 National Technical Report" (Coulston and others 2005).

Stand age—A mean standardized stand age was calculated for each ecoregion section. For example, Section M242A—Oregon and Washington Coast Ranges had a mean standardized age of 0.23. This means that if all stands only grew to be 100 years old, the average age would be 23 years. Based on the mean standardized ages, many of the ecoregion sections in the Southeast and Pacific Northwest comprised relatively young forest stands. Relatively old stands were found in Sections M221A—Northern Ridge and Valley, 221C—Upper Atlantic Coastal Plain, 212G—Northern Unglaciated Allegheny Plateau, M212D—Adirondack Highlands, M212E—Catskill Mountains, M262A—Central California Coast Ranges, M332E—Beaverhead Mountains in southwestern Montana and northeastern Idaho, M261F—Sierra Nevada Foothills, and M331E—Uinta Mountains in eastern Utah and northwestern Colorado.

Soils—Soils occupy an integrating location between aboveground and belowground processes. Two measurements associated with the forest floor were presented: forest floor depth (thickness from the top of the litter layer to the boundary between the mineral soil and the forest floor) and litter depth (thickness from the top of the litter layer to the boundary where plant parts are no longer recognizable as such because of decomposition). Most plots across the United States had a forest floor depth of 1 to 5 cm. Relatively thick forest floors were measured in northern Maine, Vermont, Pennsylvania, along the Blue Ridge and Allegheny Mountains, and in the northern North Central region, and western Washington and Oregon. Forest floor thicknesses of < 1 cm were scattered in the North Central region and in western States such as Colorado, Utah, and Nevada. Because forest floor depth is influenced by factors such as the forest type under which it forms, and climate, thicknesses found in one part of the country may be normal for that forest type and climate, yet be quite different from normally expected depths in other regions.

Integrated Look at Forest Health Indicators

The objective of this section is to determine if there are any variables (indicators), or linear combination of indicators, that discriminate between plots that had trees with poor crown condition and those that did not have trees with poor crown condition. Analyses were stratified using four forest types or forest-type groups: eastern types, loblolly/shortleaf pine, western types, and Douglas-fir. Varying combinations of the following indicators were used: DDLD, forest floor depth, standardized age, ozone biosite index, total wet nitrogen deposition, percent core forest, percent forest within 127 m of a road, percent forest in current condition class 3, relative exposure to both mortality- and defoliation-causing insects and diseases, and drought deviation.

In eastern forest types, results indicated that plots with poor crown condition, as defined in this report, tended to occur in older stands, and in areas with fewer droughts and less nitrogen deposition. In the loblolly/shortleaf pine forest type, results indicated that plots with poor crown condition, as defined in this report, tended to occur in older stands, with a higher proportion of land within 127 m of a road, and to a lesser extent, in hexagons with a higher proportion of forest classified in fire condition class 3.

In western forest types, there was no statistical difference between plots with and without trees with poor crown condition, as defined in this report. However, further evaluation using the techniques presented in the report revealed that standardized age and relative exposure to mortality-causing insects and diseases contributed the most to statistically separating the two groups of crown condition plots. In the Douglas-fir forest type, results indicated that plots with poor crown condition, as defined in this report, tended to occur in older forest stands, with a higher proportion of forest classified in fire condition class 3.

Introduction

This annual technical report is a product of the Forest Service, Forest Health Monitoring (FHM) Program, and is designed to present results from forest health data analyses from a national perspective. The indicators described in the Criteria and Indicators for the Conservation and Sustainable Management of Temperate and Boreal Forests (Anon. 1995a) are used by FHM as a national reporting framework.

This report has five main sections. The first contains introductory material. The next three contain annual information about status and change for selected indicators. The fifth presents results of analyses designed to evaluate whether or not individual indicators or linear combinations of indicators discriminate between crowns in poor condition and crowns not in poor condition.

Eleven indicators or indicator groups are included in the middle three sections: (1) distance to roads; (2) forest edge; (3) interior forest; (4) drought; (5) fire; (6) air pollution (sulfates, nitrates, and ozone); (7) insects and diseases; (8) crown condition; (9) tree mortality; (10) stand age; and (11) soils (forest floor depth). These indicators were chosen not only because they are of interest as individual indicators of forest health, but because each may have some ecological relationship with one or more others, which will also be of interest. Identifying patterns and observing possible relationships are important to national level analysis and reporting. A challenge in national scale analysis and reporting is looking for evidence of such relationships using datasets that span a wide variety of forest ecosystem characteristics, climate conditions, elevations, and other factors. This report presents the results of analyses designed to begin evaluating nationally collected data for possible relationships at a national scale.

The Forest Health Monitoring Program

The Forest Service cooperates with State forestry and agricultural agencies to conduct FHM activities. Other Federal Agencies and universities also participate. The FHM Program has five major activities (Tkacz 2003):

- Detection monitoring— nationally standardized aerial and ground surveys to evaluate status and change in condition of forest ecosystems

- Evaluation monitoring—projects to determine extent, severity, and causes of undesirable changes in forest health identified through detection monitoring
- Intensive site monitoring—projects to enhance understanding of cause and effect relationships by linking detection monitoring to ecosystem process studies and assess specific issues, such as calcium depletion and carbon sequestration, at multiple spatial scales
- Research on monitoring techniques—projects to develop or improve indicators, monitoring systems, and analytical techniques, such as urban and riparian forest health monitoring, early detection of invasive species, multivariate analyses of forest health indicators, and spatial scan statistics
- Analysis and reporting—synthesis of information from various data sources within and external to the Forest Service to produce issue-driven reports on status and change in forest health at national, regional, and State levels

FHM's five regions, in cooperation with their respective States, produce "State Highlights" factsheets (available on the FHM Web site www.fhm.fs.fed.us) and other State reports (e.g., Campbell and others 2000, Dale and others 2000, Keyes and others 2003, Koch and others 2001, Morin and others 2001, Neitlich and others 2003, Rogers and others 2001).

In 1999, the ground plot activities of FHM's detection monitoring component were integrated with the Forest Service's Forest Inventory and Analysis (FIA) plot activities (e.g., Stolte and others 2002, U.S. Department of Agriculture Forest Service[1]). More information about the sampling design is presented in "Appendix A, Supplemental Methods, Analysis of FHM and FIA ground plot data."

[1] U.S. Department of Agriculture Forest Service. 2004. Forest inventory and analysis program history. FIA Factsheet Ser. www.fia.fs.fed.us/library/fact-sheets/overview/FIA_History_FS.pdf. [Date accessed: April 2005].

Monitoring Data and Making Cause and Effect Inferences (Conkling and others 2005)

The question of whether or not large-scale monitoring data are suitable for identifying cause and effect relationships has been asked by researchers many times. In a discussion paper, Schreuder and Thomas (1991) addressed this question using Forest Service FIA data as an example. They stated that although establishing correlation is easy, establishing cause and effect is difficult. To highlight this, Schreuder and Thomas (1991) presented three criteria from Mosteller and Tukey (1977) with the note that two of the three criteria need to be met to infer cause and effect relationships:

1. Consistency—implies the presence and magnitude of the effect (y) are always associated with a minimal level of the suspected causal agent (x)
2. Responsiveness—established by experimentally exposing the population under study to the suspected causal agent and by reproducing the symptoms
3. Mechanism—established by demonstrating a cause and effect linkage in a step-by-step approach

Monitoring data or observational data, such as FIA phase 2 (FIA annual inventory plots) and phase 3 (or FHM detection monitoring data), most clearly address the consistency criterion (Olsen and Schreuder 1997). Feinstein (1988) used examples from epidemiology in his discussion of a scientific approach to use observation data, e.g., monitoring data, to help determine cause and effect relationships. Olsen and Schreuder (1997) said that two kinds of field plots, in addition to monitoring plots, are important when testing and establishing cause and effect relationships. The number of one kind of plot should be fewer than the number of monitoring plots and be measured more frequently, with the option of destructive sampling. The other kind of supplemental plots should be at long-term ecological research sites from which data will be used to study responsiveness and mechanisms. These kinds of additional plots correspond well to FHM evaluation monitoring studies, FHM intensive site monitoring sites, and Long-Term Ecological Research sites. Using data from all these various sources presents a more complete approach to identifying cause and effect relationships than using monitoring or observational data alone; however, such an approach is best suited to an in-depth, interpretive report rather than an annual report such as this.

Two important decisions that must be made when analyzing monitoring data and presenting the results are choice of assessment unit, and applicability of the data to making cause and effect inferences. First, we use Bailey's ecoregion sections (Bailey 1995), which are based on climate, vegetation, and soil factors, as the primary assessment unit. Ideally, the spatial scale used for analysis is appropriate for both the scale of available data and the ecological component of interest. We recognize that any single spatial scale may not be the best for every indicator to be analyzed, but Bailey's ecoregion sections do provide a common framework for an ecologically based assessment. Second, cause and effect inferences are generally not made in the national technical reports because monitoring data are the primary level of data used. More specific details about this report are in the section entitled "Details About the Report."

Details About the Report

We used the Santiago Declaration and accompanying criteria and indicators (Anon. 1995a, 1995b) that were adopted by the Forest Service as a forest sustainability assessment framework (Smith and others 2001, U.S. Department of Agriculture Forest Service 2001). The seven criteria are:

Criterion 1—conservation of biological diversity
Criterion 2—maintenance of productive capacity of forest ecosystems
Criterion 3—maintenance of forest ecosystem health and vitality
Criterion 4—conservation and maintenance of soil and water resources
Criterion 5—maintenance of forest contribution to global carbon cycles
Criterion 6—maintenance and enhancement of long-term multiple socioeconomic benefits to meet the needs of societies
Criterion 7—legal, institutional, and economic framework for forest conservation and sustainable management

This report focuses on two parts of forest health assessment: (1) the status and change of forest health indicators, and (2) the integration of indicators that may begin to reveal biologically important relationships. Most indicators discussed are parts of "Criterion 1—Conservation of Biological Diversity," "Criterion 3—Maintenance of Forest Ecosystem Health and Vitality," and "Criterion

4—Conservation and Maintenance of Soil and Water Resources." In the section entitled "Integrated Look at Forest Health Indicators," individual metrics are combined to produce additional information. Appendix A provides useful details about analyses that are different from previous reports or useful to have readily available. Appendix B provides a supplemental data table.

Forest Service data sources are: FHM ground plot data (1990 through 1999), FIA annual survey data (2000 through 2001), Forest Health Protection (FHP) (1996 through 2001), and Fire Sciences Laboratory (fire current condition class[2]). Other data sources are the National Oceanic and Atmospheric Administration (NOAA)—Palmer Drought Severity Index (1895 through 2002) (National Climate Data Center 1994); National Atmospheric Deposition Program (NADP) (1994 through 2001)[3]; and U.S. Geological Survey, Earth Resources Observations Systems (EROS) data (circa 1992).[4]

Specific field data collection methods for FHM ground plots are described in the FHM field methods guides, e.g., the field methods guide for 1999[5]. Field data collection methods for FIA field plots are presented in volumes I and II of the FIA national core field guide. [6] [7] The most recent field guides are available on the national FIA Web site http://fia.fs.fed.us/library.htm#Manuals.

When appropriate and possible, Bailey's ecoregion sections (Bailey 1995) were used as the assessment unit for analysis. Bailey's system is a national hierarchical system of ecological units that classifies the United States into ecoregion domains, divisions, provinces, sections, subsections, landtype associations, and landtypes (McNab and Avers 1994). Ecoregion sections typically have similar geologic regions and lithology, regional climate, soils, potential natural vegetation, and/or potential natural communities (Cleland and others 1997) (fig. 1). See "Appendix A: Supplemental Methods, Analysis of FHM and FIA ground plot data" for additional details about analysis of FHM and FIA ground plot data.

[2] Fire Science Laboratory. Current condition classes. Version 1.0. Unpublished database. On file with: The Fire Science Laboratory, 800 Block E. Beckwith, Missoula, MT 59807. [www.fs.fw.us/fire/fuelman/].

[3] National Atmospheric Deposition Program. Database. http://nadp.sws.uiuc.edu/nadpdata/multisite.asp?state=ALL. [Date accessed: April 22, 2003].

[4] U.S. Geological Survey, National Land Cover Data. Database. http://landcover.usgs.gov/natllandcover.asp. [Date accessed: May 18, 2004].

[5] U.S. Department of Agriculture Forest Service. 1999. Forest health monitoring 1999 field methods guide. 480 p. On file with: The Forest Health Monitoring Program National Office, 3041 Cornwallis Road, Research Triangle Park, NC 27709.

[6] U.S. Department of Agriculture Forest Service. 2001. Forest inventory and analysis national core field guide. Vol. 1. Field data collection procedures for phase 2 plots. Version 1.5. Internal report. On file with: USDA Forest Service, Forest Inventory and Analysis, Rosslyn Plaza, 1620 N. Kent St., Arlington, VA 22209.

[7] U.S. Department of Agriculture Forest Service. 2001. Forest inventory and analysis national core field guide. Vol. 2. Field data collection procedures for phase 3 plots. Version 1.5. Internal report. On file with: USDA Forest Service, Forest Inventory and Analysis, Rosslyn Plaza, 1620 N. Kent St., Arlington, VA 22209.

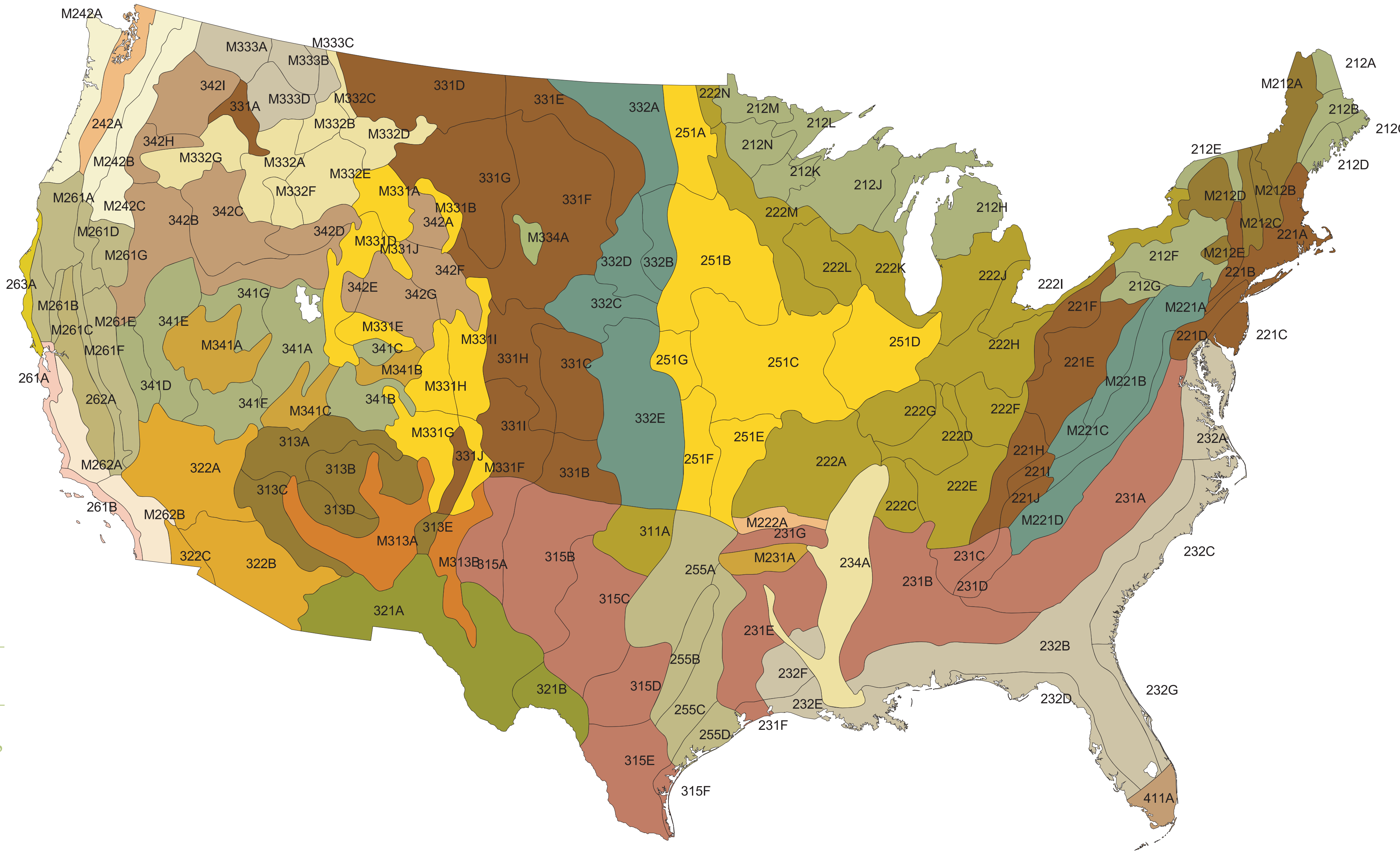


Figure 1—Bailey's ecoregion provinces and ecoregion sections for the conterminous United States. Similar colors in groups are the ecoregion sections within the ecoregion provinces.

Eastern ecoregion provinces

- Adirondack—New England Mixed Forest—Coniferous Forest—Alpine Meadow (M212)
- Central Appalachian Broadleaf Forest—Coniferous Forest—Meadow (M221)
- Eastern Broadleaf Forest (Continental) (222)
- Eastern Broadleaf Forest (Oceanic) (221)
- Everglades (411)
- Lauretian Mixed Forest (212)
- Lower Mississippi Riverine Forest (234)
- Ouachita Mixed Forest—Meadow (M231)
- Outer Coastal Plain Mixed Forest (232)
- Ozark Broadleaf Forest—Meadow (M222)
- Prairie Parkland (Subtropical) (255)
- Prairie Parkland (Temperate) (251)
- Southeastern Mixed Forest (231)

Western ecoregion provinces

- American Semi-Desert and Desert (322)
- Arizona—New Mexico Mountains Semi-Desert—Open Woodland—Coniferous Forest—Alpine Meadow (M313)
- Black Hills Coniferous Forest (M334)
- California Coastal Chapparal Forest and Shrub (261)
- California Coastal Range Open Woodland—Shrub—Coniferous Forest—Meadow (M262)
- California Coastal Steppe, Mixed Forest, and Redwood Forest (263)
- California Dry Steppe (262)
- Cascade Mixed Forest—Coniferous—Alpine Meadow (M242)
- Chihuahuan Semi-Desert (321)
- Colorado Plateau Semi-Desert (313)
- Great Plains Steppe (332)
- Great Plains Steppe and Shrub (311)
- Great Plains—Palouse Dry Steppe (331)
- Intermountain Semi-Desert (342)
- Intermountain Semi-Desert and Desert (341)
- Middle Rocky Mountains Steppe—Coniferous Forest—Alpine Meadow (M332)
- Nevada—Utah Mountains—Semi-Desert—Coniferous Forest—Alpine Meadow (M341)
- Northern Rocky Mountains Forest—Steppe—Open Woodland—Coniferous Forest—Alpine Meadow (M333)
- Pacific Lowland Mixed Forest (242)
- Sierran Steppe—Mixed Forest—Coniferous Forest—Alpine Meadow (M261)
- Southern Rocky Mountains Steppe—Open Woodland—Coniferous Forest—Alpine Meadow (M331)
- Southwest Plateau and Plains Dry Steppe and Shrub (315)

Maps in FHM annual national reports illustrate information presented in the text and spatially display the relative ranking of indicator values (Conkling and others 2005). The maps help identify possible regional patterns of the forest health indicator values. In general, the rankings are classified on the range of observed values, not on thresholds of "good" or "bad" conditions. Ecoregion sections or plot values for indicators are ranked from relatively low to relatively high for the range of values observed for all ecoregion sections or plot values. For example, the average ecoregion section values in figure 2 range from 1 to 25. The total range (25) is arbitrarily divided into five categories (1 to 5, 6 to 10, 11 to 15, 16 to 20, and 21 to 25). Each ecoregion section is color coded according to the category into which it belongs, which does not inherently indicate which categories are of concern. The reader can evaluate each ecoregion section and compare it to all other ecoregion sections across the United States. The text associated with the maps is integral to interpreting the information.

On maps where only the forested parts of ecoregion sections are shaded with the ecoregion section ranking, the actual distribution of forestland appears as a backdrop. The forestland backdrop comes from landcover maps derived from 1-km-resolution Advanced Very High Resolution Radiometer satellite imagery (fig. 3). In addition, several maps portray State or regional boundaries to help orient readers geographically.

Recognizing characteristics of the indicators helps explain why we chose them. Indicators with national coverage are appropriate because of the national scale. Also, similar geographic coverage of the indicators was needed for the integrated analysis presented in the section entitled "Integrated Look at Forest Health Indicators." Certain indicators are included regularly in FHM national reporting because the national results are of interest at the regional level. Another important reason for including the chosen indicators is their potential for ecologically significant or important interactions.

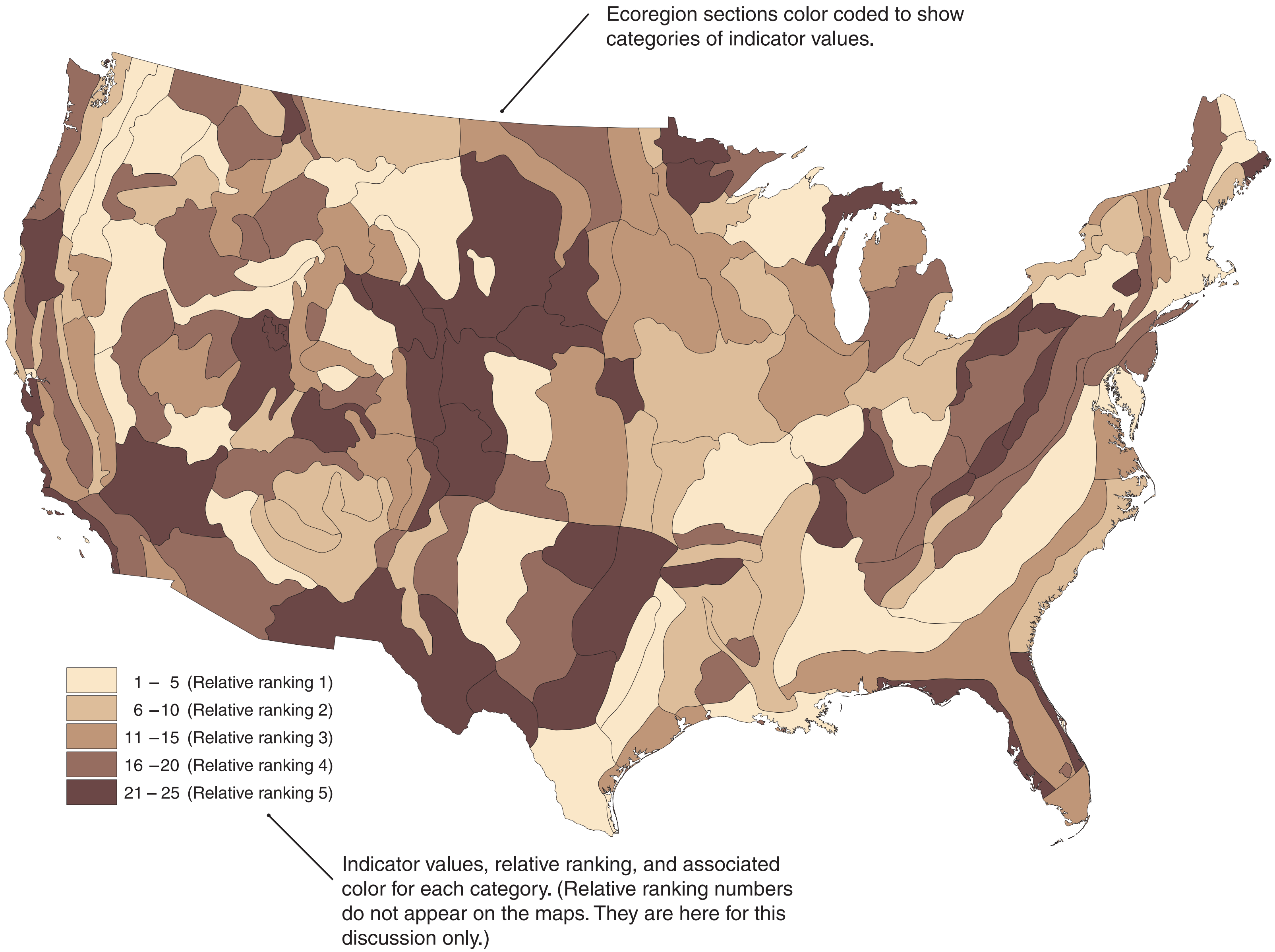


Figure 2—How to read a map in this report.

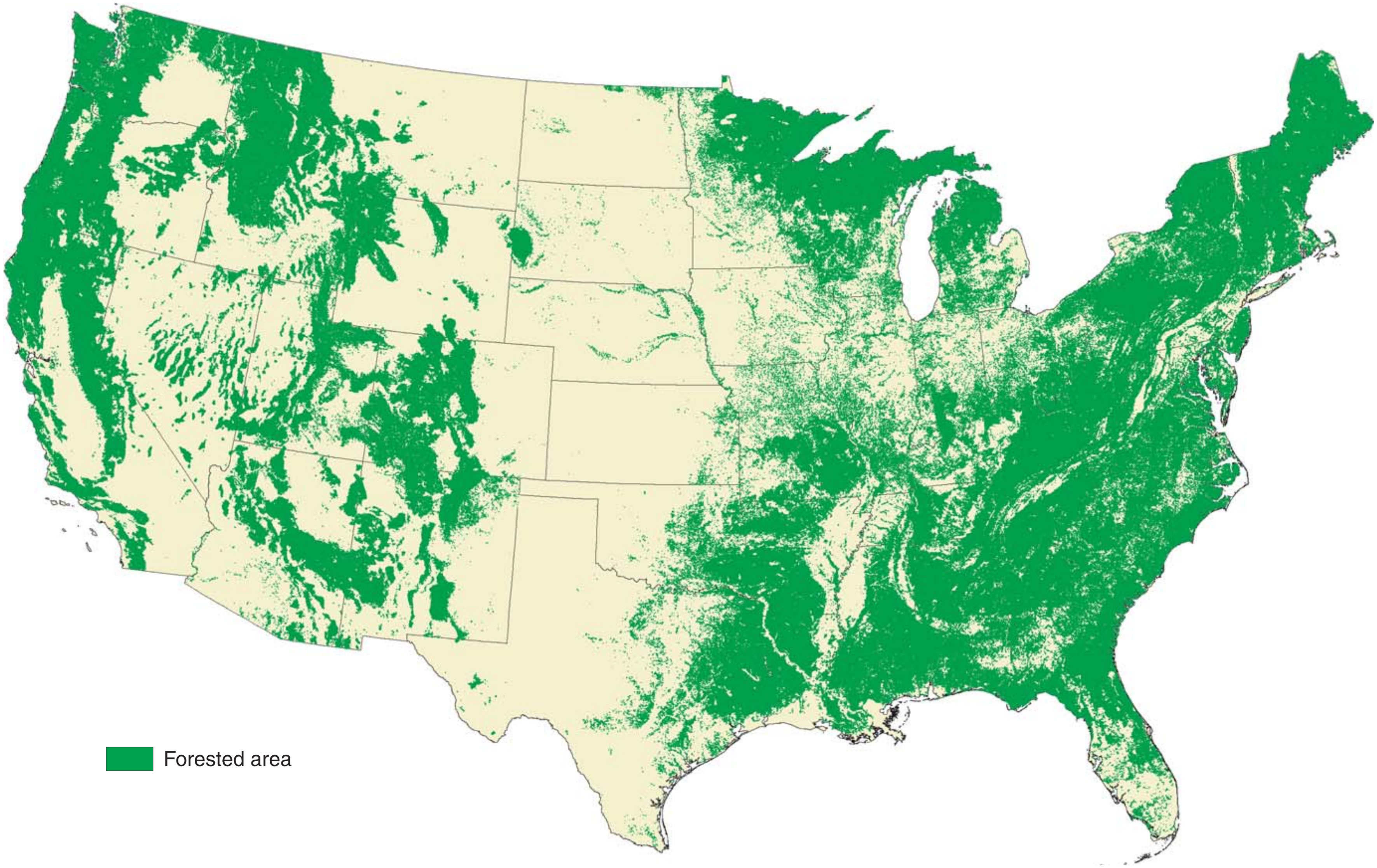


Figure 3—Forestland backdrop derived from Advanced Very High Resolution Radiometer satellite imagery (Zhu and Evans 1994).

The scientific literature contains many examples of research results documenting potential or observed relationships among forest ecosystem components and outside influences, both natural and anthropogenic. For example, Dale and others (2001) name land use and disturbance history as key influences on U.S. forests. Among the eight natural disturbances listed by Dale and others (2001) that have the greatest influences are fire, drought, and insect and pathogen outbreaks (indicators included in this report). Anthropogenic effects such as air pollution and land use are addressed using indicators such as wet deposition of sulfates and nitrates, ozone bioindicators and exposure, and landscape-oriented indicators such as distance to roads, amount and kind of borders of forest and other land uses, and amount of interior forest area.

The condition of the forest ecosystem is the crux of forest health evaluation and reporting, presented as status and changes in components of the forest ecosystem. The authors used four indicators to examine different characteristics of the forests: (1) tree crowns, (2) tree mortality, (3) stand age, and (4) forest floor depth. These indicators move forest health evaluations in the direction of assessing sustainability. In addition to crown status and change results in this section, the last main section, "Integrated Look at Forest Health Indicators," presents crown condition as a classifying variable for looking at potential indicator relationships.

Landscape Structure

Distance to Roads

The extensive road network that spans the United States has significant ecological impacts. Road influence zones extend tens to hundreds of meters from roads, affecting many ecological processes (Forman and Alexander 1998, Forman and others 2002). The potential for road impacts is significant because one-fifth of the total forestland area of the conterminous United States is within about 125 m of the nearest road, and the proportion increases rapidly with distance such that four-fifths of total forestland area is within 1 km of a road (Riitters and Wickham 2003). Clearly, potential impacts depend on the assumed distance for those impacts. However, the sheer pervasiveness of roads suggests that ecological impacts associated with roads may be the rule rather than the exception in most of the conterminous United States. This section provides a comparison of road influence zones for different ecoregion sections.

Following procedures described by Riitters and Wickham (2003), the base map for area calculations was the 1992 National Land Cover Data (NLCD) national landcover map (Vogelmann and others 1998, 2001) derived from satellite imagery with 0.09-ha-per-grid-cell spatial resolution. Total area calculations were based on all 21 NLCD landcover types, and the forestland area calculations combined 4 NLCD forest landcover types (table 1). The national road map was a 1995 modification of the Bureau of the Census TIGER/Line files (Geographic Data Technology 2002). By geographic overlay, the minimum distance to a road was determined for each 0.09-ha grid cell on the NLCD map. A total of approximately 8.6 billion grid cells including approximately 2.8 billion forestland cells were used in the analysis.

Table 1—Aggregation of the 21 landcover types in the National Land Cover Data database for the analysis of forest edge and roads

National Land Cover Data categories	Aggregated category
Open water, perennial ice/snow	Water
Low intensity residential, high intensity residential, commercial/industrial/transportation, urban/recreational grasses	Developed/urban
Bare rock/sand/clay, quarries/mines, transitional	Barren/disturbed
Deciduous forest, evergreen forest, mixed forest, woody wetlands	Forest
Shrubland	Shrubland
Orchards/vineyards, pasture/hay, row crops, small grains, fallow	Agriculture
Grasslands/herbaceous	Grassland
Emergent herbaceous wetlands	Wetland

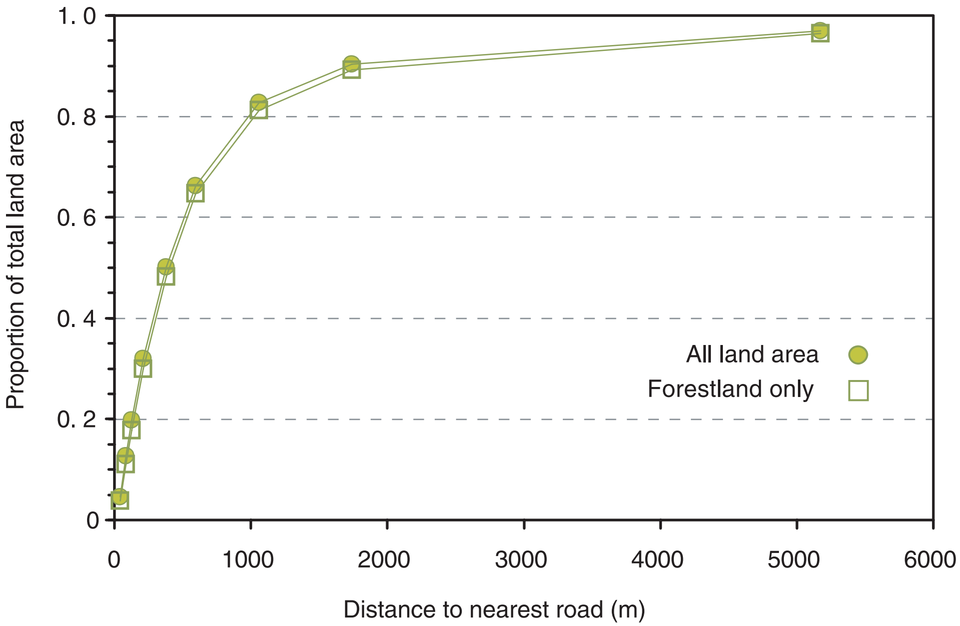


Figure 4—The proportion of total land area that is within a specified distance from the nearest road increases rapidly with distance (adapted from Riitters and Wickham 2003).

Approximately 4.5 percent of the grid cells contained at least one road, and the proportion of total land area within a defined distance of the nearest road increased rapidly with distance (fig. 4). Overall, 20 percent of all land area was located within 127 m of the nearest road, half was within 382 m, and < 20 percent was more than 1 km away from a road. With the exception of some areas in the Great Plains and Great Basin regions, forestland was more remote from roads in comparison to other landcover types (Riitters and Wickham 2003). However, the differences among landcover types were small (fig. 4).

Figure 5 shows the proportion of total area in each ecoregion section that was within 42 m, 127 m, and 1061 m of the nearest road (Riitters and Wickham 2003). The map showing the results for the 42-m distance (fig. 5A) may be interpreted, roughly, as a "road density" map; higher values identify ecoregion sections where roads are extensively distributed throughout the ecoregion section. The highest values were found in ecoregion sections comprising the Boston–Washington and Los Angeles–San Diego metroplex regions. Values exceeding the national average (4.5 percent) were found throughout most of the Eastern United States, and values below the national average were primarily in the Western United States. Exceptions to those broad patterns included several ecoregion sections in the boreal forest zone in the East, and the ecoregion sections with relatively large human populations in the West.

If the ecological impact zone is assumed to be 127 m from a road of any type, then about 20 ecoregion sections have more than 20 percent of total land area affected (fig. 5B). If the assumed zone extends 1061 m from the nearest road, then only 12 ecoregion sections have < 50 percent of total land area affected (fig. 5C). Generally, eastern ecoregion sections are at more risk than western sections for shorter assumed distances, because overall road density is higher in the East. For longer assumed distances, only the least populated ecoregion sections in the West are at relatively low risk.

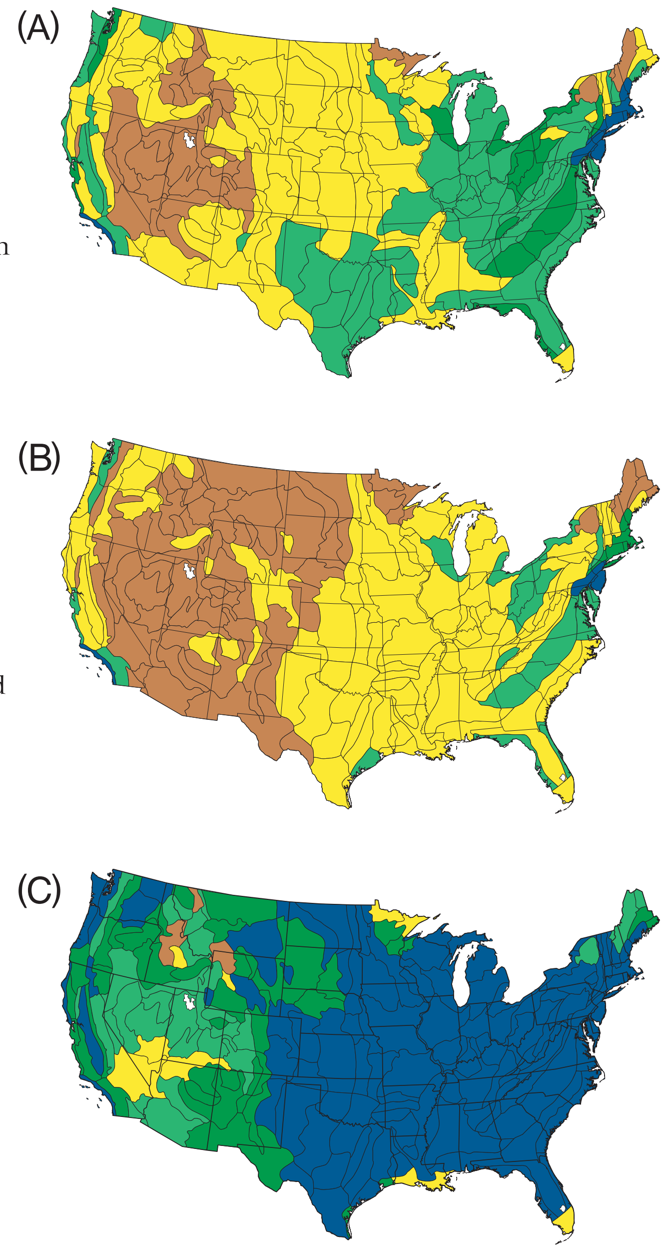


Figure 5—The proportion of total land area in 164 ecoregion sections that is within a specified distance of the nearest road is shown for 3 representative distances. Note that the legend scales differ among the three maps to accommodate differences in scale.

Forest Edge

Forest edge is one of several fragmentation indicators included in the U.S. 2003 report on sustainable forests (Darr 2004). Analysis of the overall perimeter-to-area ratio (Riitters and others 2004) indicated that most areas had 10 to 40 percent of the maximum possible per unit area of forestland (table 2). However, interpretation of the results was complicated because the ratio was typically highest in the Great Plains and Intermountain West (fig. 6) where forests are not naturally abundant, and where much of the fragmentation is associated with small parcels of artificial forests. Further, the reported regional average values did not account for any differences among ecoregions, and did not distinguish between natural and anthropogenic sources of fragmentation. Building on the earlier work referenced above, this section provides additional analysis and interpretation of ecoregion differences in forest edge. The objective is to characterize ecoregion sections in terms of the lengths of different types of forest edges that they contain.

Table 2—Summary statistics for the overall perimeter-to-area ratio within 5625-ha analysis units that contained forest, by Resources Planning Act assessment region (the maximum possible index value equals 4.0)

		Length of forest-nonforest edge per unit area forestland within 56.25-km^2 analysis units (index value)			
Resources Planning Act region	Number of analysis units	Mean	Range	Standard deviation	Median
North	30,260	0.81	0.001 – 4.00	0.69	0.64
Pacific coast	13,970	1.42	0.002 – 4.00	1.24	1.04
Rocky Mountains	46,147	1.81	0.004 – 4.00	1.11	1.82
South	36,635	0.86	0.000 – 4.00	0.91	0.48
All regions	127,012				

Source: U.S. Department of Agriculture Forest Service 2003a.

Input data were from landcover maps derived from the NLCD database (Vogelmann and others 1998, 2001), condensed to show 8 major landcover classes (table 1) at a spatial resolution of 0.09 ha, and the analysis units were defined by a grid of 5625-ha (7.5 km by 7.5 km) squares, each containing 62,500 pixels. Excluding analysis units that contained only water (large inland lakes and estuaries), or that contained missing values (near international borders), or that had no ecoregion identity (Great Salt Lake and Lake Okeechobee), 137,648 analysis units remained, including 127,012 that contained no forest. The location of the center point of each analysis unit was used to identify the ecoregion section to which the unit belonged.

In conducting our analysis we adopted the following definitions. Edge refers generally to imaginary lines that separate any two adjacent pixels on the landcover map. It includes forest-forest edge (if the adjacent pixels are both forest), forest-nonforest edge (if only one of the two pixels is forest), and nonforest-nonforest edge (if neither pixel is forest). Forest edge specifically refers to landcover that separates a

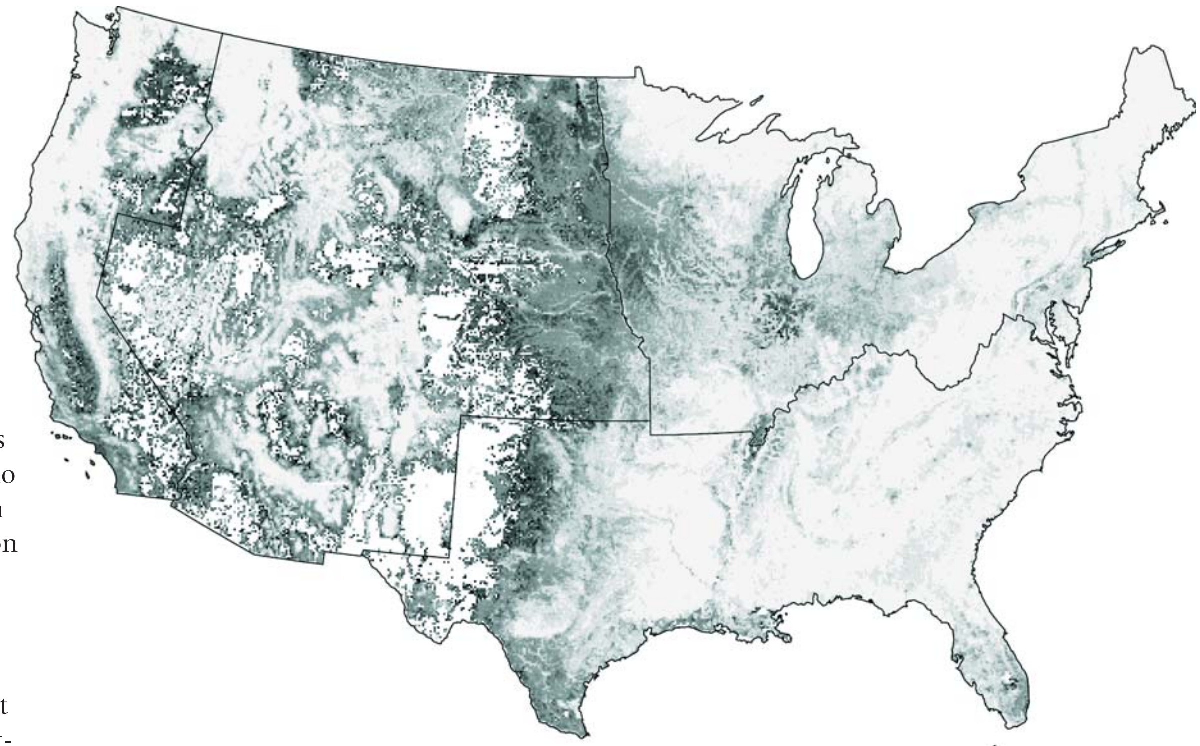


Figure 6—Surface map showing the amount of forest edge per unit area of forestland. Darker shades indicate higher overall perimeter-to-area ratios. Boundaries of Resources Planning Act regions are shown for comparison (adapted from Riitters and others 2004).

forest pixel from a nonforest pixel. Forest-anthropogenic edge is a subset of all forest edge, and it refers to forest edge with either urban or agriculture landcover types. Forest-seminatural edge is also a subset of all forest edge, and it refers to forest edge with water, wetland, barren, grassland, or shrubland (table 1).

The nominal length of an individual edge segment between two pixels is 30 m. The total number of edges among all 62,500 pixels within an analysis unit is 124,500. Thus, there are 3735 km of total edge length potentially identifiable in each analysis unit, or approximately 514 million km for all analysis units in the conterminous United States. Considering first the national totals (table 3), about 180 million km of total edge involved forest and the remainder involved landcover types other than forest. Of that amount, about 31.4 million km was forest edge (i.e., forest-nonforest edge) and the rest was forest-forest edge. The total forest edge was about equally split between forest-anthropogenic edge (approximately 15.5 million km) and forest-seminatural edge (approximately 15.9 million km).

Table 3—National totals for selected edge length statistics (excludes Alaska, Hawaii, and Puerto Rico). Total edge includes forest-forest and forest-nonforest edge. The total forest-nonforest edge is partitioned into forest-anthropogenic edge and forest-seminatural edge

Category of edge	Edge length
	km
Total edge resolved in the analysis, including forest-forest edge and all types of forest-nonforest edge	180 267 361
Total forest-forest edge	148 848 341
Total of all types of forest-nonforest edge	31 419 020
Total forest-anthropogenic edge, including forest-urban and forest-agriculture edge	15 501 284
Total forest-seminatural edge, including forest-barren, forest-water, forest-grassland, forest-shrubland, and forest-wetland edge	15 917 736

Naturally, individual analysis units contain relatively little forest edge when there is not much forest present. At the other extreme, there are physical constraints that necessarily limit the amount of forest edge in analysis units that are mostly forested. For intermediate amounts of forest, the amount of forest edge per analysis unit varied from almost none to about 1300 km. Similarly, the amount of forest-anthropogenic edge depended on the amounts of the three landcover types present and varied from none to about 1200 km. There were far more analysis units with near zero values in the latter case because many analysis units contain very little agriculture or developed landcover. In approximately 50,000 analysis units, agriculture and developed landcover accounted for < 10 percent of total forest edge. In approximately 20,000 analysis units, those 2 landcover types accounted for over 90 percent of total forest edge (fig. 7).

As for individual analysis units, some ecoregion sections were expected to contain more forest edge than others, if only because some sections contain more or less forest than

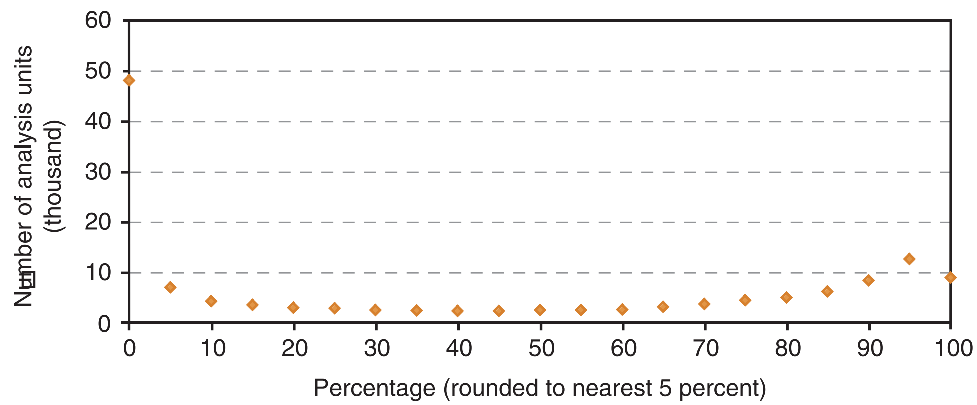


Figure 7—The number of analysis units for which the indicated percentage of total forest edge was forest-anthropogenic edge.

others. Further, agriculture and developed land will account for more or less of all forest edge within an ecoregion section depending on the particular mix of land uses there. To characterize these differences, maps were prepared to show the average edge lengths within the analysis units contained within different ecoregion sections. Figure 8 shows the average length of total forest edge within analysis units by ecoregion section; figure 9 shows the average length of forest-anthropogenic edge; and figure 10 shows the proportion of all forest edge that is forest-anthropogenic edge.

The use of absolute forest edge length instead of perimeter-to-area ratio helps to identify ecoregion sections containing the largest amounts of forest edge (compare figure 6 and figure 8). Generally, the largest amounts of forest edge are contained in eastern ecoregion sections, and in western ecoregion sections that are mostly forested (fig. 8). With one exception in the West, ecoregion sections containing large amounts of forest-anthropogenic edge are located in the Eastern United States. It was interesting that many western ecoregion sections with high human populations; e.g., Los Angeles Basin, Denver, and Salt Lake City, did not have large amounts of forest-anthropogenic edge. This reflects the greater separation of forest and anthropogenic landcover types in the West. Most of the western forest edge is associated with seminatural landcover classes, whereas most of the eastern forest edge is associated with anthropogenic landcover classes (fig. 10).

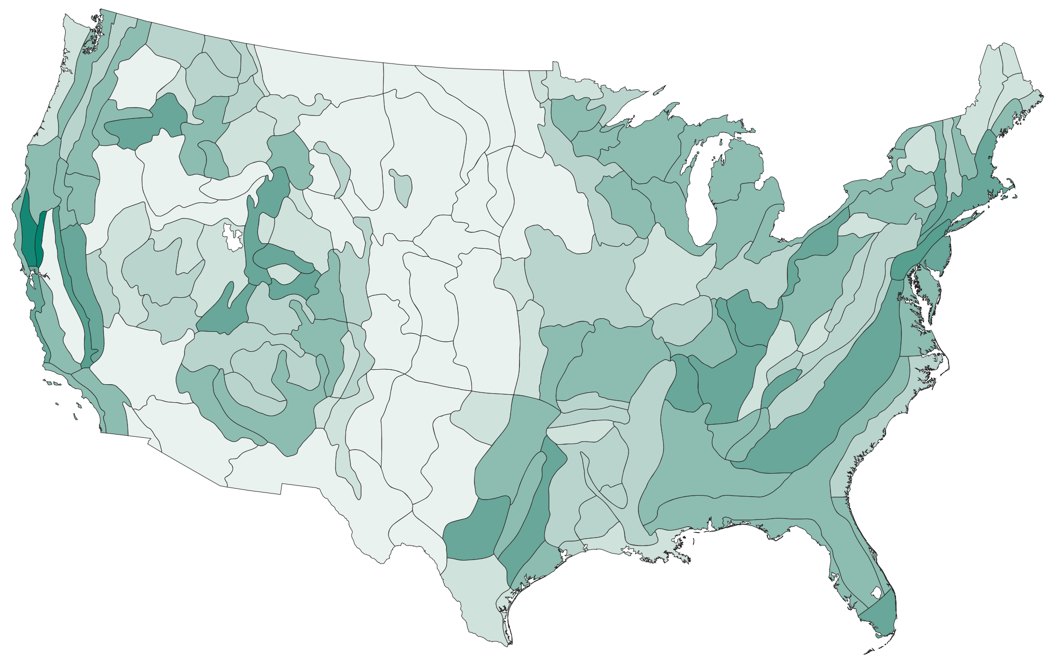


Figure 8—Average length of total forest edge within analysis units for 164 ecoregion sections. Lighter shades indicate lower values and darker shades indicate higher values.

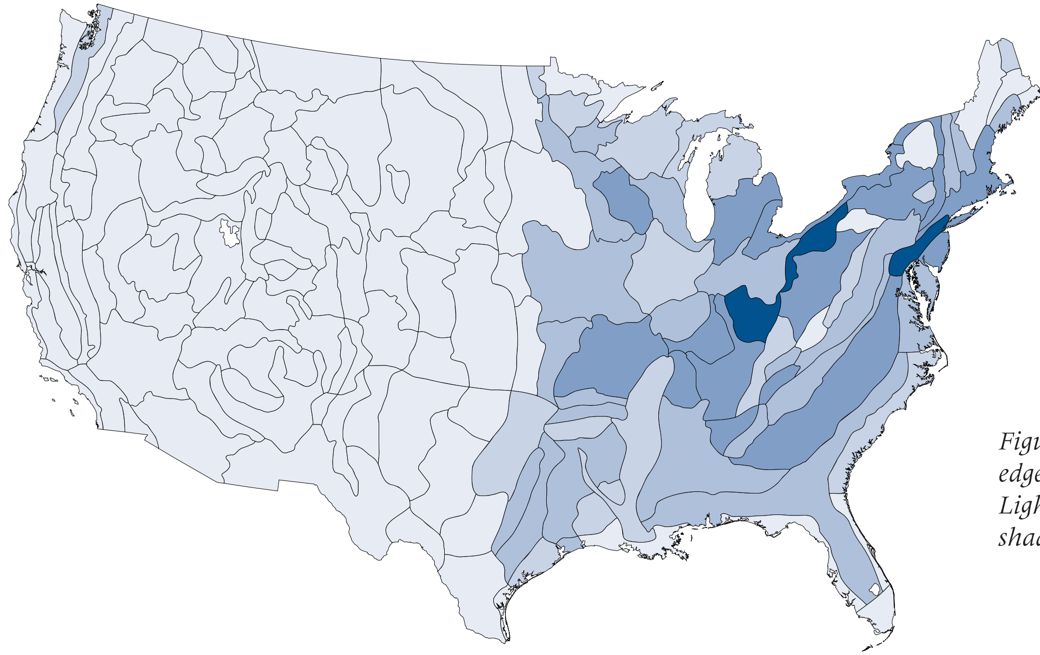


Figure 9—Average length of forest-anthropogenic edge within analysis units for 164 ecoregion sections. Lighter shades indicate lower values and darker shades indicate higher values.

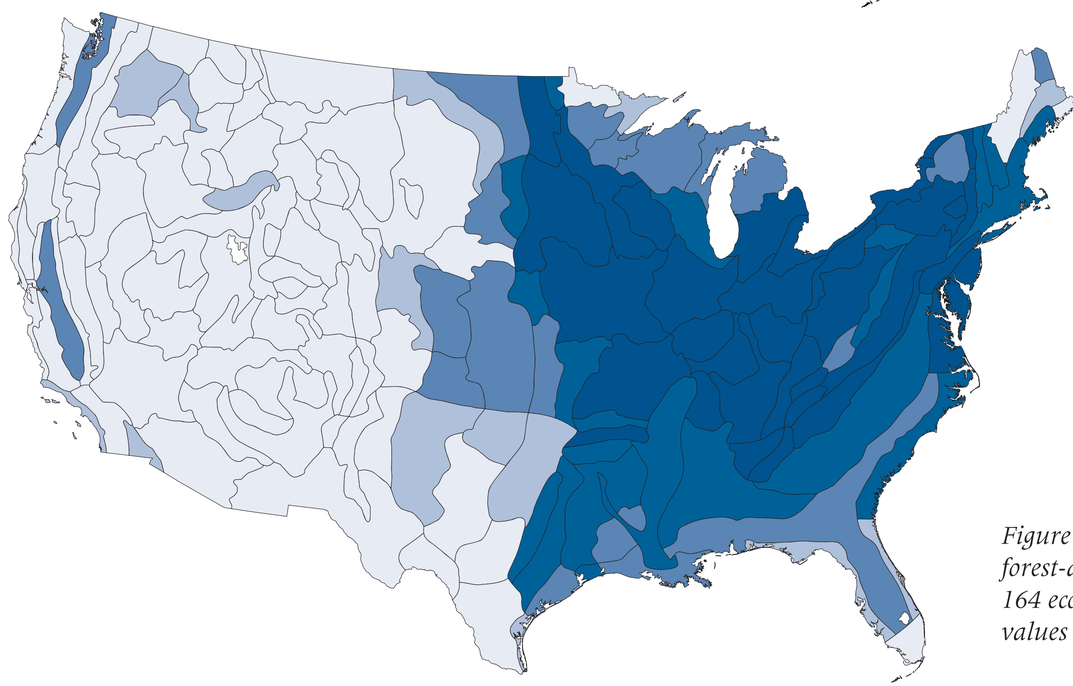


Figure 10—Average proportion of forest edge that was forest-anthropogenic edge within analysis units for 164 ecoregion sections. Lighter shades indicate lower values and darker shades indicate higher values.

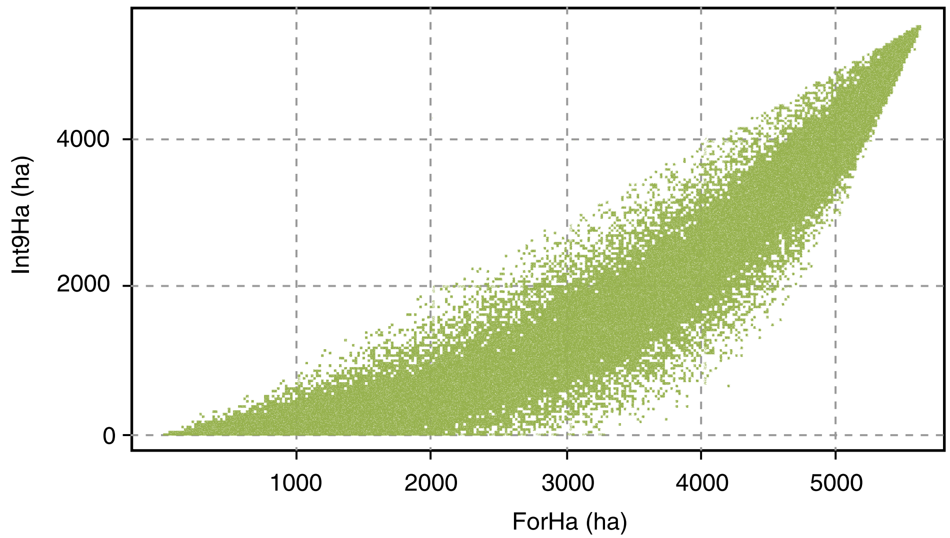
Interior Forest

An earlier assessment (Riitters and others 2002) reported a multiple-scale analysis of forest fragmentation based on 30-m (0.09 ha/pixel) landcover maps for the conterminous United States. Each 0.09-ha unit of forest was classified according to fragmentation indices, including an index of interior forest measured within the surrounding landscape, for five landscape sizes. The results suggested that forests are well connected over large regions, but fragmentation is so pervasive that edge effects potentially influence ecological processes on most forested lands. The following information builds on the earlier assessment by exploring differences in interior forest among ecoregion sections.

The input data were the landcover maps from the NLCD database (Vogelmann and others 1998, 2001), condensed to a forest-nonforest legend (table 1) at a spatial resolution of 0.09 ha. Each forest pixel on the NLCD map was evaluated to determine if it met the criterion for interior forest at each of two spatial scales (Riitters and others 2002). A forest pixel was considered interior forest if a surrounding square window was at least 90 percent forested. The two window sizes of 7.29 ha (9 pixels by 9 pixels) and 5314.41 ha (243 pixels by 243 pixels) defined the two spatial scales for the analyses. The resulting two maps of interior forest were then summarized within analysis units that were defined by a grid of 5625-ha (7.5 km by 7.5 km) squares, each containing 62,500 pixels. Excluding analysis units that contained no forest, or only water (large inland lakes and estuaries), or that contained missing values (near international borders), or that had no ecoregion identity (Great Salt Lake and Lake Okeechobee), 126,716 analysis units remained. The location of the center point of each analysis unit was used to identify the ecoregion section to which the unit belonged.

If the forest in an analysis unit was not fragmented, then the amount of interior forest would equal the amount of forest in the analysis unit. Departures from that 1:1 relationship indicate analysis units containing fragmented forests, and the degree of departure is a measure of the degree of fragmentation. The amount of interior forest is necessarily large for analysis units that are mostly forested and small for units

Figure 11—Scatter plot of interior forest area (ha) at a 7-ha scale (Int9Ha) versus total forestland area (ha) within 5625-ha analysis units (ForHa). At this scale, interior forest is a 0.09-ha parcel of forestland that is surrounded by a 7.29-ha window that is at least 90 percent forested.



that do not contain much forest. These general concepts are illustrated in figure 11 which shows the relationship between amount of interior forest and the amount of forest for the 7.29-ha scale. The effect of changing analysis scale is evident by a comparison of those results with figure 12, which shows the results for the 5314.41-ha scale. For most analysis units, as the scale of analysis increases, it becomes more difficult to achieve the 90 percent threshold, and the "data cloud" moves down and to the right in figure 12, relative to figure 11. At the same time, some units that were not 90 percent forested at the 7.29-ha scale did meet the threshold as more of the surrounding landscape was included, and for that reason the scatter of points along the 1:1 line becomes more evident in figure 12, in comparison to figure 11.

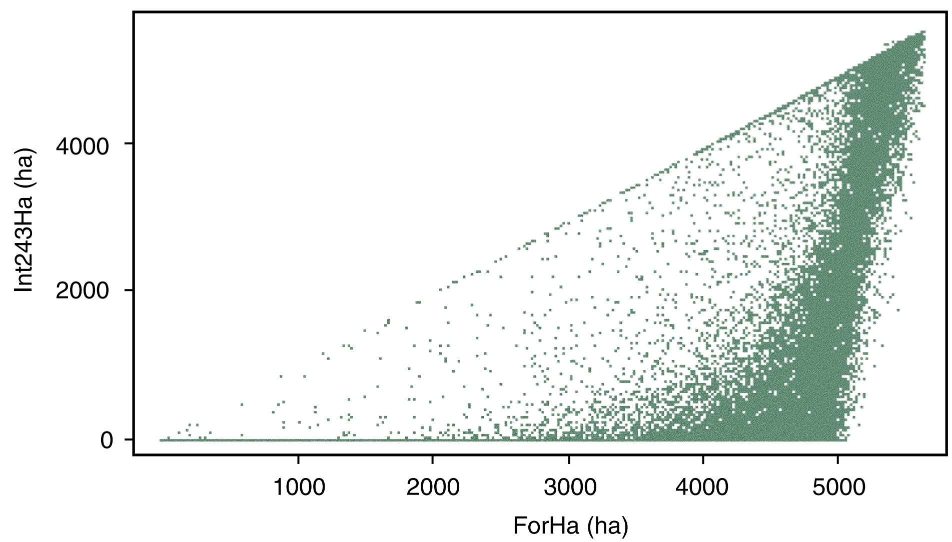


Figure 12—Scatter plot of interior forest area (ha) at a 5314-ha scale (Int243ha) versus total forestland area (ha) within 5625-ha analysis units (ForHa). At this scale, interior forest is a 0.09-ha parcel of forestland that is surrounded by a 5314.41-ha window that is at least 90 percent forested.

Expressing the values as the percentage of forest that is interior within an analysis unit helps to account for different amounts of forest among analysis units. Figure 13 portrays each ecoregion section in terms of that percentage, averaged over all analysis units in the ecoregion section for the 7.29-ha scale. Figure 14 shows the same average percentages for the 5314.41-ha scale. The two results show similar patterns among ecoregion sections—sections that have relatively high average percentage of interior forest at the 7.29-ha scale also tend to have relatively high average percentage values at the 5314.41-ha scale. However, while the average percentage exceeds 50 percent in many ecoregion sections at the 7.29-ha scale, very few ecoregion sections meet that criterion at the 5314.41-ha scale. One way to interpret the importance of the results is in terms of habitat for obligate interior forest species. For example, the darker colored ecoregion sections in figure 13 might be expected to contain significant amounts of habitat capable of supporting forest species with relatively small home range sizes,

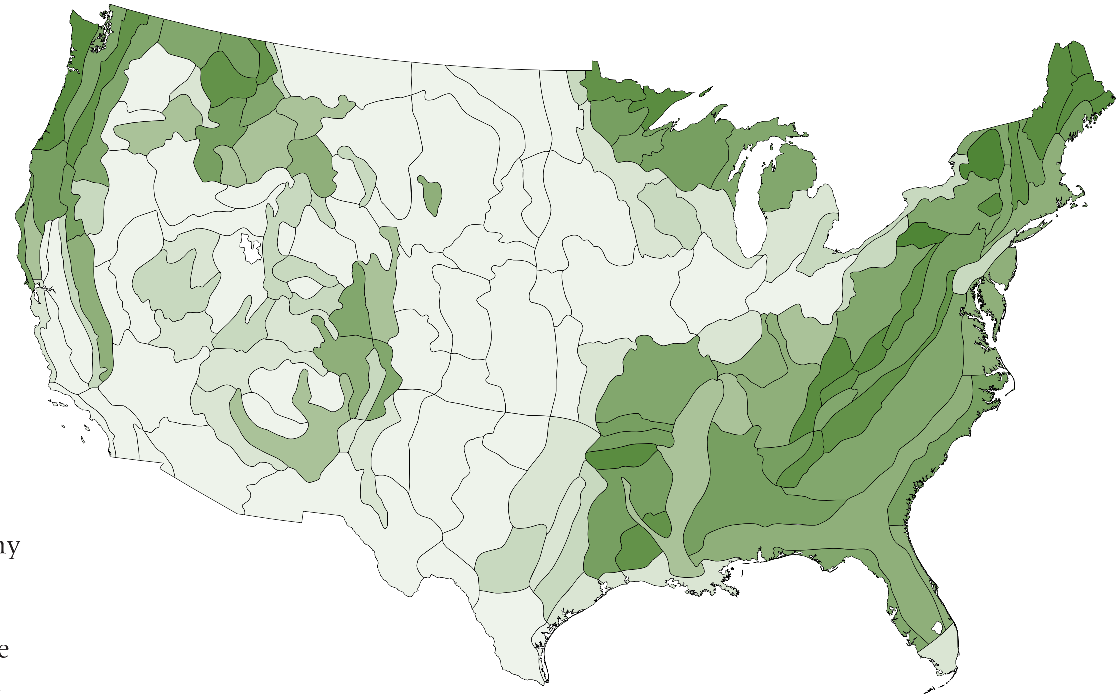


Figure 13—Average percentage of forestland that was classified as interior forest at a 7.29-ha scale within 5625-ha analysis units for 164 ecoregion sections. Lighter shades indicate lower values and darker shades indicate higher values.

whereas the darker ecoregion sections in figure 14 should contain more habitat for species with relatively large home range sizes.

A related measure of fragmentation was defined for use in the integration section entitled “Integrated Look at Forest Health Indicators.” All the procedures described earlier were followed with the exception that a forest pixel was defined as core forest if the surrounding window was completely forested. There is typically much less core forest than interior forest (as defined here) in a given region because the 100-percent forest requirement is difficult to achieve over large areas (Riitters and others 2002). Core forest was used in the integration section to focus on truly remote forested regions.

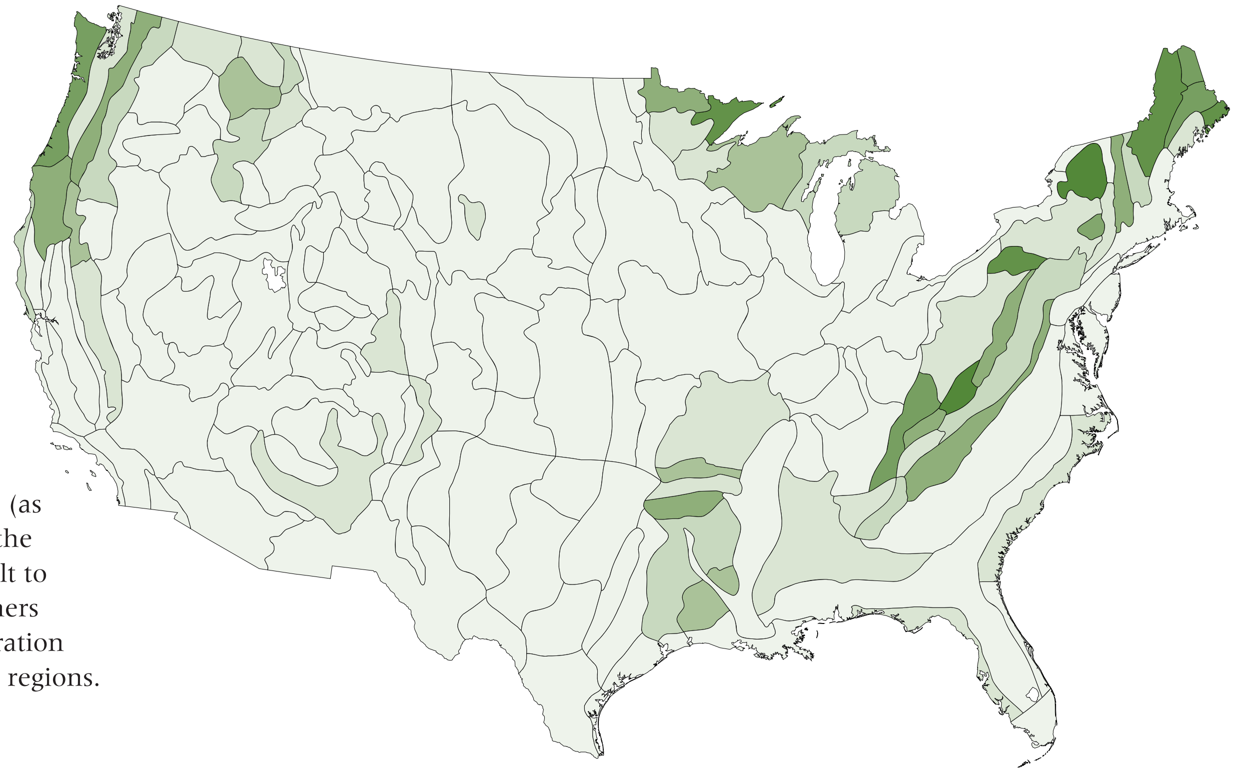


Figure 14—Average percentage of forestland that was classified as interior forest at a 5314.41-ha scale within 5625-ha analysis units for 164 ecoregion sections. Lighter shades indicate lower values and darker shades indicate higher values.

Drought

Drought, a naturally occurring disturbance to forest communities, is a function of temperature; precipitation in the form of rainfall, snow, ice, or fog drip; and soil characteristics such as water-holding capacity. In the Eastern United States, droughts occur on an irregular basis while in other areas; e.g., western interior dry forests, droughts occur annually (Dale and others 2001). Moderate drought stress tends to slow plant growth, while severe drought stress also reduces photosynthesis (Kareiva and others 1993). Drought can interact with other disturbances and site characteristics, sometimes exacerbating other forest ecosystem stresses. One example is insect communities. Mattson and Haack (1987) identified 10 insect families that historically reach outbreak status following drought episodes. Another example is poor soil nutrition. Demchik and Sharpe (2000), in a study using northern red oak trees, found that basal growth rates of trees on sites with poorer nutrition levels did not recover following consecutive years of drought, while trees on sites with better nutrition levels did recover. Stand structure can also be affected by drought (Olano and Palmer 2003). Decomposition of organic matter can be slowed during periods of drought, resulting in more favorable fire conditions.

Because drought is a naturally occurring event to which ecosystems are adapted, we examined the deviation from its historic occurrence (drought deviation). For our purposes, drought deviation represents the departure of drought occurrence in the current 20-year period from historic averages. A 20-year period was chosen to facilitate use of the data in the integrated analyses discussed in the section entitled “Integrated Look at Forest Health Indicators.” Frequency of drought from 1895 through 2002 was used as a historical reference point for each ecoregion section. For example, if 384 months of drought were recorded in an ecoregion section from 1895 through 2002 (i.e., drought occurs in approximately 30 percent of the months), then approximately 72 months of drought would be expected on a 240-month (20-year) basis. The historical reference was then compared to the current 20-year period. If the expected number of months with drought conditions was 72, and 96 months of drought were recorded in the current 20-year period, then the drought deviation was 96 – 72 = 24.

In the current 20-year period (1983 through 2002), some ecoregion sections experienced more frequent droughts than expected based on historical averages while others experienced less (fig. 15A). Several ecoregion sections in the Eastern United States had a drought deviation of > 12 months (12 months of drought over a 20-year period in addition to that expected based on the historical average)—M221D—Blue Ridge Mountains, 232A—Middle Atlantic Coastal Plain, 232G—Florida Coastal Lowlands (Eastern), 221C—Upper Atlantic Coastal Plain, and 212A—Aroostook Hills and Lowlands in northern Maine. Section M221D—Blue Ridge Mountains was the most droughty with a drought deviation of 33 months. Many areas in the Northeast, South, and Northcentral United States experienced less drought than expected (fig. 15A).

Several ecoregion sections in the Western United States had a drought deviation of 12 months or more. The most droughty areas included: parts of Provinces M261—Sierran Steppe—Mixed Forest—Coniferous Forest—

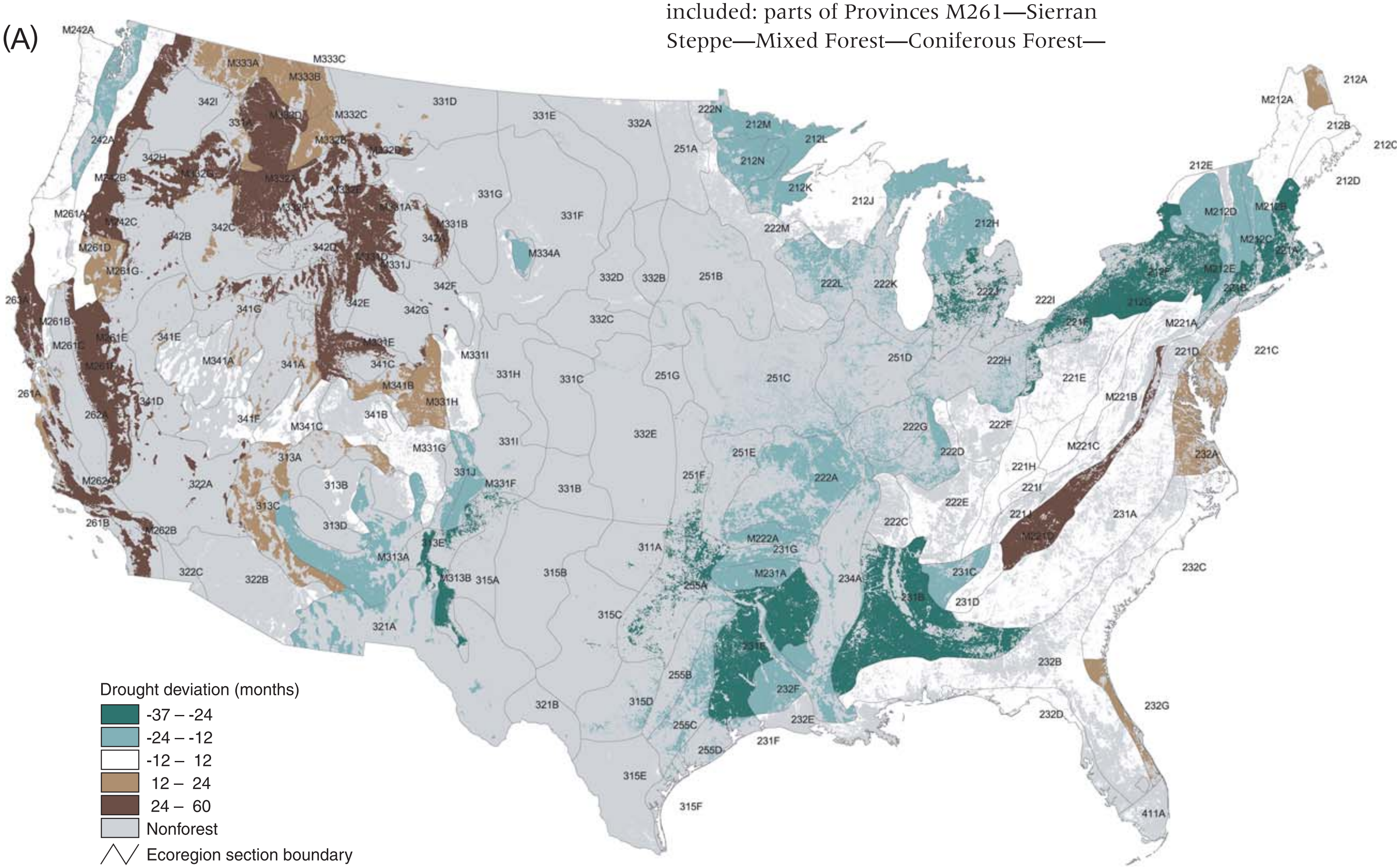
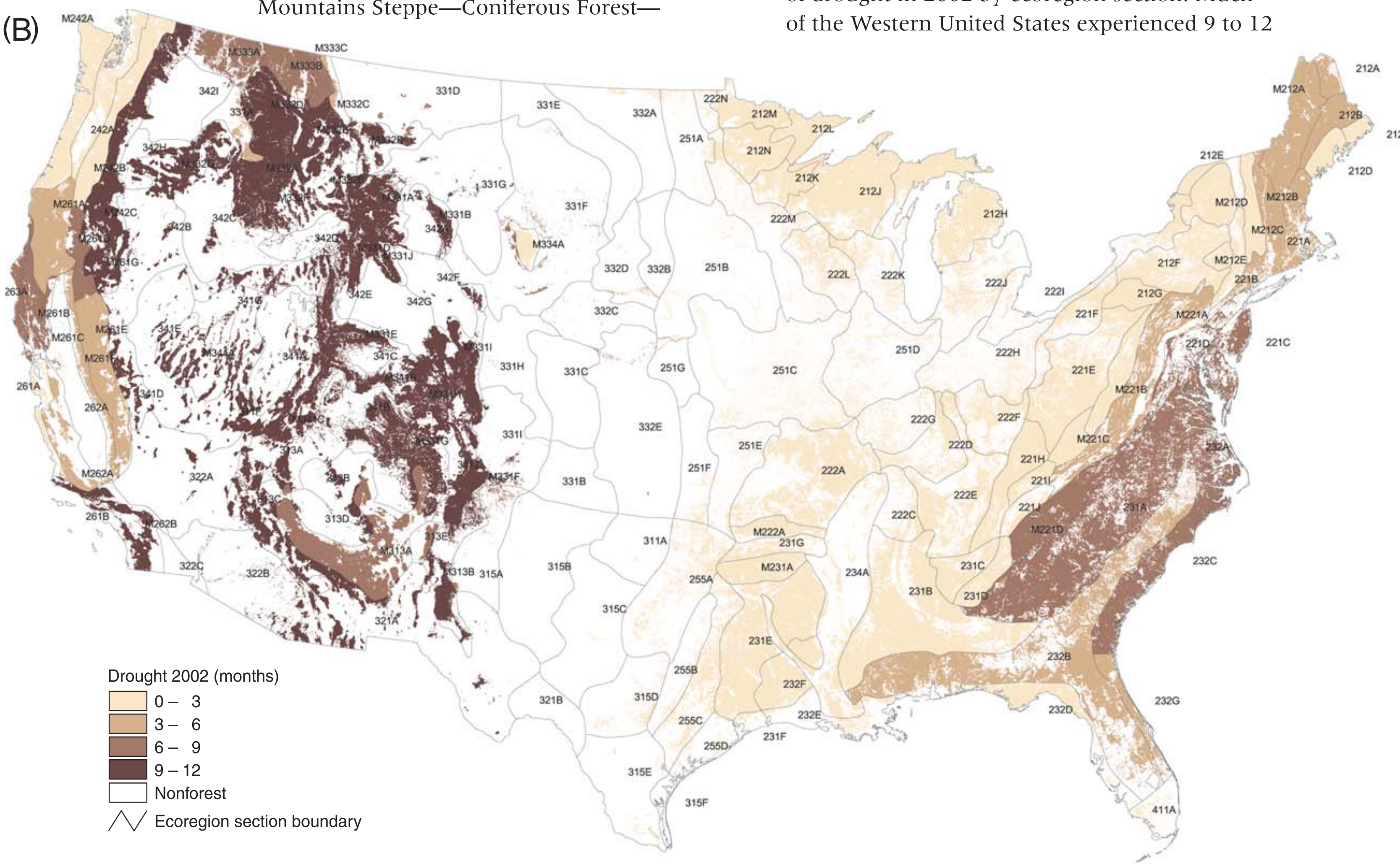


Figure 15—(A) Deviation from historical drought occurrence in months, by Bailey's ecoregion section. The frequency of drought from 1895 through 2002 was the historical reference and the frequency of drought from 1983 through 2002 (20-year period) was compared to it. (B) The number of months of drought in 2002 by ecoregion section.

Alpine Meadow in California and M262—California Coastal Range Open Woodland—Shrub—Coniferous Forest—Meadow; Section 263A—Northern California Coast; parts of Provinces M331—Southern Rocky Mountains Steppe—Open Woodland—Coniferous Forest—Alpine Meadow and M332—Middle Rocky Mountains Steppe—Coniferous Forest—Alpine Meadow; and Section M242C—Eastern Cascades. The most droughty ecoregion section was Section M262B—Southern California Mountains and Valleys, which had a drought deviation of 60 months.

Figure 15B shows the number of months of drought in 2002 by ecoregion section. Much of the Western United States experienced 9 to 12

(B)



months of drought. The fewest months of drought occurred west of the Cascade Mountains in Washington and Oregon (fig. 15B). Several ecoregion sections in the East experienced 6 to 9 months of drought: M221D—Blue Ridge Mountains, 231A—Southern Appalachian Piedmont, 232A—Middle Atlantic Coastal Plain, 232C—Atlantic Coastal Flatlands, and 221C—Upper Atlantic Coastal Plain. Three to six months of drought occurred all along the eastern seaboard (fig. 15B).

Fire

Fire is a powerful, selective regulatory mechanism in forest ecosystems. It is a disturbance factor that can be either natural or anthropogenic. Effects of fire on a forest depend both on characteristics of the fire and characteristics of the trees (Agee 1993, Stephens and Finney 2002). Fire has been and remains a natural part of forested ecosystems. Fire-dependent ecosystems are adapted to a particular frequency and intensity of fire. These ecosystems will remain in their natural state only if the fire regime to which they are adapted is present (Kimmins 1987). The frequency and intensity of burning depend on fuel buildup, weather conditions, and the occurrence of ignition sources. Although historically most fires were started by lightning strikes, humans have altered historic fire regimes by fire suppression, tree harvesting, and prescribed burning. Changes in either fire frequency or intensity can possibly change the species composition and age structure of a fire-adapted community (Kimmins 1987). Fire also affects soil characteristics (Caldwell and others 2002, Fisher and Binkley 2000).

From 1938 to 2002, the areal extent of wildfire varied from approximately 136 900 km^2 in 1938 to approximately 6800 km^2 in 1975 (fig. 16). There was a marked reduction in areal extent of wildfire between 1938 and 1957, with a relative leveling off from 1957 to present. However, 2000 was one of the most intense years of fire activity in the Western United States since 1916 (Ciesla and Coulston 2004). Areal extent dropped in 2001 to approximately 14 400 km^2 and increased to approximately 28 100 km^2 in 2002. Examining temporal trends in the areal extent of wildfire does not address any change in the intensity of wildfire or any spatial differentiation.

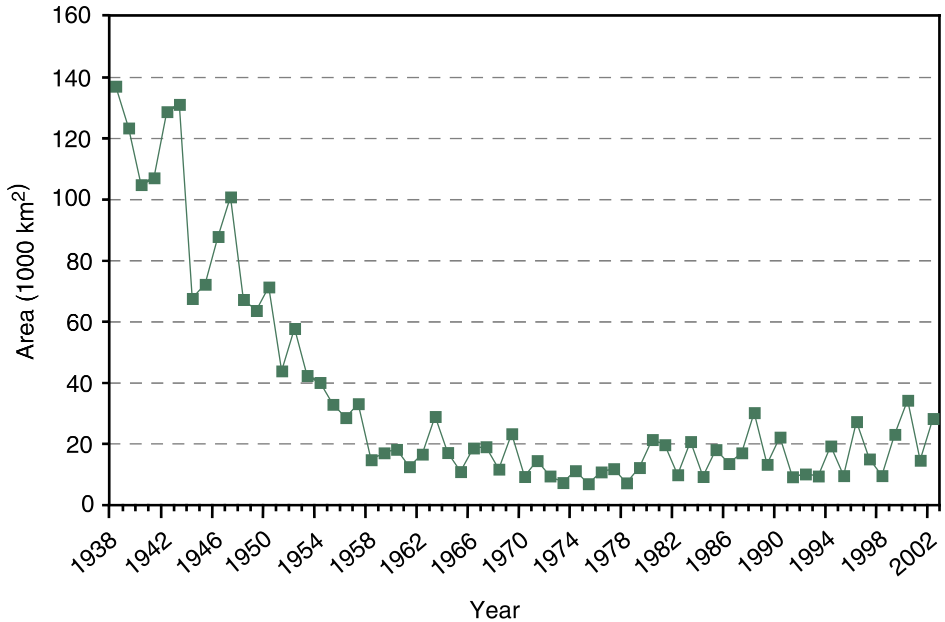


Figure 16—Areal extent of forest fire in the conterminous United States from 1938 through 2002.

Looking at current condition classes is another way to assess fire disturbance at a national scale. Because no additional condition class data were available in 2003 (see footnote 2), the following discussion about current condition classes and the most current map using the data are repeated from the "Forest Health Monitoring 2002 National Technical Report" (Coulston and others 2005).

Current condition classes categorize departure from ecological conditions compatible with historic fire regimes based on five ecosystem attributes (Schmidt and others 2002). They are: (1) disturbance regimes, (2) disturbance agents, (3) smoke production, (4) hydrologic function, and (5) vegetative attributes. Current condition class 1 represents a minor deviation from ecological conditions compatible with historic fire regimes, and condition class 2 represents a moderate deviation. Current condition class 3 represents a major deviation from the ecological conditions compatible with historic fire regimes.

In the conterminous United States, 38.7 percent of forested land was classified in condition class 1, 37.5 percent was classified in condition class 2, and 23.8 percent was classified in condition class 3. Most of the forest area classified in condition class 1 was in the Southeastern United States (fig. 17). Other areas, such as Section M242A—Oregon and Washington Coast Ranges, were also of note with approximately 87 percent of the forestland classified in condition class 1. Several areas were classified as having a major deviation from ecological conditions compatible with the historic fire regime. Many of these areas were in Province 212—Laurentian Mixed Forest in the North and Northcentral United States (fig.17). In Section 212M—Northern Minnesota and Ontario in northern Minnesota, approximately 80 percent of the forested area was classified in condition class 3. About 75 percent of the forestland in Section 212G—Northern Unglaciated Allegheny Plateau in Pennsylvania and New York was classified in condition class 3. Section 212F—Northern Glaciated Allegheny Plateau in New York and Pennsylvania, and Section 212K—Western Superior in Minnesota and Wisconsin had 70 percent and 65 percent of the forestland, respectively, in condition class 3. In the Interior West, Sections M334A—Black Hills in South Dakota, M333D—Bitterroot Mountains in Idaho and Montana, and 331J—Northern Rio Grande Basin in New Mexico and Colorado all had approximately 50 percent or more of the forested area classified in condition class 3.

Air Pollution

Air pollution effects on terrestrial ecosystems, such as acid deposition and ozone, are an important environmental issue in the United States. Acid deposition can affect soil and water acidity (Driscoll and others 2001, 2003; MacDonald and others 1992), and ozone can cause foliar injury (Chappelka and Samuelson 1998, Cleveland and Graedel 1979, Lefohn and Pinkerton 1988). Although low dosages of air pollutants can have negligible effects on a forest ecosystem, moderate dosages may result in reduced growth, changes in species composition, and altered insect or disease interactions. High dosages, associated with a major point source, for example, may affect hydrology, nutrient cycling, erosion, and overall ecosystem stability. These impacts can influence forest productivity and genetic diversity, as well as forest habitat (Kareiva and others 1993).

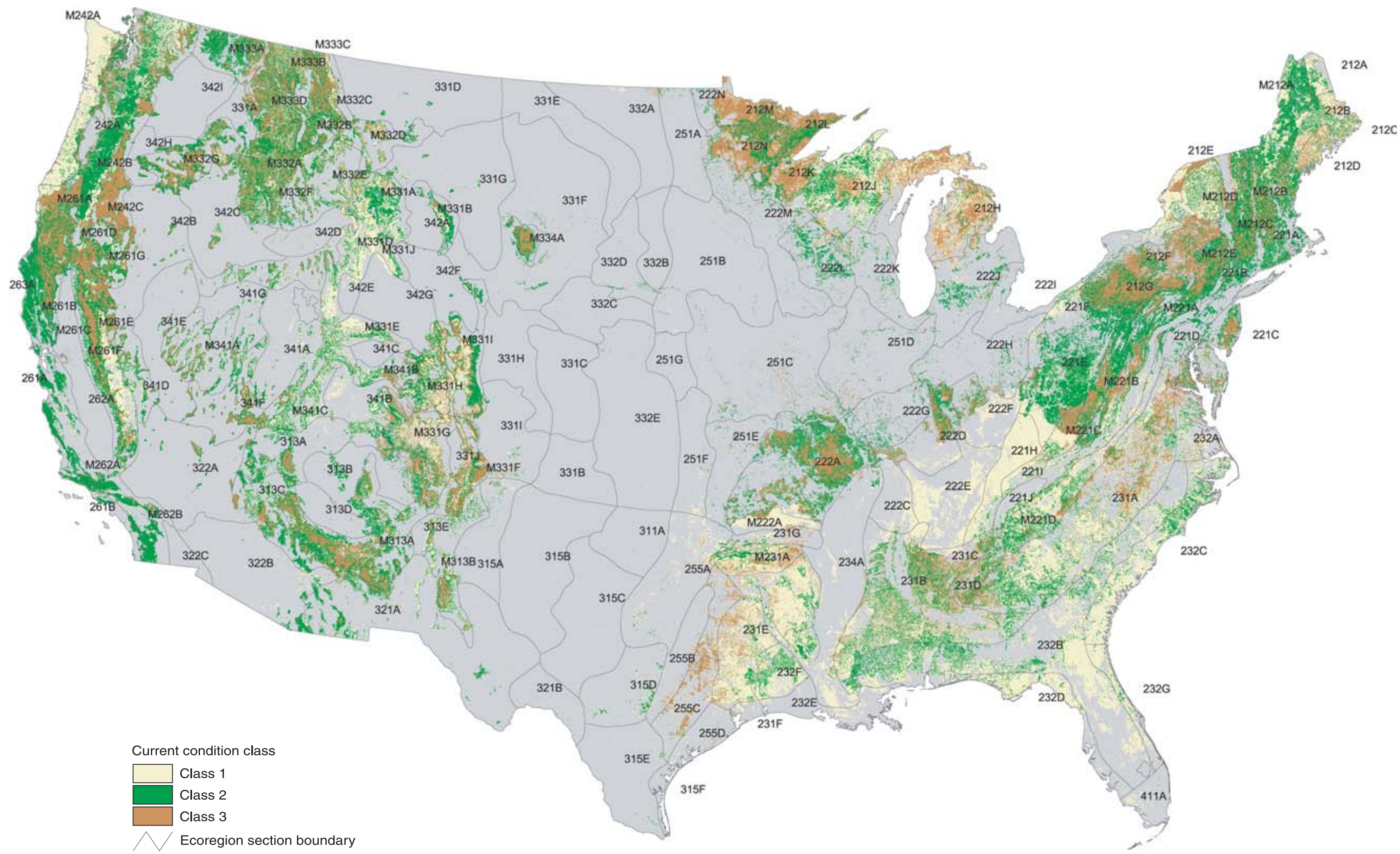


Figure 17—Deviation from ecological conditions compatible with historical fire regimes. (See text for explanation.)

The main pollutants affecting forested ecosystems are sulfur, nitrogen, and tropospheric ozone (Driscoll and others 2001, Hakkarienen 1987). Emissions of gaseous sulfur dioxide and nitrogen oxides are wet deposited as sulfate and nitrate in forested ecosystems by rain, snow, and sleet. Inputs of sulfur and nitrogen also can occur as dry deposition (not discussed in this report), or from cloud/fog drip that is more common in high elevation and coastal areas. Plant uptake of tropospheric ozone occurs during gas exchange. These air pollutants and their effects are an issue across forested landscapes because of long-range transport of contaminated air masses. For example, prevailing west-to-east winds are responsible for pollutants emitted in the Midwest being deposited in New England (Driscoll and others 2001).

Although sulfur inputs from air pollution can lead to the depletion of base cations such as calcium, magnesium, and potassium (Ecological Society of America 1999), base cation depletion and acid cation (i.e., hydrogen and aluminum) release ultimately depend on the soil's ability to neutralize strong acid inputs (Driscoll and others 2001). In most temperate forests, growth is limited by a lack of available nitrogen. However, accumulation of nitrogen in soils and nitrogen saturation are a concern because nitrogen saturation can lead to base cation leaching, decreased plant function, loss of fine root biomass, decreases in symbiotic mycorrhizal fungi, and changes in the plant community (Ecological Society of America 1999, Fenn and others 2003). Tropospheric ozone can impact tree physiology and growth, forest succession, forest species composition, and causes visible injury on some forest tree species (Hakkarienen 1987, Miller and Millecan 1971, Skelly and others 1987, Treshow and Stewart 1973). Although ozone sensitivity varies among tree species, ozone-induced tree stress may also influence forest insect and pathogen activity.

For the purposes of this report we examined wet sulfate and inorganic nitrogen deposition from 1994 through 2001, and ozone-induced foliar injury from 1997 through 2001. Inorganic nitrogen refers to the total amount of nitrogen present as nitrate and ammonium. Ozone-induced foliar injury was based on a biosite index (see "Appendix A: Supplemental Methods, Ozone biomonitoring"). Average values of wet sulfate and nitrate deposition, and biosite index were then calculated for each ecoregion section. Specific thresholds for the biosite index were used (table 4). These thresholds were based on information presented in Smith,[8] Coulston and others (2003), and Smith and others (2003). No thresholds were applicable across ecoregion sections for wet nitrate and sulfate deposition. In this case, we identified ecoregion sections that could be classified as outliers by examining the ecoregion sections that had values exceeding the 95th percentile for each variable. Identifying the outliers provided information about areas that had much higher deposition than the mean deposition. For more information, see "Appendix A: Supplemental Methods, Wet deposition."

Table 4—Ozone biosite index categories, risk assumption, and possible impact

Biosite index	Bioindicator response	Assumption of risk to forest resource	Possible impact
0 to < 5.0	Little or no foliar injury	None	Visible injury to isolated genotypes of sensitive species; e.g. common milkweed, black cherry
5.0 to < 15.0	Light to moderate foliar injury	Low	Visible injury to highly sensitive species, e.g. black cherry; effects noted primarily at the tree level
15.0 to < 25.0	Moderate to severe foliar injury	Moderate	Visible injury to moderately sensitive species, e.g. tulip poplar; effects noted primarily at the tree level
≥ 25	Severe foliar injury	High	Visible injury leading to changes in structure and function of the ecosystem

[8] Smith, G.C. FHM 2nd ozone bioindicator workshop – summary of proceedings. Unpublished manuscript. 12 p. On file with: USDA Forest Service, Forest Health Monitoring Program, P.O. Box 12254, Research Triangle Park, NC 27709.

The spatial trends in wet sulfate and inorganic nitrogen deposition in the United States were similar. The Eastern United States received higher amounts of wet sulfate and inorganic nitrogen deposition than the Western United States during the 1994 through 2001 period (figs. 18 and 19). Average annual wet sulfate deposition amounts exceeded the 95th percentile in nine ecoregion sections. Many of these sections were in Province 221—Eastern Broadleaf Forest (Oceanic), which includes parts of Pennsylvania, Ohio, West Virginia, Virginia, Kentucky, Tennessee, North and South Carolina, and Georgia. The highest average annual wet sulfate deposition rate (23.64 kg/ha/year) was recorded in Section 221E—Southern Unglaciated Allegheny Plateau, located in Pennsylvania, Ohio, Kentucky, and West Virginia, which is part of the Eastern Broadleaf Forest (Oceanic) Province. Other ecoregion sections exceeding the 95th percentile were Section M212E—Catskill Mountains; Section M221B—Allegheny Mountains; Section 212G—Northern Unglaciated Allegheny Plateau in Pennsylvania; and Section 222H—Central Till Plains, Beech-Maple in Indiana and Ohio.

Average wet deposition of inorganic nitrogen also exceeded the 95th percentile in several ecoregion sections in the Eastern United States (fig. 19). This included areas around the Great Lakes. Section 222I—Erie and Ontario Lake Plain, along the coast of Michigan, Ohio, Pennsylvania, and New York, experienced the highest inorganic nitrogen wet deposition levels (6.45 kg/ha/year) during the 1994 through 2001 period. Section M212E—Catskill Mountains; Section 221E—Southern Unglaciated Allegheny Plateau in Pennsylvania, Ohio, West Virginia, and Kentucky; Section 221F—Western Glaciated Allegheny Plateau in New York, Pennsylvania, and Ohio; Section 212G—Northern Unglaciated Allegheny Plateau in Pennsylvania and New York; and Section 222H—Central Till Plains, Beech-Maple exceeded the 95th percentile for both wet inorganic nitrogen and sulfate deposition.

Wet deposition of sulfate and inorganic nitrogen in forested areas was highest in the Northeast from1994 through 2001. Several sensitive populations, such as high-elevation spruce-fir, were found in ecoregion sections identified as outliers in the report. For example,

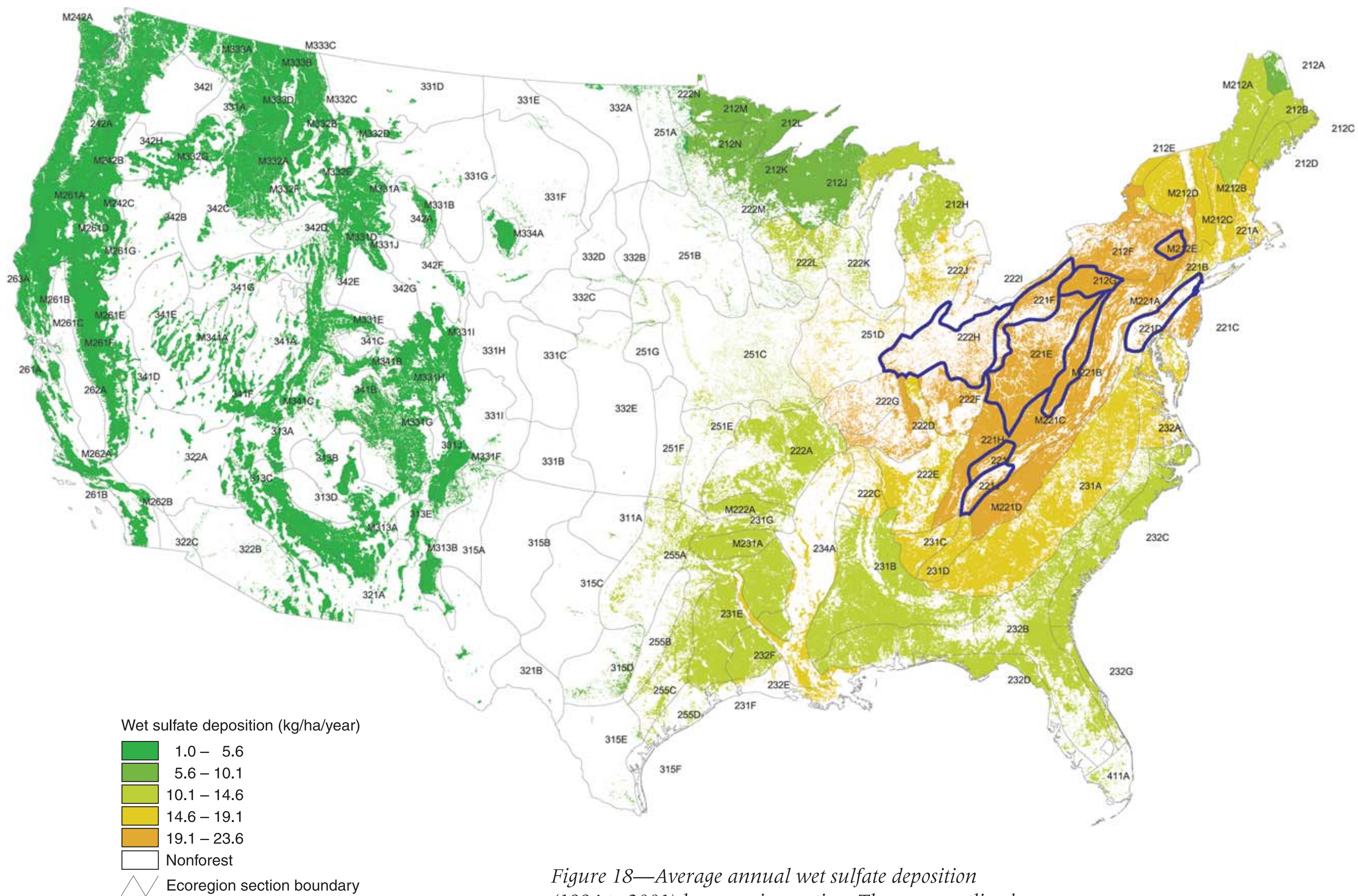


Figure 18—Average annual wet sulfate deposition (1994 to 2001) by ecoregion section. The areas outlined in blue highlight ecoregion sections whose deposition rates exceed the 95th percentile.

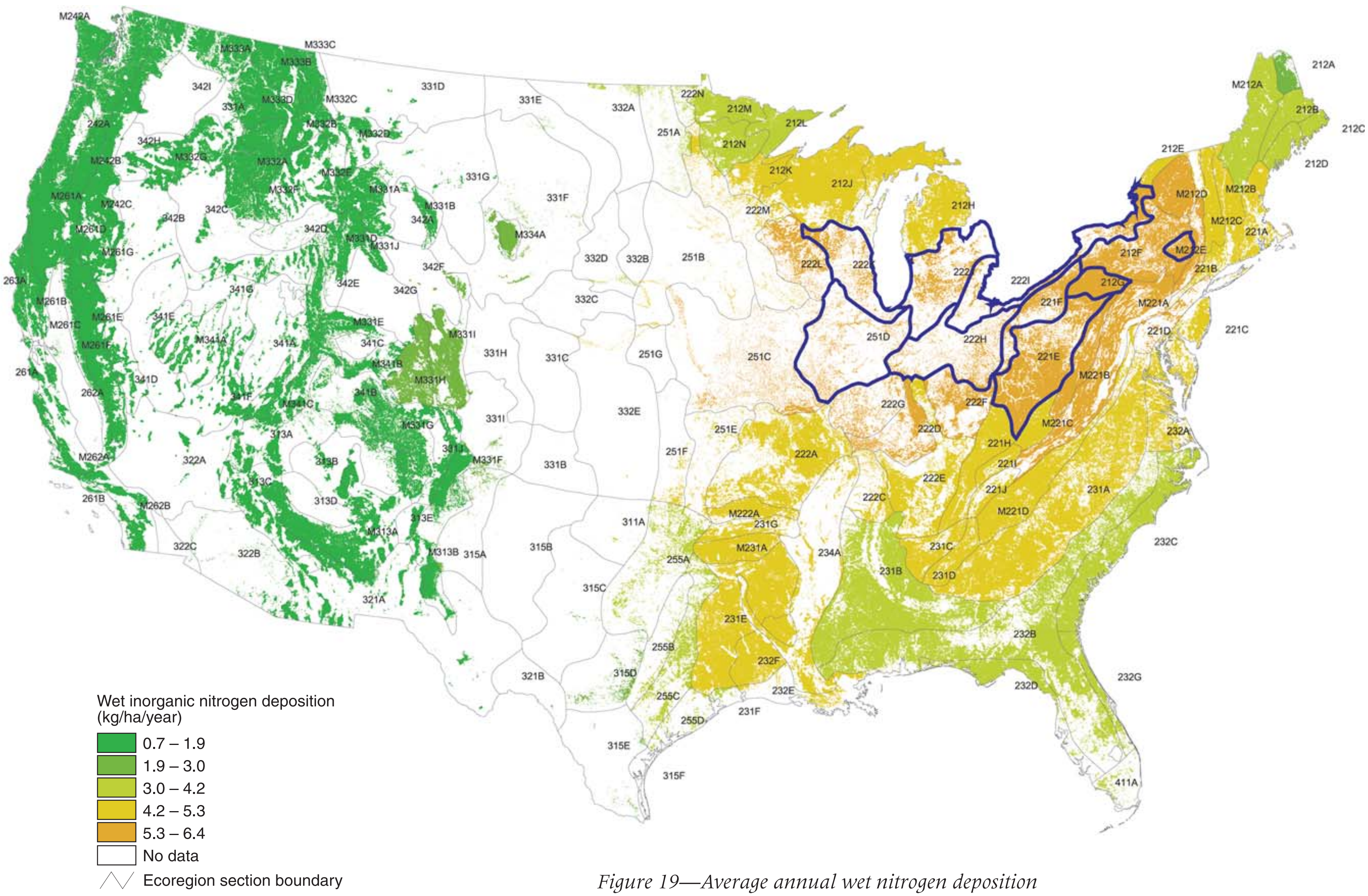


Figure 19—Average annual wet nitrogen deposition (1994 to 2001) by ecoregion section. The areas outlined in blue highlight ecoregion sections whose deposition rates exceed the 95th percentile.

high-elevation spruce-fir is found in both Section M221D—Blue Ridge Mountains and Section M221A—Northern Ridge and Valley. However, wet deposition of sulfate and nitrate to forested areas is decreasing in these areas (Coulston and others 2004). The deposition analysis presented in this report is based on only wet deposition. It does not include dry deposition, which can contribute significantly to the overall input of sulfur and nitrogen. Future analysis will include dry deposition as the information becomes available.

Ozone-induced foliar injury to bioindicator plants also occurred more frequently in the Eastern United States from 1997 through 2001. Section 222G—Central Till Plains, Oak-Hickory in southern Illinois and Indiana had an average biosite index of 25.8 (fig. 20), which fell in the highest risk category (table 4). Sections 232A—Middle Atlantic Coastal Plain, M221B—Allegheny Mountains, and 212G—Northern Unglaciated Allegheny Plateau were all classified in the moderate risk category. Most of the ecoregion sections in the Northcentral and Western United States had an average biosite index < 5 (fig. 20). However, several ecoregion sections in California such as Section M262B—Southern California Mountains and Valleys and Section M261F—Sierra Nevada Foothills, fell in the low risk (5 to 15 ozone biosite index) category (table 4).

Plant injury from ozone was also highest in the Northeast but occurred in many ecoregion sections across the country. Several of the ecoregion sections discussed in this report corresponded with areas determined to have sensitive tree species and relatively high incidence of ozone-induced foliar injury (Coulston and others 2003). They included Section 232A—Middle Atlantic Coastal Plain and Section 212G—Northern Unglaciated Allegheny Plateau in Pennsylvania and New York. While most foliar injury was found in the Northeast, it was also the only area in the country where exposure of forest to tropospheric ozone was decreasing during the 1994 through 2000 period (Coulston and others 2004).

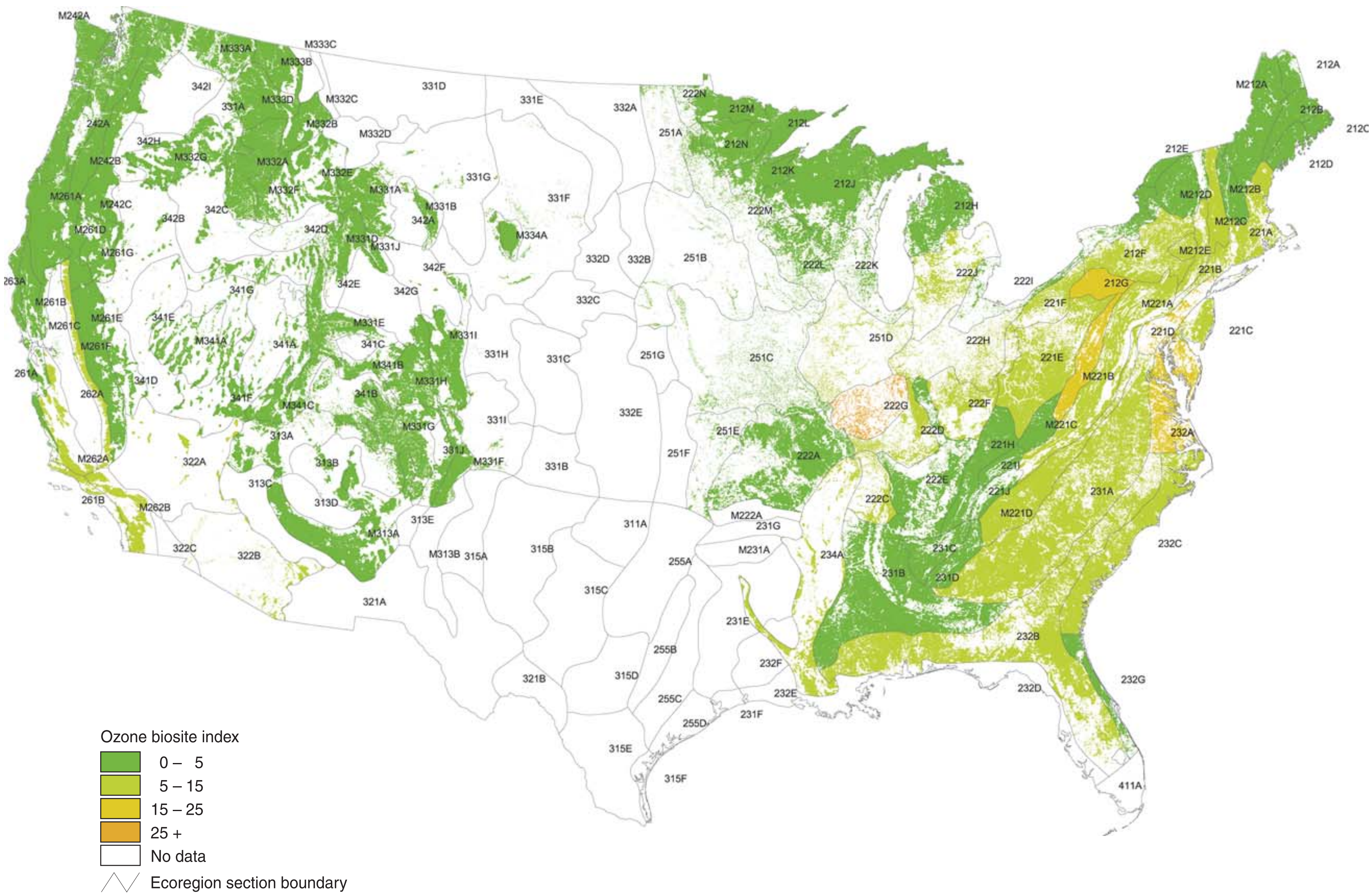


Figure 20—Average annual (1997 to 2001) biosite index by ecoregion section (see table 4 for a description of each category).

Insects and Diseases

Insects and diseases are a natural part of ecosystems and are essential to ecological balance in natural forests (Castello and others 1995). Their populations are influenced by climate, management activities, natural tree defenses, and natural enemies. Insects and diseases influence forest succession, productivity, and stability through complex ecosystem interactions (Berryman 1986). They affect pattern and process of forested landscapes mostly through tree mortality, reduced tree vigor, or both. These effects may occur at small scales (gap phase) or large scales (forest development) and at any seral stage (Castello and others 1995).

National information on insects and diseases is maintained by Forest Service FHP, which produces a yearly forest insect and disease conditions report to convey the current situation. There were several highlights in 2001 (U.S. Department of Agriculture Forest Service 2003b). Several southern pine species were affected by southern pine beetle and fusiform rust. Southern pine beetle affected approximately 50 000 km^2, and fusiform rust was recorded on approximately 56 000 km^2. In the Western United States, the areal extent of both mountain pine beetle and spruce beetle have increased. Dwarf mistletoe (a parasitic plant) was estimated to have infected over 11 000 km^2 of western species such as ponderosa pine, Douglas-fir, lodgepole pine, and true firs.

Nonnative insects and diseases can be serious problems because native tree species do not always have defense mechanisms. In the Eastern United States, hemlock woolly adelgid is a risk to the entire eastern hemlock population. In the North, the areal extent of gypsy moth defoliation increased to approximately 6900 km^2. Beech bark disease is established from Maine to Pennsylvania, and white pine blister rust occurs throughout the ranges of five-needled pines. Butternut canker, a disease of unknown origin, can be found through most of the range of butternut. Sudden oak death is a disease of unknown origin and is currently being studied intensely. More information on sudden oak death research is available at www.na.fs.fed.us/SOD and www.suddenoakdeath.org.

We used the nationally compiled FHP aerial survey data from 1996 to 2001 to assess insect and disease activity at the landscape level.[9] Each agent was classified in the database by FHP as mortality- or defoliation-causing. Spatial-temporal trends (1996 through 2001) in exposure to mortality- and defoliation-causing agents were assessed within each FHM region (see footnote 9). Exposure was defined as the area in hectares with mortality- or defoliation-causing agents present. The spatial-temporal trend analysis was based on relative exposure (observed versus expected) on a base grid hexagon basis and was used to identify hot spots of activity during the time period.

Expected amounts of exposure to insects and diseases were based on a Poisson model (Coulston and Riitters 2003). The measure is referred to as relative exposure and is the ratio of observed to expected exposure. Relative exposure was calculated for mortality- and defoliation-causing agents, and used to identify forested areas within FHM regions that were hot spots when compared to the rest of the region. The possible values calculated ranged from zero to infinity, where < 1 represented low relative exposure and less-than-expected defoliation or mortality within the region. Values > 1 represented more-than-expected exposure to defoliation- or mortality-causing agents within the FHM region of interest. The measure is linear, so a relative exposure value of 2 indicates an area has experienced twice the exposure expected for the region.

[9] Data were from 1996 through 2001 for all FHM regions except the South, where data were from 1998 through 2001.

In the Northeast FHM region, the most intense mortality-causing activity was recorded in parts of Sections M221B—Allegheny Mountains and M221A—Northern Ridge and Valley in West Virginia (fig. 21). The activity in Section M221B—Allegheny Mountains was mostly from high levels of beech bark disease in 1996 and 1997. The most intense defoliation-causing agent activity was in Section M221A—Northern Ridge and Valley where 2001 gypsy moth activity was relatively high (fig. 22). There were also several areas in Section M212C—Green, Taconic, Berkshire Mountains in Vermont and Section 212G—Northern Unglaciated Allegheny Plateau in Pennsylvania with more than double the expected exposure to defoliation-causing agents.

In the South FHM region, southern pine beetle is the predominant mortality-causing agent recorded, and the relative exposure analysis highlights its activity. This is because in the South most aerial surveys only identify southern pine beetle activity; other mortality-causing agents are generally not recorded. More than twice the expected exposure was observed in parts of Section 232B—Coastal Plains and Flatwoods, Lower and Section M221D—Blue Ridge Mountains. Large areas of Provinces 221—Eastern Broadleaf Forest (Oceanic) and 231—Southeastern Mixed Forest were exposed to more than double the expected amount of activity (fig. 21). There were three hot spots of defoliation-causing agent activity. The most intense activity was in Section 232E—Louisiana Coast Prairies and Marshes and the southern extent of the Mississippi Alluvial Basin sections. Portions of Section 232C—Atlantic Coastal Flatlands and Section 232B—Coastal Plains and Flatlands, Lower in North and South Carolina also had over three times the expected exposure rates for the region (fig. 22). These hot spots were mainly a result of the forest tent caterpillar.

In the North Central FHM region, triple the expected exposure rates to mortality-causing insects and diseases were found in areas of Section M334A—Black Hills and scattered areas of the Great Lake States (fig. 21). The areal extent of mortality caused by the mountain pine beetle in Section M334A—Black Hills has been

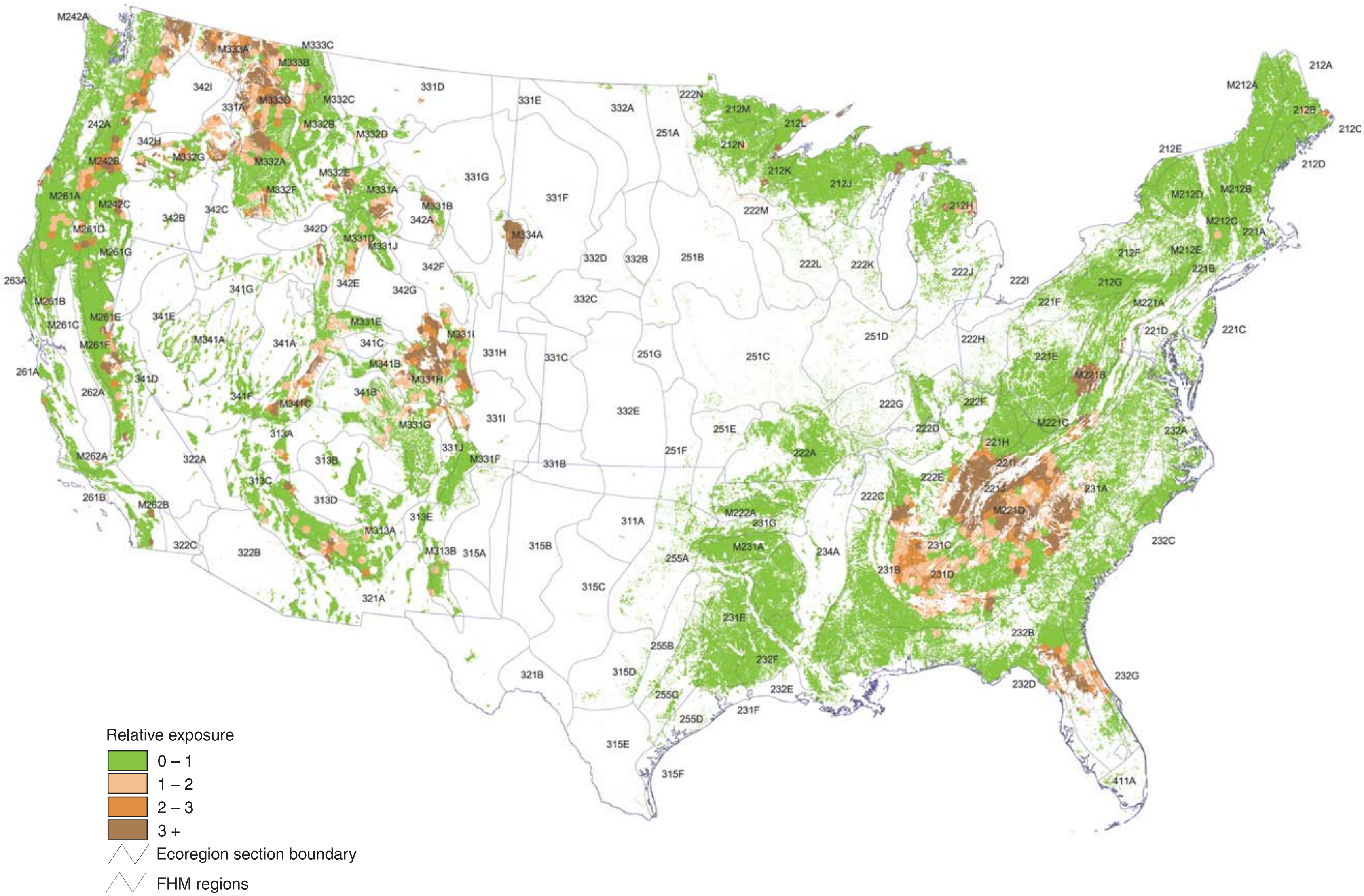


Figure 21—Relative exposure of forests to mortality-causing agents by FHM region from 1996 through 2001. (See text for explanation.)

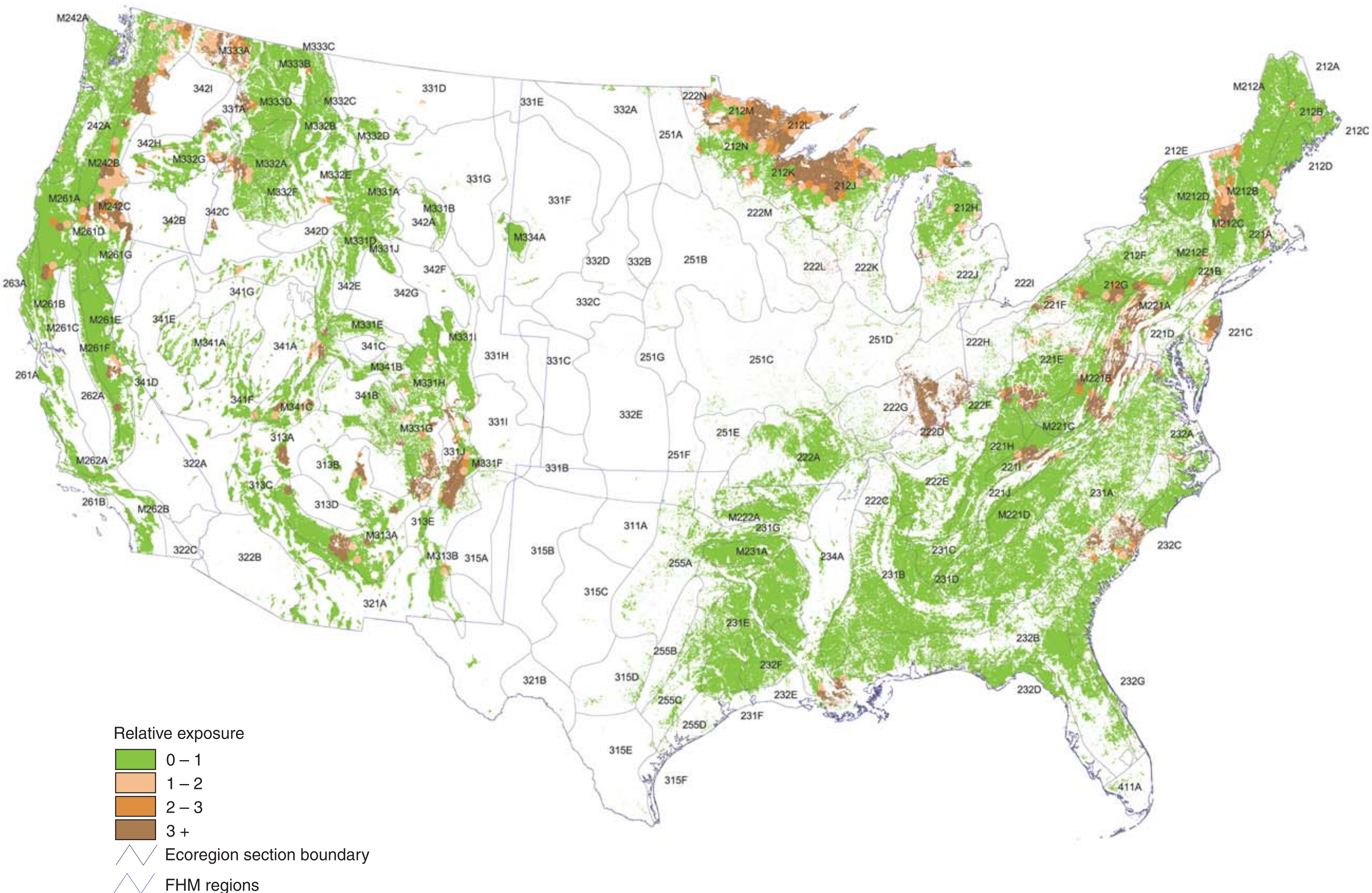


Figure 22—Relative exposure of forests to defoliation-causing agents by FHM region from 1996 through 2001. (See text for explanation.)

increasing since 1996. Within the North Central FHM region, activity of defoliation-causing agents was widespread in the southern extent of Province 222—Eastern Broadleaf Forest (Continental). However, Sections 212L—Northern Superior Uplands and 212M—Northern Minnesota and Ontario also had portions of the forested area with more than triple the expected exposure for the region (fig. 22). Much of the defoliation in ecoregion sections surrounding the Great Lakes was caused by the forest tent caterpillar.

The Interior West FHM region had widespread activity of mortality-causing agents (fig. 21). The most intense activity was found in Section M333D—Bitterroot Mountains in Idaho and Montana, Section M331I—Northern Parks and Ranges in Colorado and Wyoming, and Section M331H—North-Central Highlands and Rocky Mountain in Colorado and Wyoming. In Section M333D—Bitterroot Mountains, the Douglas-fir beetle was responsible for much of the recorded activity. Mountain pine beetle was often recorded in Section M331I—Northern Parks and Ranges. The most intense activity of defoliation-causing agents was in Section M331F—Southern Parks and Rocky Mountain Ranges in Colorado and New Mexico and Section M331G—South-Central Highlands in Colorado and New Mexico where western spruce budworm was often recorded.

In the West Coast FHM region, forested portions of Sections M333A—Okanogan Highlands in northern Washington, and M242C—Eastern Cascades were exposed to more than triple the expected amounts of both mortality- and defoliation-causing insects and diseases (figs. 21 and 22). Mountain pine beetle, Douglas-fir beetle, and western spruce budworm accounted for much of this activity. Section M261E—Sierra Nevada in California also had areas with relatively high amounts of insect and disease activity.

The insect and disease activity analysis was based on cumulative exposure of forested areas to mortality- and defoliation-causing insects and diseases. Many of the areas identified represent current areas of infestation, but others reflect past activity. To examine possible changes in overall ecosystem disturbances, this type of analysis and continuous monitoring is needed. For more details on individual insects and diseases see FHP's annual conditions report (www.fs.fed.us/foresthealth/annual_i_d_conditions/index.html).

Crown Condition

Tree crown condition can serve as an indicator of forest health at the individual tree level, as well as at the forest-stand level. The net primary production of a tree, stand, or forest partially depends on the ability of the tree crown to intercept light (Kimmins 1987). Generally, trees with large, full crowns have the potential to maximize photosynthesis because they are able to capture a large portion of the solar radiation available during the growing season (Stolte 1997). Deteriorating crown condition may reflect a variety of forest stressors, both natural and anthropogenic. Diminished crowns may reflect the impact of serious forest stressors of major concern, such as air pollution, diseases, or insect pests (Skelly and others 1987) as well as more transient stressors, such as periodic drought (Lorenz and others 2001).

FIA measures several variables on phase 3 plots that relate to amount and fullness of foliage and the vigor of the apical growing points of the crown including mortality of terminal twigs in the sun-exposed portions of tree crowns (dieback) and transparency (sparseness) of foliage of the whole tree crown to sunlight. Crown dieback is recorded as the percent mortality of the terminal portion of branches that are > 1-inch diameter and in the upper, sun-exposed portion of the crown (Burkman and others 1995). Foliar transparency is recorded as the percent of sky visible through the live, normally foliated portion of the crown. Both are determined via ocular estimates to the nearest 5 percent.

There are many possible approaches to analyzing crown variables. For this report, basic analysis of crown condition began at the individual tree level. The crown variables were used to classify each tree as having good or poor crown condition. The trees with poor crowns might be diseased, damaged, or otherwise severely stressed.

To evaluate each tree, foliar transparency and crown dieback were combined to produce a composite foliage index for each tree. Using a variation of the method proposed by Zarnoch and others,[10] an index, hereafter referred to as the adjusted ZB-index, is given by the formula (Ambrose 2004):

$$Z_a = [1-(1-\frac{(T-15)}{100})(1-\frac{D}{100})] \qquad T \geq 15$$

$$Z_a = \frac{D}{100} \qquad T < 15$$

where

Z_a = adjusted ZB-index ($0 \leq Z_a \leq 1$)
T = percent foliar transparency ($0 \leq T \leq 100$)
D = percent crown dieback ($0 \leq D \leq 100$)

The adjusted ZB-index, in theory, represents the amount by which the foliage of the tree is reduced relative to an ideal, fully foliated tree having the same crown diameter, live crown ratio, and crown density (other crown variables measured by FIA). For example, a tree with Z_a = 0.25 would have 75 percent of the foliage that the ideal fully foliated tree would have.

Use of Z_a assumes that any transparency up to 15 percent is healthy. Only the amount that the transparency exceeds 15 percent is used as an indicator of poor crown condition (Coulston and others 2005). This is a reasonable assumption because zero transparency has only rarely been recorded for any tree, and most trees surveyed across all species have transparencies of 10 to 20 percent.[11]

Preliminary analyses were performed using several threshold values for the adjusted ZB-index. A threshold value of 0.25 was selected to indicate trees that had poor or unhealthy crowns. This threshold value was selected because (1) it is biologically reasonable (i.e., most people would agree that a tree with either 40 percent transparency or 25 percent dieback usually is unhealthy); and (2) using this threshold does not classify all U.S. forests as having mostly good crown condition, neither does it classify the vast majority of U.S. forests as having poor crowns.

[10] Zarnoch, S.J.; Stolte, K.W.; Binns, R. Chapter 6 – crown condition. In: Lewis, T.E.; Conkling, B.L., eds. Forest health monitoring southeast loblolly/shortleaf pine demonstration project final report. Chapter 6.1–6.51. Unpublished manuscript. On file with: The Forest Health Monitoring Program National Office, 3041 Cornwallis Road, Research Triangle Park, NC 27709.

[11] Under certain limited circumstances, the assumption behind the adjusted ZB-index may not hold true. For example, in extremely arid areas where sparse crowns are a natural adaptation to conserve water, transparency levels much higher than 15 percent may be normal. Using the adjusted ZB-index in such areas may classify trees as having poor crowns when, in fact, they are healthy.

Components of the adjusted ZB-index can also be analyzed independently. Because different species have different crown responses to various environmental stressors, such analyses by species group may enable crown condition to be used as a more direct indicator of changes in tree health. For example, Steinman (2000) found that lower dieback levels were associated with tree mortality in softwoods than in hardwoods. It is known that hardwoods may experience low levels of dieback in response to environmental stressors such as drought. If the stressor abates within a relatively short time, the dieback often ceases and the trees recover. Only if the stress continues and the tree is attacked by secondary stressors (pests or pathogens) do higher dieback levels occur, and mortality usually follows (Skelly and others 1987). However, softwood dieback, as defined and measured by FIA and FHM, is often the direct result of damage or disease that is already severely affecting the tree (Bauer, no date; Skelly and others 1987). Therefore, a softwood tree having ≥10-percent dieback was also considered to have an unhealthy crown, regardless of the overall adjusted ZB-index value. Thus, in this crown analysis, a tree crown was considered to be poor if either (1) the adjusted ZB-index was ≥ 0.25, or (2) the tree was a softwood and had dieback of ≥ 10 percent.

Crowns data were available for time intervals that varied by State. The following tabulation shows the years of FHM and FIA phase 3 plot crown data that were available for this analysis:

Years	States
1990–2001	CT, MA, ME, NH, RI, VT
1991–2001	AL, DE, GA, MD, NJ, VA
1992–2001	CA, CO
1994–1999	MI, MN, WI
1995–2001	WV
1995, 1998–2001	PA
1996–1999	IN
1996–2001	ID
1997–2000	IL
1997–2001	OR, WA, WY
1998–2001	NC, SC
1999	MO
1999–2001	NV, NY, TN, UT
2000–2001	AR, KY, LA
2001	AZ, FL, TX

Data from 1990 to 1999 were collected using the FHM four-panel sampling design with overlap, in which one panel (i.e., one-fourth of the plots) was measured each year and one-third of the panel measured the previous year (overlap) was remeasured (Smith and Conkling 2005). Data from 2000 and 2001 were collected using the FIA five-panel sampling design with no annual overlap (Bechtold and Patterson 2005).

The percentage of basal area represented by trees with crowns in poor condition was calculated for each plot every year that it was surveyed. Then, the average percentage of basal area of trees with poor crowns was estimated for each ecoregion section.

For most of the United States we estimated the average percentage of basal area of trees with poor crowns for each ecoregion section using a generalized least-squares mixed-modeling procedure (Smith and Conkling 2005). This procedure is particularly useful for analyzing data, such as the FHM/FIA data, where not all plots have been measured at the same time intervals (Gregoire and others 1995). With this procedure we could use 2001 and all prior plot measurements to estimate simultaneously the year 2001 status, as well as the periodic annual change in the crown indicator. Periodic annual change is defined as the total change observed from plot establishment to the most recent measurement expressed on an annual basis.

To date, only single measurements have been made on plots in Arizona, Arkansas, Florida, Kentucky, Louisiana, Missouri, and Texas. For ecoregion sections located mostly or entirely in those States, if at least some 2001 data were available, percentage of basal area having poor crown condition was estimated by simply averaging the most recent plot values. It was not possible to estimate change for those ecoregion sections. Change in crown condition also was not estimated for ecoregion sections for which the only available data came from Nevada, New York, Tennessee, and Utah—States where fewer than half of the plots had been remeasured.

From States in the North Central FIA region, the most recent data available for this report were Illinois- 2000 and all other States- 1999.

Because no 2001 data were available, status was not estimated for ecoregion sections in those States unless more recent data were available from some portion of the same ecoregion section in other States.

Because not all plots are measured every year in the rotating panel sampling design, for each plot that was not measured in 2001, the percent basal area having poor crowns was estimated from past measurements of that plot and past and current measurements of other plots using the mixed modeling procedure [for details on the method, see "Forest Health Monitoring 2001 National Technical Report" (Conkling and others 2005)]. Plot values shown in figure 23 are actual values if the plot was measured in 2001; values are estimates for plots not measured in 2001.

The average percent of plot basal area represented by trees classified as having poor crown condition by ecoregion section is shown in figure 23. In most of the ecoregion sections for which estimates could be made, 10 percent or less of the basal area was associated with poor crowns. In the East, areas with the highest percentage of basal area associated with poor crowns were Sections 212A—Aroostook Hills and Lowlands and 212C—Fundy Coastal and Interior in eastern Maine. In the West, the highest percentage of basal area associated with poor crowns was found in Sections M331A—Yellowstone Highlands, M331B—Bighorn Mountains, M331J—Wind River Mountain, 342F—Central Basin and Hills, and 342G—Green River Basin in Wyoming; and Section 313A—Grand Canyon in southwestern Colorado, southern Utah, and northern Arizona.

Annual change in percent of plot basal area represented by trees classified as having poor crown condition is shown in figure 24. Throughout most of the United States, the percent of basal area having poor crowns was remaining constant or decreasing over the period for which data were available. The percent of basal area associated with poor crown condition decreased at the highest rate in Section 212L—Northern Superior Uplands in northeastern Minnesota; Sections 251D—Central Till Plains and 222G—Central Till Plains, Oak-Hickory in Illinois and western Indiana; Section M332F—Challis Volcanics in Idaho;

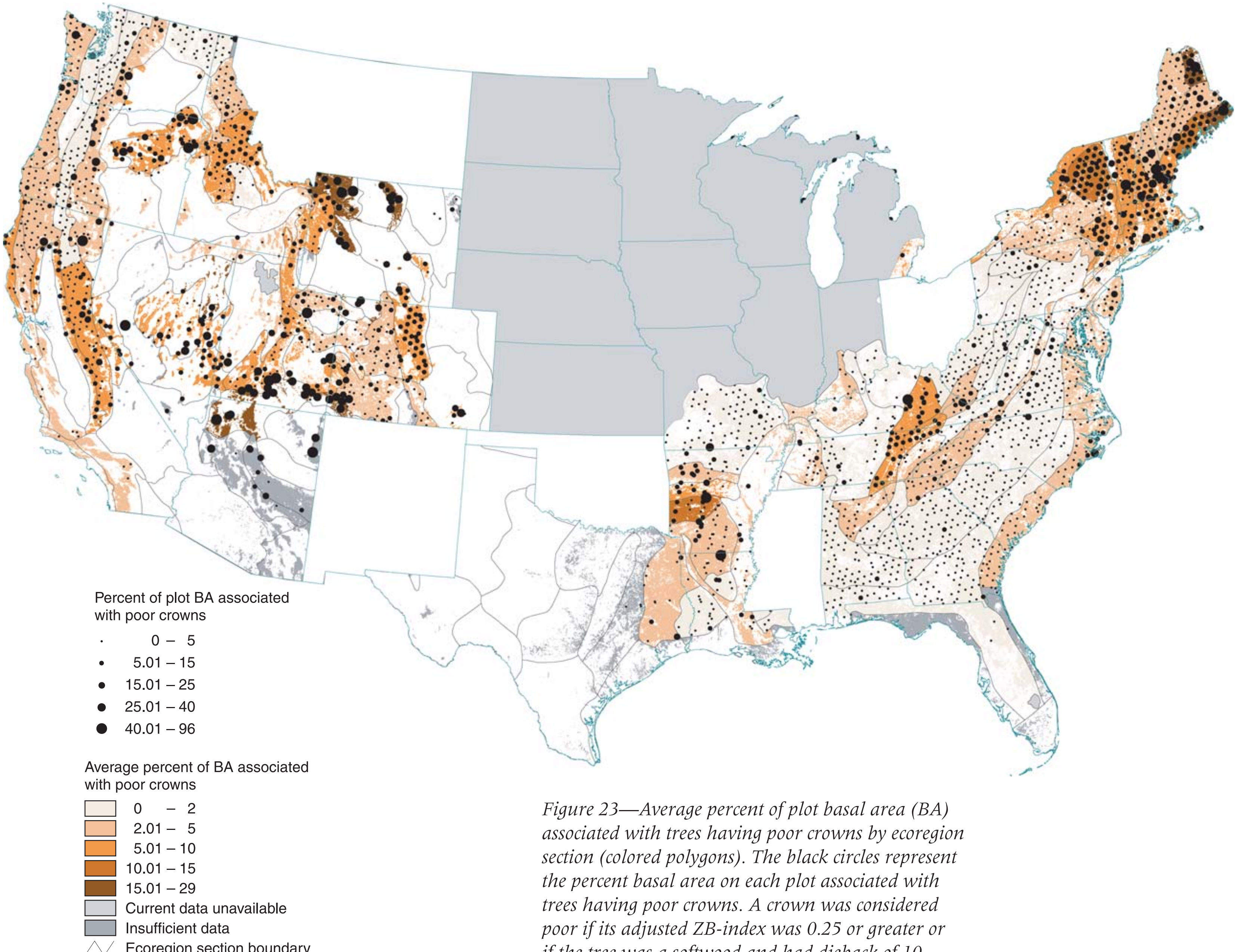


Figure 23—Average percent of plot basal area (BA) associated with trees having poor crowns by ecoregion section (colored polygons). The black circles represent the percent basal area on each plot associated with trees having poor crowns. A crown was considered poor if its adjusted ZB-index was 0.25 or greater or if the tree was a softwood and had dieback of 10 percent or greater. Plot locations are approximate.

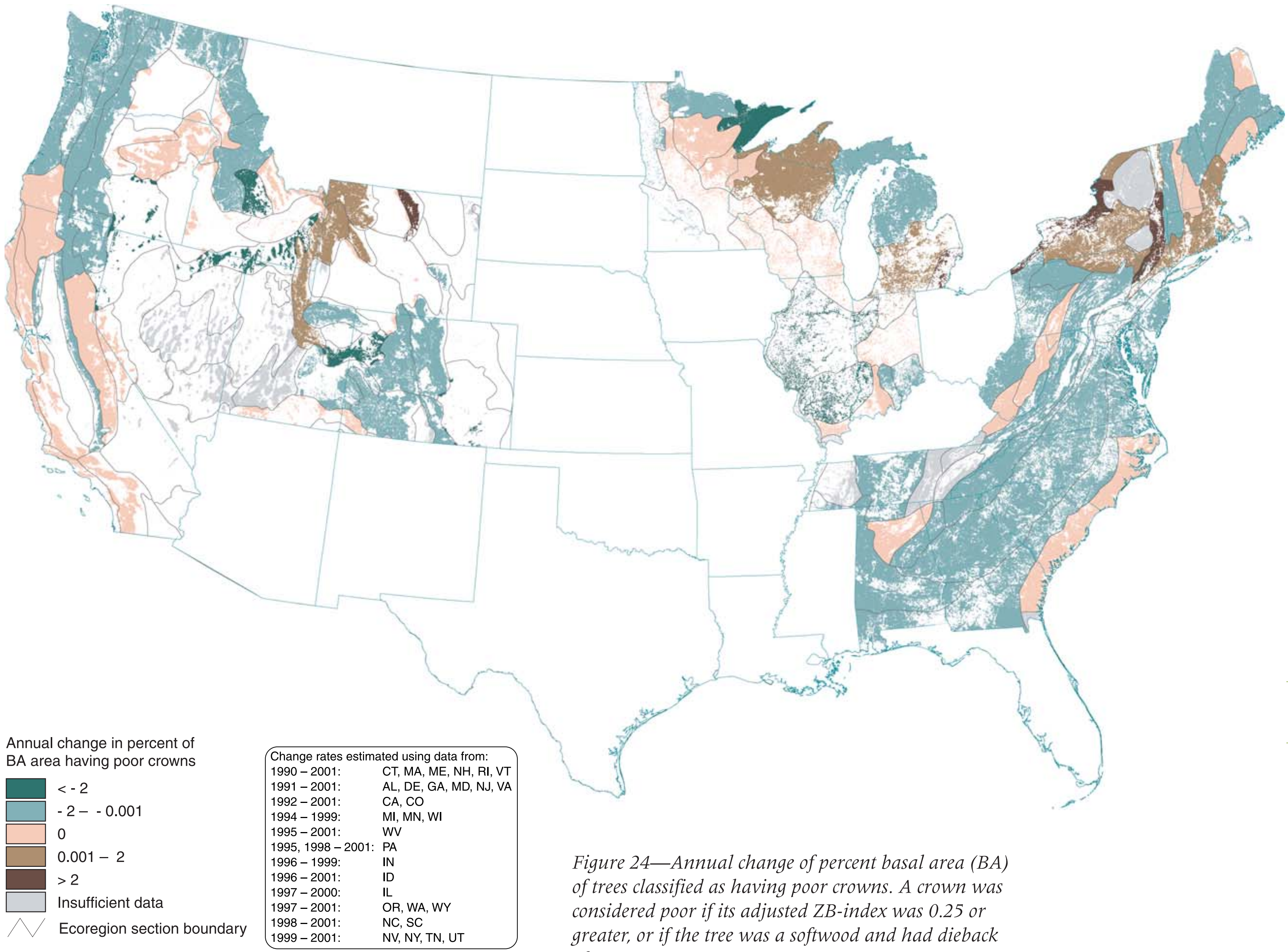


Figure 24—Annual change of percent basal area (BA) of trees classified as having poor crowns. A crown was considered poor if its adjusted ZB-index was 0.25 or greater, or if the tree was a softwood and had dieback of 10 percent or greater.

Section M341B—Tavaputs Plateau in Colorado and Utah; and Section 342B—Northwestern Basin and Range in southern Oregon and Idaho and northern Nevada.

The percent of basal area associated with poor crowns increased at the highest rate in Section 221B—Hudson Valley in eastern New York, New Jersey, and Pennsylvania; Section 222I—Erie and Ontario Lake Plain in New York, Pennsylvania, and Michigan; and Section 342A—Bighorn Basin in northcentral Wyoming.

There are many possible causes for change in crown condition. Crowns may deteriorate as a result of insect attacks or diseases or tree senescence. Crown condition also may change in response to a change in annual rainfall. A decrease in the percent of basal area associated with poor crowns is not necessarily a good or a bad thing. Improved crown conditions may mean that trees are recovering from past stress. Improved plot-level crown condition can also result from highly stressed trees dying, leaving only those trees with healthier crowns. In Section 212L—Northern Superior Uplands, improving crown condition coincides with an area of high mortality (see figure 25). There the improved plot-level crown condition may be due to the death of the trees that had the poorest crowns.

Tree Mortality

FHM estimates annual mortality, in terms of wood volume per acre, based on trees and saplings that have died since plot establishment. However, mortality rates are expected to vary with forest type and climate condition, regardless of the health of the forest. Therefore, mortality rate is not a useful national scale indicator of forest health unless it is adjusted for the variation among forest types and climate regimes. One way to do this is to consider mortality relative to the growth rate of the forest. As a mortality indicator, we calculate the ratio of average annual mortality volume to gross volume growth (MRATIO) (Stolte and others, in press). An MRATIO value greater than 1 indicates that mortality exceeds growth and live standing volume is actually decreasing. MRATIOs were calculated for each ecoregion section from independently derived gross growth and mortality rates. For details on the method, see Stolte and others (in press) and Conkling and others (2005).

The following tabulation shows the years of FHM and FIA phase 3 plot data that were used for this analysis:

Years	States
1990–2001	CT, MA, ME, NH, RI, VT
1991–2001	AL, DE, GA, MD, NJ, VA
1992–1999	CA
1992–2001	CO
1994–1999	MI, MN, WI
1995–2001	WV
1995,1998–2001	PA
1996–1999	IN
1996–2001	ID
1997–2000	IL
1997–2001	OR, WA, WY
1998–2001	NC, SC
1999–2001[12]	NV, NY, TN, UT

Data from 1990 to 1999 were collected using the FHM four-panel sampling design with overlap. Data from 2000 and 2001 were collected using the FIA five-panel sampling design with no annual overlap (Bechtold and Patterson 2005).

MRATIOs were estimated using data from all States in which there were repeated measurements. MRATIO values are reported for all ecoregion sections that are at least partially in States where data were available for a minimum of three remeasured panels. MRATIOs were estimated for the North Central FIA region even though 2000 and 2001 data from most States in that region were not available for this analysis. Because growth and mortality rates over large areas, such as ecoregion sections, change rather slowly unless a catastrophic event occurs, MRATIO values calculated for Northcentral States using only data through 1999 probably are reasonable estimates of current values.

No 2000 and 2001 data from California were used in the mortality analysis because the phase 3 plots there were not colocated with the FHM plots. As with the North Central region, MRATIO estimates using data through 1999 probably are reasonable estimates of current values. However, because the plots were not colocated, MRATIO estimates for ecoregion sections located entirely within California cannot be updated until the FIA phase 3 plots are remeasured, starting in 2006.

The MRATIO can be large if an overmature forest is senescing and losing a cohort of older trees. If forests are not naturally senescing, a high MRATIO (> 0.6) may indicate high

[12] Results not reported for ecoregion sections located entirely within these States, where less than half of the panels had been measured.

mortality due to some acute cause (insects or pathogens) or generally deteriorating forest health conditions. To further analyze tree mortality, the ratio of average dead tree diameter to average live tree diameter (DDLD ratio) was also calculated for each plot where mortality occurred. Low DDLD ratios (much < 1) usually indicate competition-induced mortality typical of young, vigorous stands, while high ratios (much > 1) indicate mortality associated with senescence or some external factors such as insects or disease (Smith and Conkling 2005). The DDLD ratio is most useful for analyzing mortality in regions that also have high MRATIOs. High DDLD values in regions with very low MRATIOs may indicate small areas experiencing high mortality of large trees or locations where the death of a single large tree, such as a remnant pine in a young hardwood stand, produced a deceptively high DDLD.

Figure 25 shows MRATIO values by ecoregion section, representing the annual mortality over the time interval from the earliest plot establishment in each section through the most recent data available for each section, and the plot values of the DDLD ratio for the most recent plot measurement. Throughout most of the country, MRATIO values have changed only slightly from values reported in the "Forest Health Monitoring 2002 National Technical Report" (Coulston and others 2005). This is to be expected because mortality rates change rather slowly in the absence of catastrophic events. Based on this assumption, the MRATIO and DDLD values for the North Central region are included in figure 25, even though the most recent data from most of the region were from 1999, and data from only three remeasured panels were available from Illinois and Indiana. In the North Central region, the highest MRATIO values based on data through 1999 occurred in Sections 212L—Northern Superior Uplands in eastern Minnesota (MRATIO = 0.74); 222D—Interior Low Plateau, Shawnee Hills (MRATIO = 1.05); and 222H—Central Till Plains, Beech-Maple (MRATIO = 0.94) in Indiana and southern Illinois.

MRATIO values were also relatively high (> 0.6) in several western ecoregion sections: M242C—Eastern Cascades in central Washington and Oregon, M333A—Okanogan Highlands in northern Idaho and eastern Washington, M332A—Idaho Batholith in

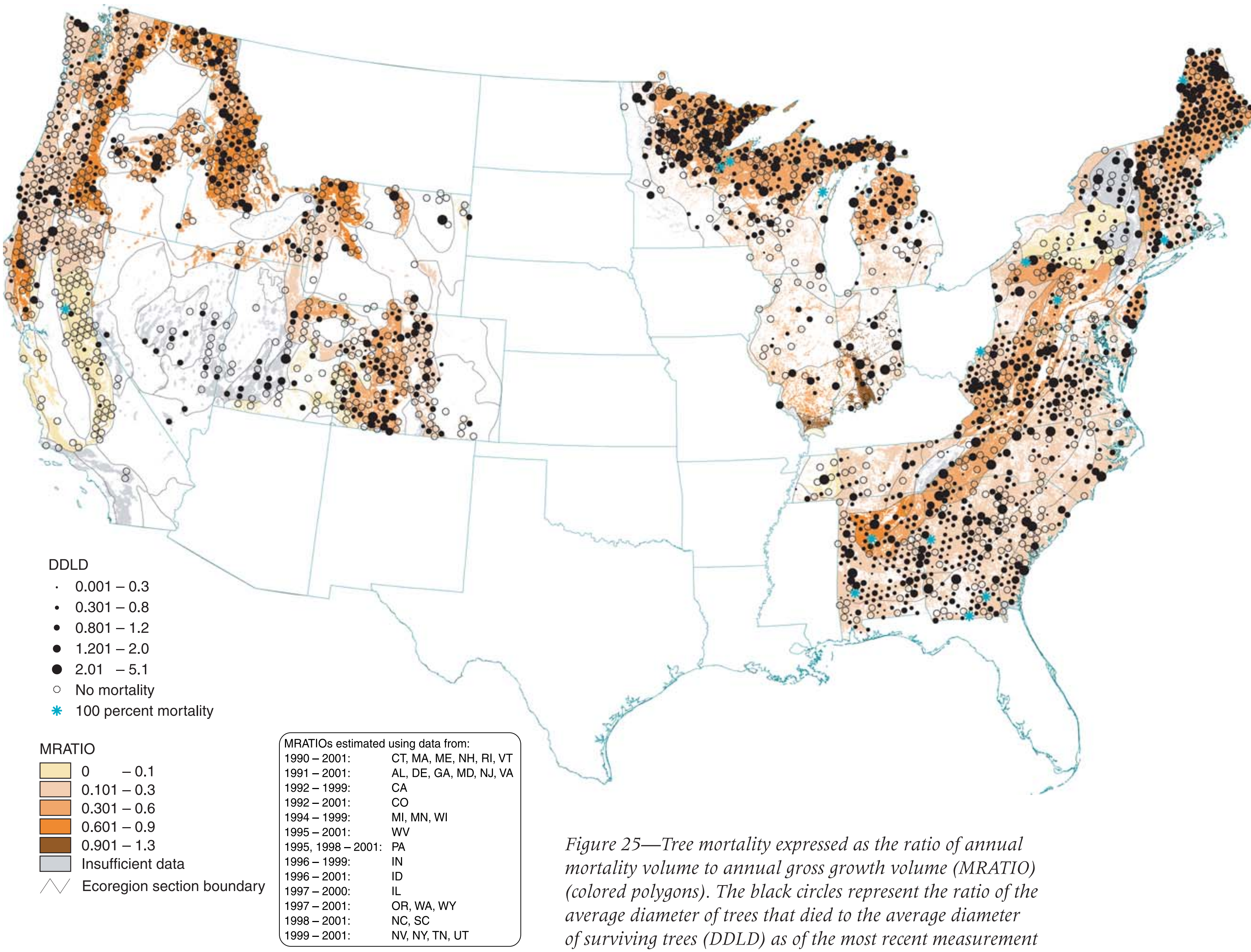


Figure 25—Tree mortality expressed as the ratio of annual mortality volume to annual gross growth volume (MRATIO) (colored polygons). The black circles represent the ratio of the average diameter of trees that died to the average diameter of surviving trees (DDLD) as of the most recent measurement of each plot. Plot locations are approximate.

central Idaho, and Sections M331A—Yellowstone Highlands and M331J—Wind River Mountain in northwestern Wyoming. In these sections many plots suffered no mortality, but of those experiencing mortality, many had high DDLD ratios. Thus, larger trees are dying on those plots, suggesting that stands may be senescing or that pathogens or insects may be a problem. In the South, the MRATIO was also > 0.6 in Section 231C—Southern Cumberland Plateau in northern Alabama and Georgia.

Appendix B provides a summary of mortality statistics by ecoregion section. These statistics provide additional information about what is occurring in a region of interest. The reader should consult this table before drawing any conclusions from the map alone, especially where the period of estimation is short, the sample size is small, and forest growth rates are low.

The standard errors associated with MRATIO estimates vary a great deal among ecoregion sections. The standard errors are affected by a number of factors, including the diversity of the forests within the ecoregion section, the size of the ecoregion section forest growth rates, the number of forested sample plots, and the temporal range of the data. Wherever estimates are made over relatively short time intervals, the standard error associated with both growth and mortality rate estimates will be high, so the standard error on the MRATIO will be high (for information on calculation of the standard error, see "Appendix A: Supplemental Methods, Tree mortality"). Because mortality is a discrete event—while growth is continuous—the deaths of very large, old trees can produce highly variable MRATIO estimates if the sample has an inadequate number of plots or too few years of data.

There will be a relatively high uncertainty associated with the MRATIO estimate for any ecoregion sections where not all panels of plots have been remeasured. There are two reasons for this: (1) the estimate was based on what is effectively a less intense sample (fewer plots per unit area), and (2) the mortality and growth rates from which the MRATIO was calculated were estimated over a short time interval. In such areas, MRATIO estimates may change a great deal from year to year as additional panels are remeasured. These changes generally do not represent genuine recent changes in forest condition between the last two measurement years. Rather, the newer MRATIO estimate should be considered a better characterization of the forest based on an expanded dataset.

Such changes from the results reported in the "Forest Health Monitoring 2002 National Technical Report" (Coulston and others 2005) might be noticed in parts of Washington, Oregon, and Wyoming. For the 2002 report, only three panels of remeasurement data were available from those States. The analysis in the current report included an additional panel of remeasurement data from those States, improving estimates over those in the previous report. MRATIO results presented in the current report also include values for some ecoregion sections where most of the data were from New York, Tennessee, and Utah—States with only two panels of remeasurement data. Future MRATIO estimates for those ecoregions may differ noticeably from those presented here as additional panels of data improve the estimates.

Better estimates of MRATIOs will be possible throughout the United States as more years of data are accumulated. In addition, once FIA phase 2 plots have been remeasured, data from that more intensive sample can be incorporated into the mortality analysis.

Stand Age

Forests change over time; new forest communities successively develop and replace the previous ones. These changes can be dictated either by processes associated with the living community or those associated with the physical environment (Kimmins 1987). One process associated with the living community is aging. The age of a forest stand or individual tree has a direct influence on its productivity and photosynthetic efficiency (Smith and Long 2001). Age also can influence crown condition. Pouttu and Dobbertin (2000) suggest that needle retention is significantly correlated with tree age and that decreased needle retention may be partially due to increased tree age. Old trees may also gradually decline in the upper part of the crown (Niklasson and Zielonka 1999). Stand age can influence susceptibility to declines. For example, Hess and others (2002) found loblolly pine stands declined (sparse crowns, reduced radial growth, deterioration of fine roots) by age 50 on the Oakmulgee Ranger District in

Alabama. They found that this decline was mostly attributable to the onset of littleleaf disease by age 50.

We first calculated the standardized age for each plot and then examined mean standardized age for each ecoregion section. Standardized age was calculated for each plot by forest type using the following equation:

$$A_s = A_{px}/A95_x \text{ for } A_{px} \leq A95_x$$
$$A_s = 1 \text{ for } A_{px} > A95_x$$

where

A_s = standardized age for a plot
A_{px} = stand age of a plot of forest type x
$A95_x$ = 95th percentile of stand age for forest type x

By rescaling stand age to a minimum of 0 and maximum of 1, stand age was comparable across forest types. We then calculated the mean standardized age for each ecoregion section with at least seven plots.

Many of the ecoregion sections in the Southeast and Pacific Northwest were comprised of relatively young forest stands (fig. 26). Section M242A—Oregon and Washington Coast Ranges had a mean standardized age of 0.23. This means that if stands only grew to be 100 years old, then the average age would be 23 years. Several of the ecoregion sections in the Northeast were composed of relatively old forest stands. These included Sections M221A—Northern Ridge and Valley, 221C—Upper Atlantic Coastal Plain, 212G—Northern Unglaciated Allegheny Plateau, M212D—Adirondack Highlands, and M212E—Catskill Mountains. The forest stands in Section 221C—Upper Atlantic Coastal Plain were of note because they had a mean standardized age of 0.72. All the ecoregion sections directly adjacent to the Great Lakes were composed of forest stands with mean standardized ages ranging from 0.56 to 0.59. In the Western United States, there were several ecoregion sections composed of relatively old forest stands. Section M262A—Central California Coast Ranges and Section M332E—Beaverhead Mountains in southwestern Montana and northeastern Idaho had mean standardized age values > 0.70. Forest stands had a mean standardized age of 0.66 and 0.68 in Section M261F—Sierra Nevada Foothills and Section M331E—Uinta Mountains in eastern Utah and northwestern Colorado, respectively.

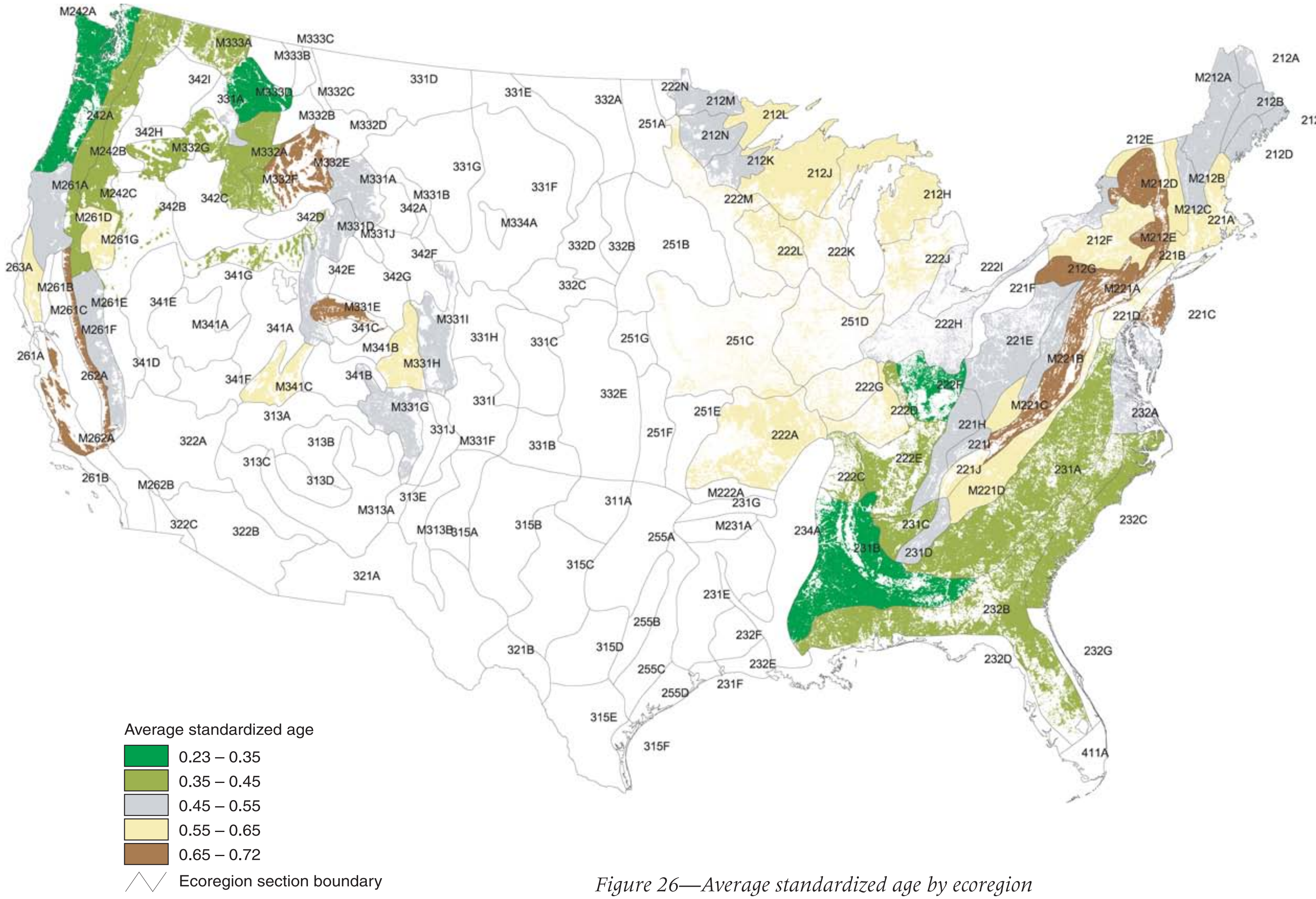


Figure 26—Average standardized age by ecoregion section. For example, if the standardized age is 0.23, this means that if stands only grew to be 100 years old, the average age would be 23 years.

The age of a forest is relative to forest type or sere. It is hypothesized that because the Nation's forests are getting older there may be a decrease in the extent of some forest types and seral stages, because later successional stages will continue to increase at the expense of earlier stages (U.S. Department of Agriculture Forest Service 2001). This has implications on forest health, particularly if persistence of later successional stages is a result of disturbance exclusion. Disturbance often plays a role in succession; and in the absence of one type of disturbance, another type may occur. For example, ecosystem stress caused by fire exclusion can result in increased insect and pathogen activity (Filip 1994).

Soils

Soils integrate aboveground and belowground biological processes. Vegetation is dependent on soils for mechanical support, heat, air, water, and nutrients (Brady 1984). Soils interact with belowground microfaunal and microfloral communities and also can affect water quality. Physical and chemical properties of soils are influenced by several soil-forming factors, e.g., climate, vegetation and soil fauna, relief, parent material, and time (Brady 1984). Forest floor data are presented for FHM plots measured in 1999, and FIA phase 3 plots measured in 2000 and 2001.

The forest floor is an important, biologically active component of a forest ecosystem. It is a rich source of organic matter for microbial populations and soil development. Generally, the forest floor is considered to include all organic matter (litter and decomposing organic layers) present on the mineral soil surface (Fisher and Binkley 2000). Two common measures associated with the forest floor are mass and depth. Much work has been published reporting investigations of relationships between forest floor mass and nutrients, effects of disturbances such as fire and clearcutting, and rates of organic matter decomposition (examples are Gomez and others 2002, Krause 1998, Liechty and others 2002, Martin and others 2002, Stephens and Finney 2002).

In other research, forest floor depth has been related to fuel-loading information used in assessment studies for fire management (Finney and Martin 1993, Harrington 1986). Presence/absence of forest floor also has been shown to influence the effects of soil compaction on nitrogen uptake, and the status and growth of ponderosa pine (Gomez and others 2002). Forests continue to be integral in assessments of carbon sequestration (Birdsey and Lewis 2003), and the forest floor is an important part of the soil component of the carbon pool.

Two measurements associated with the forest floor are presented here: (1) forest floor depth (from the top of the litter layer to mineral soil), and (2) litter depth (from the top of the litter layer to the boundary where plant parts are no longer recognizable due to decomposition). Detailed methods of field data collection are in the 1999 field methods guide (see footnote 2) and the FIA field methods guides used in 2000[13] and 2001 (see footnote 4). The mean forest floor and litter depths by plot were calculated by averaging the measurements on each soil sampling site associated with each subplot (four measurements at each soil sampling site) and then averaging the subplot values (one to three sites per plot).

Figure 27 shows the average forest floor depths by plot using data from 1999 through 2001. Most plots across the United States had a forest floor depth of 1 to 5 cm. Depths of 6 to 10 cm were found on many plots in the Northeast and also in areas scattered throughout the rest of the United States. Relatively thick forest floors were measured in northern Maine, Vermont, and Pennsylvania, along the Blue Ridge Mountain area, the northern North Central region, and western Washington and Oregon. Forest floor depths of < 1 cm were found in scattered areas in the North Central region and in western States such as Colorado, Utah, and Nevada. Because forest floor depth is influenced by factors such as forest type and climate, depths found in one part of the country may be considered normal, whereas the same depths might be unusual in another.

Average plot litter depths are shown in figure 28. Because litter depth is measured from the top of the forest floor to the boundary where plant parts no longer are distinguishable, the litter depths are less than the forest floor depths. Most plots had litter depths from 1 to 4 cm. Comparing figure 27 and figure 28 provides an indication of the depth of forest floor layers that are not well-decomposed (litter) and the more decomposed material underneath.

[13] U.S. Department of Agriculture Forest Service. 2000. Forest inventory and analysis national core field guide. Vol. 2. Field data collection procedures for phase 3 plots. Version 1.4. Internal report. [Number of pages unknown]. On file with: U.S. Department of Agriculture Forest Service, Forest Inventory and Analysis, Rosslyn Plaza, 1620 N. Kent St., Arlington, VA 22209.

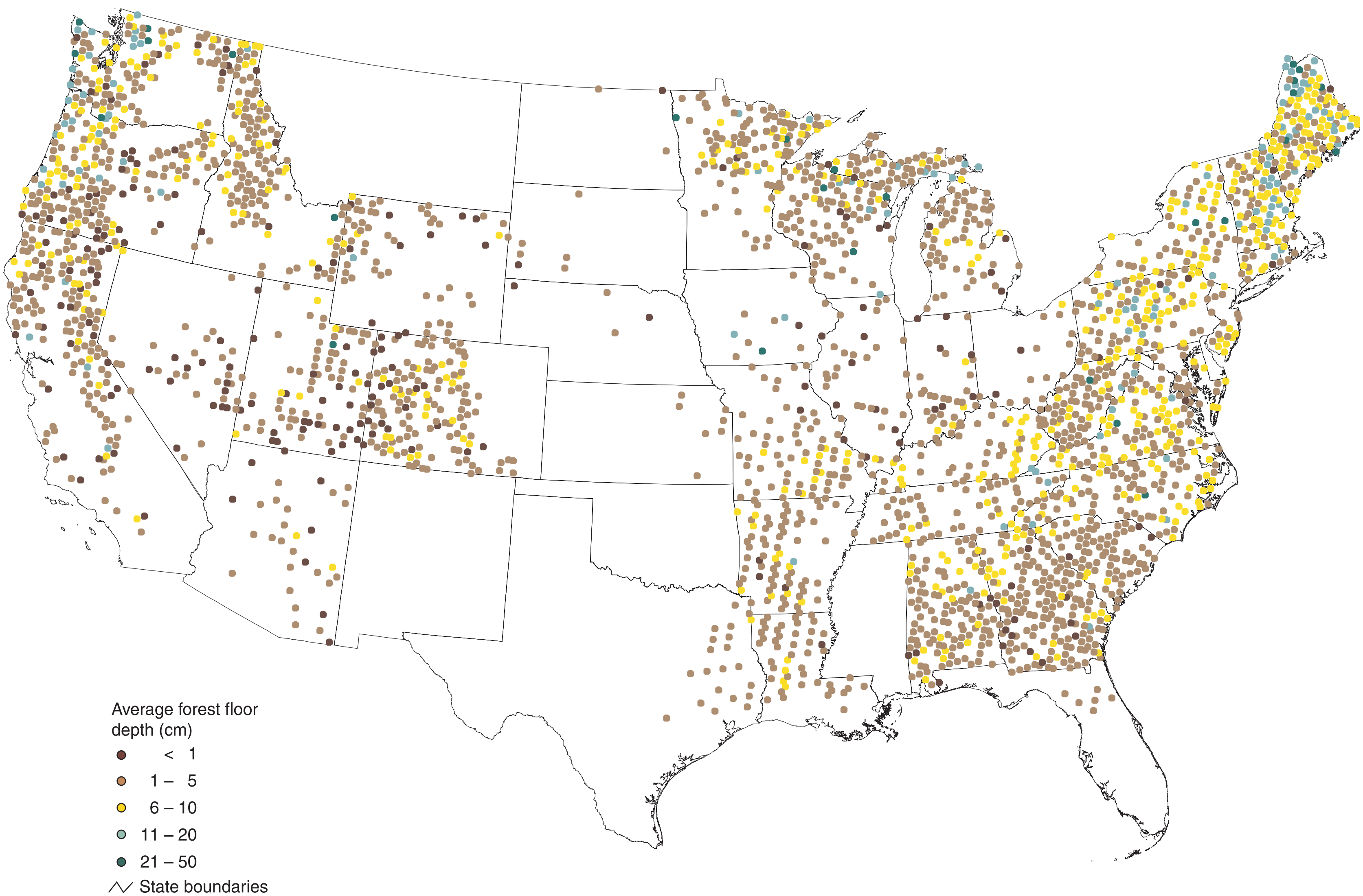


Figure 27—Average forest floor depth (cm) by plot for 1999, 2000, and 2001. Plot locations are approximate.

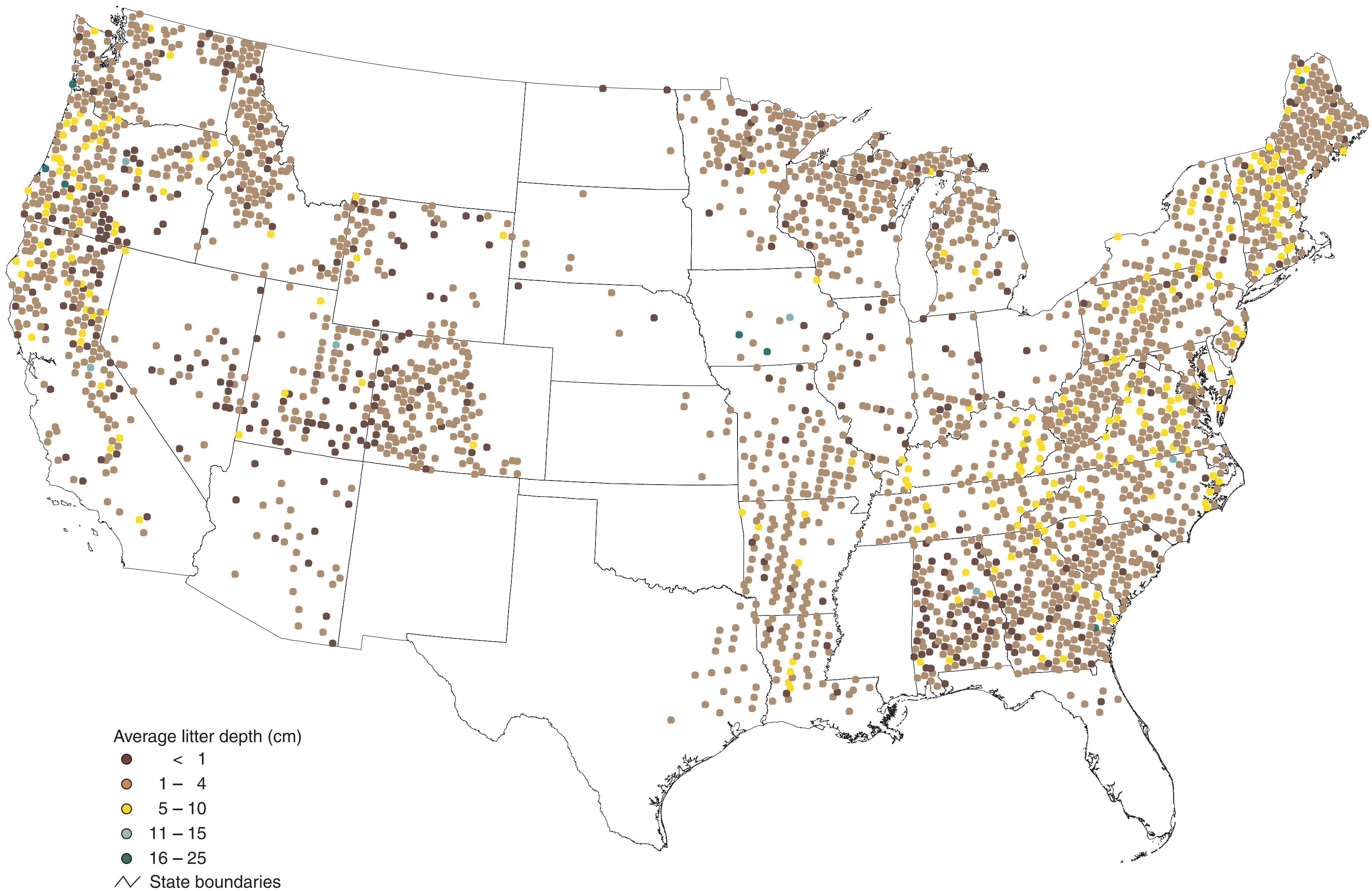


Figure 28—Average litter depth (cm) by plot for 1999, 2000, and 2001. Plot locations are approximate.

Integrated Look at Forest Health Indicators

Crown condition is an important indicator of forest health at the tree, stand, and forest levels. The net primary production of a tree, stand, or forest partially depends on the ability of the tree crown to intercept light (Kimmins 1987). Forests with sparse foliage have a lower photosynthetic efficiency, and less energy enters the ecosystem. This has implications on forest productivity and forest health. Natural and anthropogenic disturbances, as well as edaphic factors such as site quality influence crown condition (Ferretti 1998). Interactions are important because all of those factors act on tree crowns simultaneously (Godbold 1998). Also, some factors have a larger influence than others. This section integrates information about the individual indicators and examines potential relationships with tree crown condition.

Several indicators might be used to differentiate between good and poor crown conditions. Those indicators fall into two categories: hexagon-level and plot-level indicators (tables 5 and 6). Plot-level indicators are based on measurements taken on the plot to describe its conditions. Hexagon-level indicators are based on data summaries for the hexagon surrounding the plot, and they describe the physical context within which the plots are established. Our objective is to determine if there are any variables, or linear combinations of variables, that discriminate between plots that had trees with poor crown condition and those that did not.

Methods

We compared populations of plots containing trees with poor crown condition to plots that did not have trees with poor crown condition. This comparison was based on the difference in mean vectors from the two populations (see Johnson and Wichern 2002). A mean vector is a collection of mean values from several observed variables in a population. For example, if there are *n* variables, then

$$\bar{x} = \begin{bmatrix} \bar{x}_1 \\ \bar{x}_2 \\ \cdot \\ \cdot \\ \bar{x}_n \end{bmatrix}$$

is the mean vector for a population, and each element of the vector is the mean for one variable.

The two populations were defined as (1) plots that contained trees with poor crown condition and (2) plots that did not. We considered a plot to have trees with poor crown condition if one or more trees had an adjusted ZB-index > 0.25.

Table 5—Indicators or variables used in the integrated analysis

Indicator	Abbreviation	Tree mortality	Site quality	Stand age	Air pollution	Drought	Fire	Insects and pathogens	Landscape structure
DDLD ratio	DDLD	p							
Forest floor depth	FFD		p						
Litter depth	LD		p						
Standardized age	Age			p					
Ozone biosite index	BI				h				
Sulfate deposition	SO4				h				
Total nitrogen deposition	Nt				h				
Percent anthropogenic edge	PEdge								h
Percent core forest	PCore								h
Percent dominant forest	PDom								h
Percent forest	PFor								h
Percent interior forest	PInt								h
Percent land within 127 m of a road	RD127								h
Percent land within 1740 m of a road	RD1740								h
Percent fire condition class 1	PCC1						h		
Percent fire condition class 2	PCC2						h		
Percent fire condition class 3	PCC3						h		
Relative exposure to defoliation-causing insects and pathogens	DefolRE							h	
Relative exposure to mortality-causing insects and pathogens	MortRE							h	
Drought deviation	DD					h			

p = a plot-level indicator; based on measurements that were taken on the plot to describe its conditions; h = a hexagon-level indicator; based on data summaries for the hexagon and describes the context of the plot.

Table 6—Quick reference of definitions of variables used in the integrated analysis

Variable or indicator	Definition
DDLD ratio	Ratio of the average dead tree diameter to the average live tree diameter
Forest floor depth	Thickness from the top of the litter layer to the boundary between the mineral soil and the forest floor
Litter depth	Thickness from the top of the litter layer to the boundary where plant parts are no longer recognizable as such because of decomposition
Standardized age	Scaled so that stand age is comparable across forest types
Ozone biosite index	Calculated as a function of the number of species evaluated, the number of plants of each species evaluated, the proportion of injured leaves on each plant evaluated, and the average severity of injury on each plant evaluated
Sulfate deposition	Wet sulfate deposition
Total nitrogen deposition	Total amount of nitrogen present in nitrate and ammonium (wet deposition)
Percent anthropogenic edge	Percent of forest-anthropogenic edge—forest-nonforest edge with either urban or agriculture landcover types
Percent core forest	Percent of forest pixels surrounded by evaluation window (regardless of size) that is 100 percent forested
Percent dominant forest	Percent of forest pixels surrounded by evaluation window (regardless of size) that is at least 60 percent forested
Percent forest	Percent of hexagon that has forestland cover
Percent interior forest	Percent of forest pixels surrounded by evaluation window (regardless of size) that is at least 90 percent forested
Percent land within 127 m of a road	Percent forestland within 127 m of a road
Percent land within 1740 m of a road	Percent forestland within 1740 m of a road
Percent fire condition class 1	Percent forestland in fire condition class 1, which represents a minor deviation from ecological conditions compatible with historic fire regimes
Percent fire condition class 2	Percent forestland in fire condition class 2, which represents a moderate deviation from ecological conditions compatible with historic fire regimes
Percent fire condition class 3	Percent forestland in fire condition class 3, which represents a major deviation from ecological conditions compatible with historic fire regimes
Relative exposure to defoliation-causing insects and diseases	Ratio of observed to expected exposure to defoliation-causing insects and diseases
Relative exposure to mortality-causing insects and diseases	Ratio of observed to expected exposure to mortality-causing insects and diseases
Drought deviation	Months of drought recorded in the current 20-year period minus the historic reference months of drought expected on a 20-year basis

The mean vector for each population was a set of variables with correlation coefficients < 0.4 selected from table 5. We used Hotelling's T^2 statistic to test if the difference between the mean vectors from the two populations was zero and Bonferroni simultaneous confidence intervals to determine if there were single variables that were significantly different between populations. When the simultaneous confidence interval for the difference between a mean variable from the two populations does not include zero, then there is a significant difference for that variable. We also identified the linear combination of variables that established the greatest difference between mean vectors (see "Appendix A: Supplemental Methods, Integrated look at forest health indicators" for details on the statistical methods).

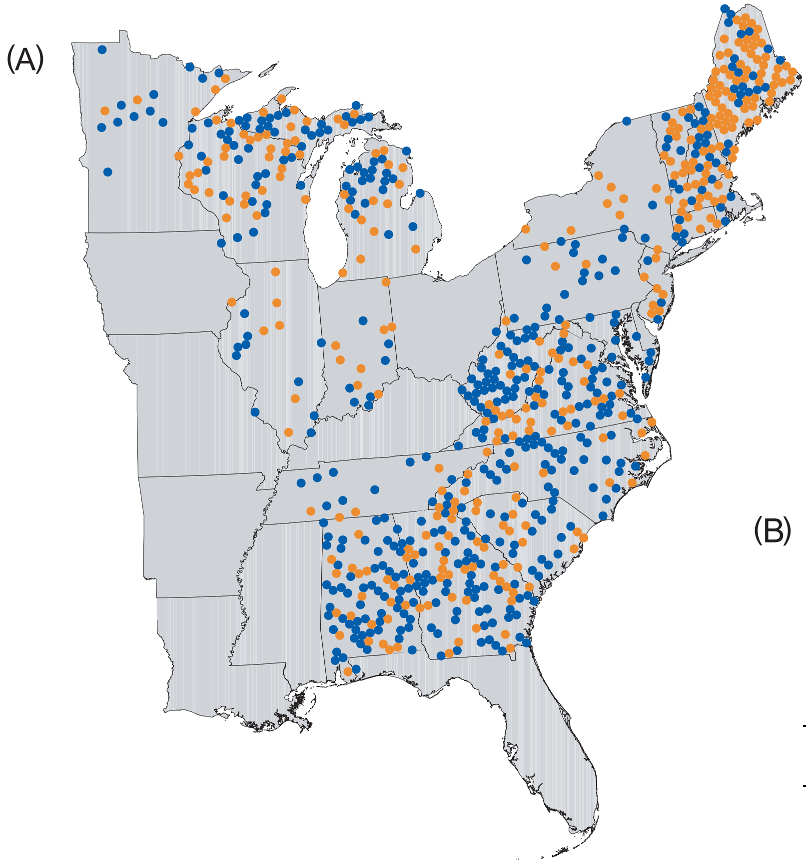
The adjusted ZB-index was used to identify plots in the two populations (see section "Crown Condition" for a description of the index). Using the adjusted ZB-index data presented in the "Forest Health Monitoring 2002 National Technical Report" (Coulston and others 2005), we considered a plot to have trees with poor crown condition if one or more trees had an adjusted ZB-index > 0.25. This threshold approach makes sense because as Ambrose (2004) points out, either a crown transparency score > 40 percent or dieback > 25 percent is unhealthy.

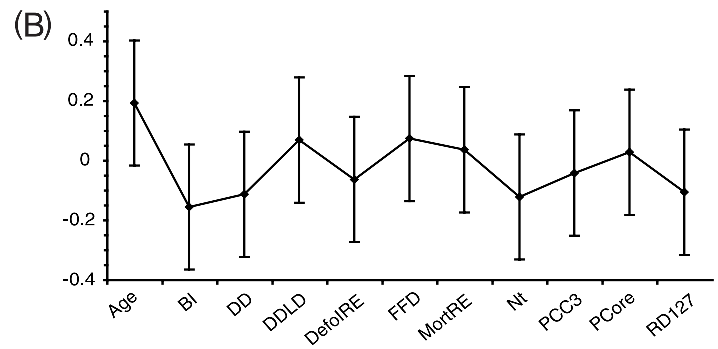
Each variable in table 5 was first standardized to mean zero and variance one. This put all variables on the same statistical scale and allowed for comparisons across variables and between populations. The correlation between each standardized variable was then calculated, and variables with a correlation ≥ 0.4 were excluded from the analysis. We calculated the T^2 statistic, Bonferroni simultaneous confidence intervals, and the linear combination describing the largest difference between populations.

A separate analysis was conducted for each of the following strata: all eastern forest types, the loblolly pine forest type, all western forest types, and the Douglas-fir forest type. They were selected because they are known to be of interest and because a relatively large sample size is desirable for the analysis. The purpose of this analysis was descriptive, and we were most interested in the linear combination of variables responsible for the largest difference between populations. As a result, the analysis does not determine cause and effect relationships.

Results

Eastern forest types—There were 315 plots identified in eastern forest types that had trees with poor crown condition and 441 plots that did not (fig. 29A). We examined differences among these plots using 11 variables: (1) DDLD ratio, (2) forest floor depth, (3) standardized age, (4) ozone biosite index, (5) total wet nitrogen deposition, (6) percent core forest, (7) percent forest within 127 m of a road, (8) percent forest in fire condition class 3, (9 and 10) relative exposure to both mortality- and defoliation-causing insects and diseases, and (11) drought deviation. The two mean vectors differed significantly ($\alpha = 0.05$), but there was no variable whose simultaneous confidence interval did not contain zero (fig. 29B). This means that no single variable was significantly different between the two multivariate populations. The linear combination responsible for the largest difference was most heavily weighted by standardized age, indicating that the plots with unhealthy tree crowns, as defined in this report, tended to occur in older stands (fig. 29C). Total wet nitrogen deposition and drought deviation also had relatively high weights but were in the negative direction. This means that plots with





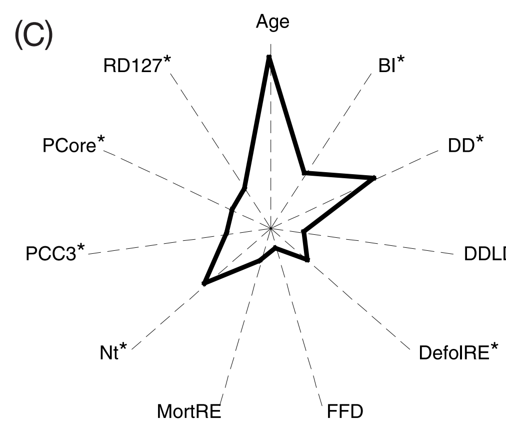


Figure 29—(A) The geographic distribution of plots in eastern forest types that had trees with poor crown condition (denoted with orange dots) and those that did not (denoted with blue dots). Plot locations are approximate. (B) The difference between mean vectors and 95 percent Bonferroni simultaneous confidence intervals. (C) The linear combination of variables responsible for the largest difference between mean vectors. This figure only shows the magnitude of the weights. Variables with negative weights are denoted by an asterisk. Definitions of variables: Age—standardized age; BI—ozone biosite index; DD—drought deviation; DDLD—DDLD ratio, ratio of the average dead tree diameter to the average live tree diameter; DefoIRE—relative exposure to defoliation-causing insects and pathogens; FFD—forest floor depth; MortRE—relative exposure to mortality-causing insects and pathogens; Nt—total nitrogen deposition; PCC3—percent fire condition class 3; PCore—percent core forest; and RD127—percent land within 127 m of a road. More information about these indicators is presented in tables 5 and 6.

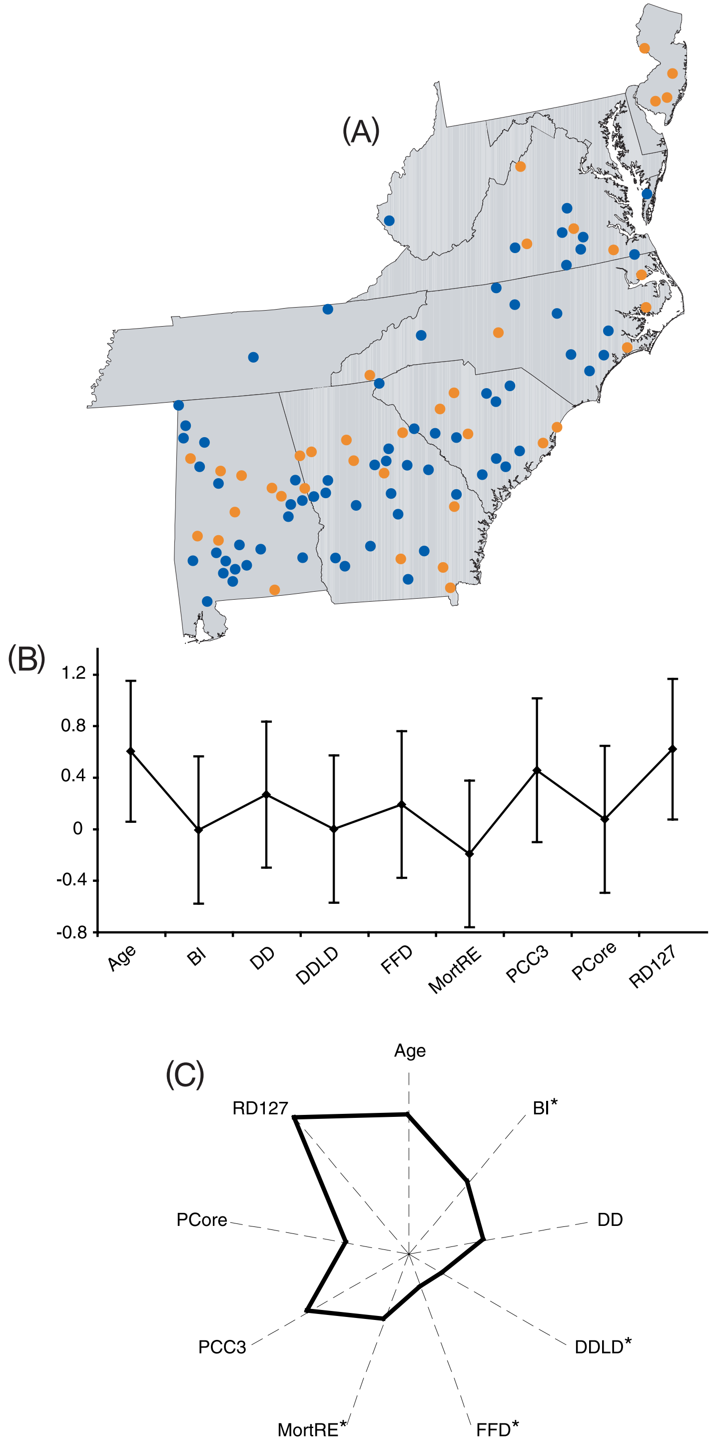


Figure 30—(A) The geographic distribution of plots in the loblolly/shortleaf pine forest type that had trees with poor crown condition (denoted with orange dots) and those that did not (denoted with blue dots). Plot locations are approximate. (B) The difference between mean vectors and 95 percent Bonferroni simultaneous confidence intervals. (C) The linear combination of variables responsible for the largest difference between mean vectors. This figure only shows the magnitude of the weights. Variables with negative weights are denoted by an asterisk. Definitions of variables: Age—standardized age; BI—ozone biosite index; DD—drought deviation; DDLD—DDLD ratio, ratio of the average dead tree diameter to the average live tree diameter; FFD—forest floor depth; MortRE—relative exposure to mortality-causing insects and pathogens; PCC3—percent fire condition class 3; PCore—percent core forest; and RD127—percent land within 127 m of a road. More information about these indicators is presented in tables 5 and 6.

trees that had poor crown condition, as defined in this report, tended to occur in areas with fewer droughts and less nitrogen deposition.

We then selected the loblolly/shortleaf pine forest type for further examination. Thirty-nine out of one hundred and seven plots had trees with poor crown condition (fig. 30A). The analysis for this forest type was based on nine variables. They were: (1) DDLD ratio, (2) forest floor depth, (3) standardized age, (4) ozone biosite index, (5) percent core forest, (6) percent forest within 127 m of a road, (7) percent forest in fire condition class 3, (8) relative exposure to mortality-causing insects and diseases, and (9) drought deviation. The two mean vectors differed significantly ($\alpha = 0.05$), and the simultaneous confidence intervals for both standardized age and percent forest within 127 m of a road did not include zero (fig. 30B). These two variables also had the greatest weight in the linear combination responsible for the largest difference between vectors (fig. 30C). The proportion of forest in fire condition class 3 also had a relatively high weight when discriminating between plots that had trees with poor crown conditions and those that did not. This means that plots with trees that had poor crown condition, as defined in this report, tended to occur in older forest stands, with a higher proportion of land within 127 m of a road, and to a lesser extent in hexagons with a higher proportion of forest classified in fire condition class 3.

Western forest types—Approximately half of the 378 plots located in western forest types were classified as having trees with poor crown condition (fig. 31A). The following variables were used: DDLD ratio, forest floor depth, standardized age, total wet nitrogen deposition, percent anthropogenic edge, percent core forest, percent forest within 127 m of a road, percent forest in fire condition class 3, relative exposure to both mortality- and defoliation-causing insects and diseases, and drought deviation. There was no statistical difference between the two mean vectors ($p = 0.8$), and all simultaneous confidence intervals included zero (fig. 31B). Even though there was no statistical difference between mean vectors, the linear combination that produced the greatest separation between them was examined. It was most heavily weighted by standardized age and relative exposure to mortality-causing insects and diseases. The DDLD ratio also had a relatively high weight (fig. 31C).

The Douglas-fir forest type was then selected for further examination. There were 40 plots that had trees with poor crown conditions and 60 plots that did not (fig. 32A). We examined differences between these plots using eight variables: (1) DDLD ratio, (2) forest floor depth, (3) standardized age, (4) total wet nitrogen deposition, (5) percent anthropogenic edge, (6) percent core forest, (7) percent forest in fire condition class 3, and (8) relative exposure to mortality-causing insects and diseases. There was only weak evidence ($p = 0.186$) that the two mean vectors differed significantly, and the simultaneous confidence intervals all contained zero (fig. 32B). Standardized age and percent forest in fire condition class 3 had the greatest weights in the linear combination responsible for the largest difference between vectors (fig. 32C). This means that plots with trees that had poor crown condition, as defined in this report,

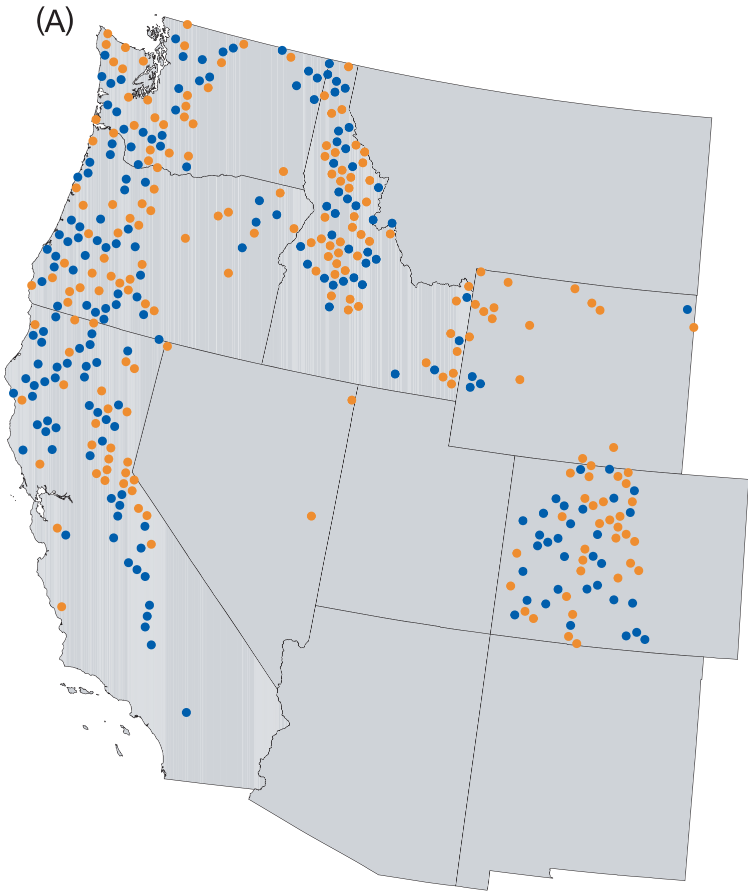
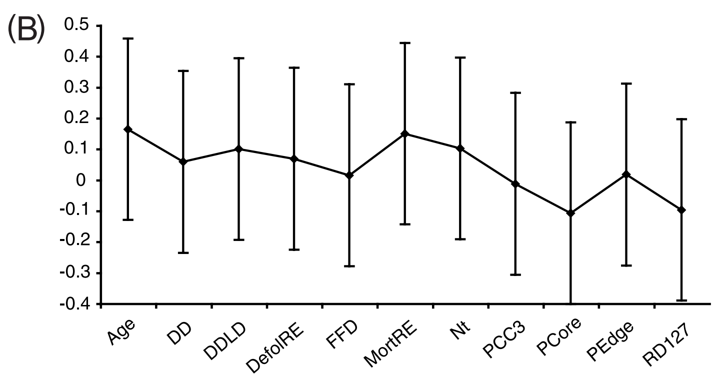
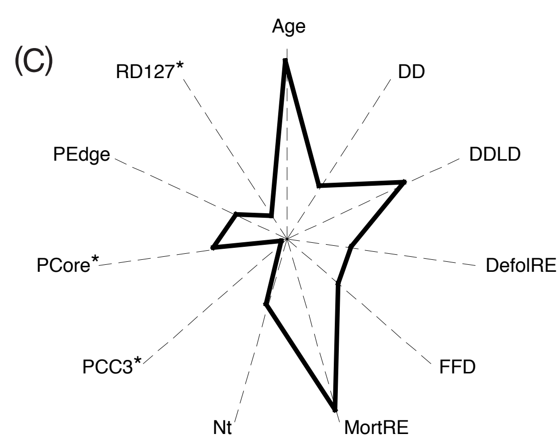


Figure 31—(A) The geographic distribution of plots in western forest types that had trees with poor crown condition (denoted with orange dots) and those that did not (denoted with blue dots). Plot locations are approximate. (B) The difference between mean vectors and 95 percent Bonferroni simultaneous confidence intervals. (C) The linear combination of variables responsible for the largest difference between mean vectors. This figure only shows the magnitude of the weights. Variables with negative weights are denoted by an asterisk. Definitions of variables: Age—standardized age; DD—drought deviation; DDLD—DDLD ratio, ratio of the average dead tree diameter to the average live tree diameter; DefoIRE—relative exposure to defoliation-causing insects and pathogens; FFD—forest floor depth; MortRE—relative exposure to mortality-causing insects and pathogens; Nt—total nitrogen deposition; PCC3—percent fire condition class 3; PCore—percent core forest; PEdge—percent anthropogenic edge; and RD127—percent land within 127 m of a road. More information about these indicators is presented in tables 5 and 6.





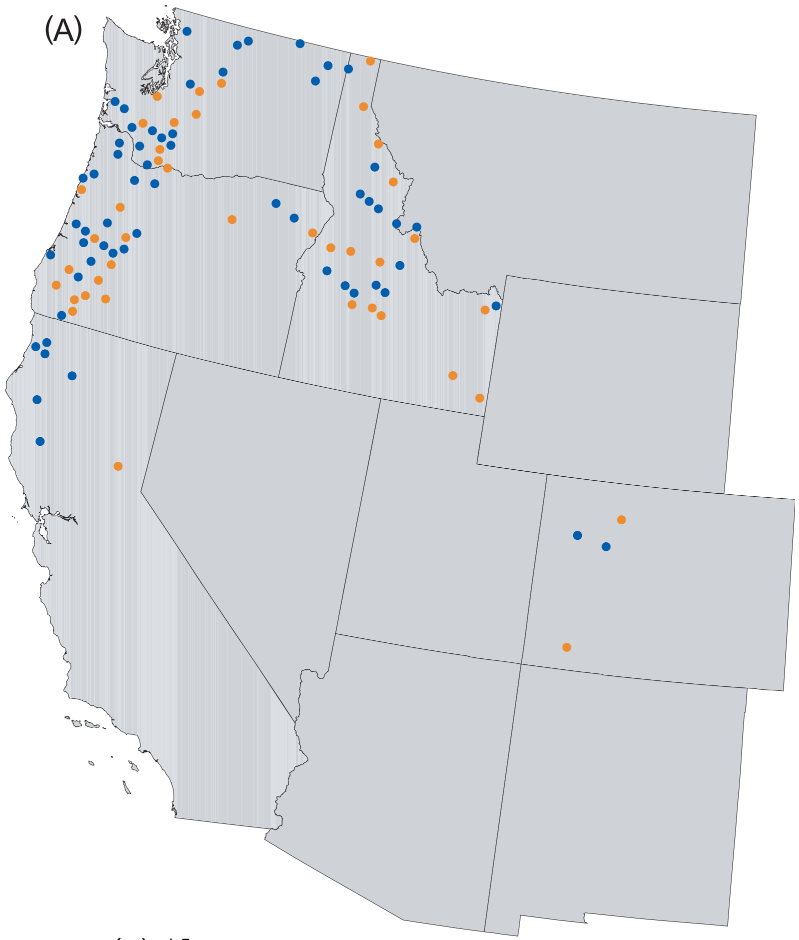
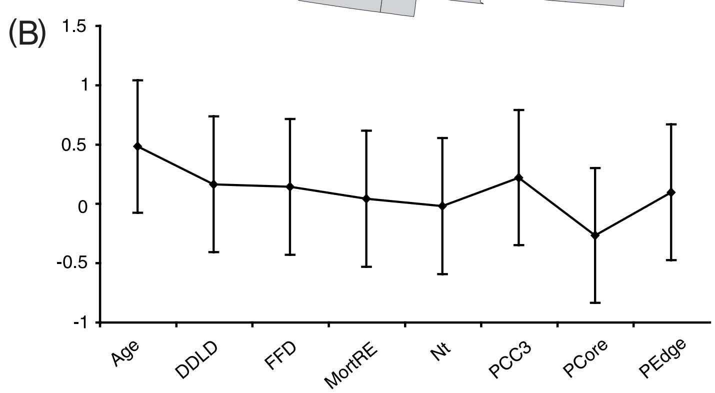
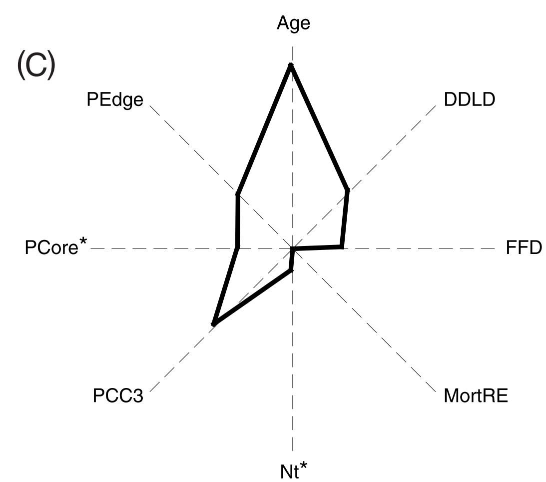


Figure 32—(A) The geographic distribution of plots in the Douglas-fir forest type that had trees with poor crown condition (denoted with orange dots) and those that did not (denoted with blue dots). Plot locations are approximate. (B) The difference between mean vectors and 95 percent Bonferroni simultaneous confidence intervals. (C) The linear combination of variables responsible for the largest difference between mean vectors. This figure only shows the magnitude of the weights. Variables with negative weights are denoted by an asterisk. Definition of variables: Age—standardized age; DDLD—DDLD ratio, ratio of the average dead tree diameter to the average live tree diameter; FFD—forest floor depth; MortRE—relative exposure to mortality-causing insects and pathogens; Nt—total nitrogen deposition; PCC3—percent fire condition class 3; PCore—percent core forest; and PEdge—percent anthropogenic edge. More information about these indicators is presented in tables 5 and 6.





tended to occur in older forest stands, with a higher proportion of forest classified in fire condition class 3.

Discussion

This section has introduced a new method of integrating information with respect to crown condition. We examined eastern forest types, the loblolly pine forest type, western forest types, and the Douglas-fir forest type to determine if there were any variables, or linear combinations of variables, that discriminated between plots that had trees with poor crown condition and those that did not. Standardized age consistently had a high weight in the linear combinations responsible for the largest difference between mean population vectors. Percent forest in fire condition class 3 had a consistently high weight when examining both the loblolly pine and Douglas-fir forest types. The discrimination was more successful in the East. One potential reason for this is that the set of variables did not include climate variables that are important in the Western United States. This analysis should be updated as more information becomes available.

The result that plots in older forest stands tend to be more likely to contain trees with poor crown condition is plausible (Niklasson and Zielonka 1999, Pouttu and Dobbertin 2000). However, there were plots containing trees with poor crown condition, as defined in this report, in relatively young forest stands. These plots were found mostly in the Southeast and Northwest United States (fig. 33). There was a cluster of plots in the fir-spruce and hemlock-spruce forest types in Section M333D—Bitterroot Mountains that had a standardized age ≤ 0.2 and contained trees with poor crown condition, as defined in this report. Province M242—Cascade Mixed Forest—Coniferous Forest-Alpine Meadow contained scattered plots located in relatively young stands of Douglas-fir and hemlock-spruce that contained trees with poor crown condition as defined in this report. In the Piedmont and Coastal Plain of the Southeast, there were plots, mostly in loblolly-shortleaf and oak-pine forest types, that also were in this condition. All of these young stands are of interest because they do not fit the overall patterns identified in this analysis. Further investigation is warranted to elucidate any potential forest health issue.

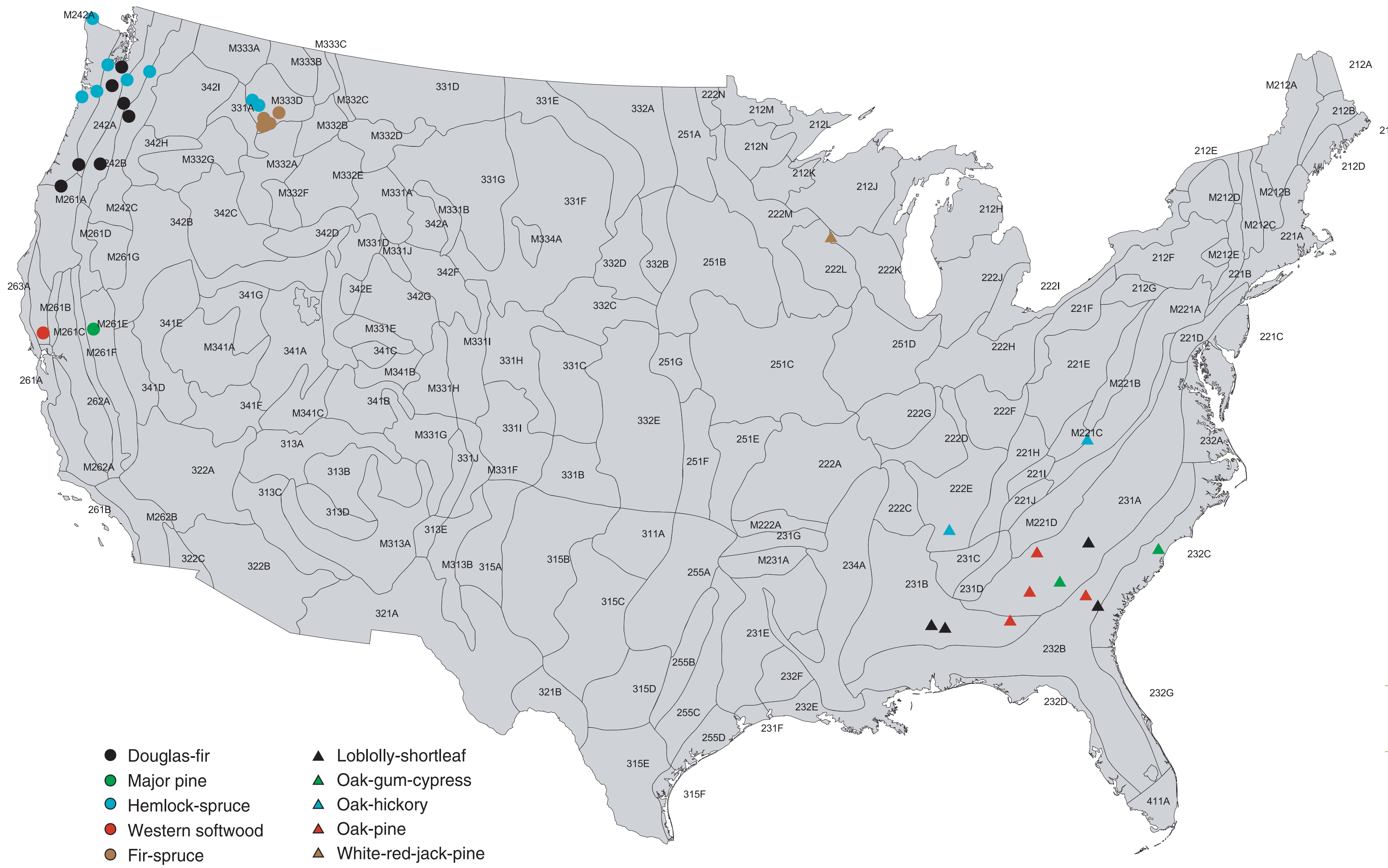


Figure 33—The geographic location and forest type of plots containing trees with poor crown condition and a standardized age ≤ 0.2. Plot locations are approximate.

A Brief Look Forward

FHM annual national technical reports will continue to provide results of national indicator analyses. Each year we will be able to make better estimates of tree growth and mortality as additional data are available from the FIA phase 3 plots.

In future FHM national reports, we expect to begin including results from evaluation monitoring projects that relate to information presented in the national report. Relating evaluation monitoring results to national analyses will provide readers with a link to that component of the FHM Program.

We will continue to present and use analytical techniques that are applicable to large datasets and spatial scales. Sharing data analysis techniques is one of the objectives of the report, and methods along with example applications will be included in future reports.

Readers who are interested in specific forest health concerns in their region or State are encouraged to access reports listed in the "Introduction." Additional information, including forest health highlights, is available online at the FHM (www.fhm.fs.fed.us) and Forest Service (www.fs.fed.us) Web sites.

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Appendix A
Supplemental Methods

Analysis of FHM and FIA ground plot data—Plot data were stratified using Bailey's ecoregion sections (Bailey 1995, McNab and Avers 1994, Miles and Goudy 1997) to conduct many of the analyses presented in this report. Generally, the minimum level of analysis was the mean plot value of each variable, metric, or both, by ecoregion section.[1] If an ecoregion section contained an insufficient number of plots for analysis, its plot data were combined with the data from an adjacent section in the same ecoregion province. A minimum of five plots was required for analysis. In addition, for the analyses of crown condition and mortality using generalized least squares models, data from adjacent ecoregion sections were sometimes combined to obtain sufficient data for PROC MIXED (SAS Institute 1999) to converge on a solution.

The FHM Program strives to use the wealth of data collected by FIA. The FIA Program's phase 3 contains many of the forest health indicators that were previously measured as part of the FHM detection monitoring ground plot system. The FIA Program adopted the hexagonal grid used by FHM to establish a systematic grid of annual survey plots (phase 2), which are designed for measurement on a 5-year rotation such that one-fifth of the plots are measured each year. The phase 3 plots are a subset of phase 2 plots (see footnote 9). The plot design for phase 3 is shown in figure A.1 (appendix).

There was not perfect continuity between the plot data collected from the FHM detection monitoring plots and the FIA phase 3 plots. Although, in theory, all FHM detection monitoring plots were to be maintained as FIA phase 3 plots, in some cases new phase 3 plots were established at locations different from the FHM plots. Data from the newly established plots cannot be used for analysis of mortality until the plots have been remeasured after 5 years. In particular, because the phase 3 plots in California were not colocated with the FHM plots, no 2000 or 2001 data from California were used in this analysis.

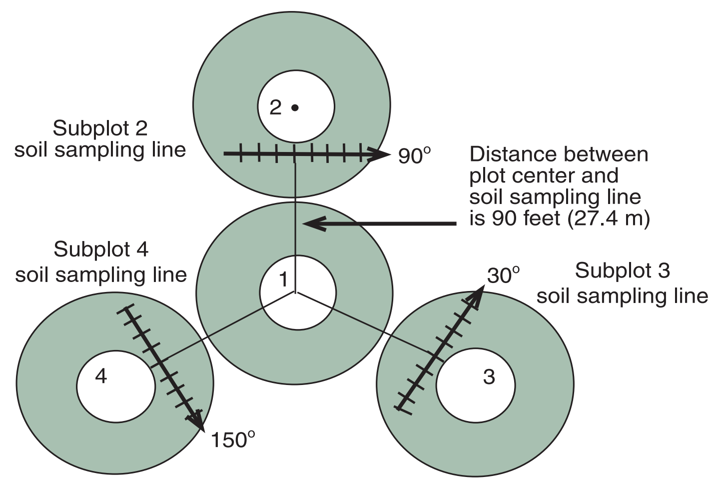

Figure A.1—Phases 2 and 3 common plot design.

[1] Smith, W.D.; Gumpertz, M.L.; Catts, G.C. 1996. An analysis of the precision of change estimation of four alternative sampling designs for forest health monitoring. For. Health Monit. Tech. Rep. Ser. 25 p. On file with: Forest Health Monitoring Program National Office, 3041 Cornwallis Road, Research Triangle Park, NC 27709.

Also, data collected on phase 3 plots do not always document whether individual trees from FHM plots died or were logged. Because FIA treated all plots measured in 2000 and 2001 as new installations, even if the plots had been measured by FHM previously, there were no history codes to track mortality (if the tree was no longer standing), removals, or ingrowth. Determinations of whether a particular tree died or had been logged were made on the basis of other plot variables indicating logging on the site. Thus, there is some increased uncertainty associated with mortality estimates for periods ending in 2001.

Because not all trees measured in 2000 or 2001 corresponded with trees recorded previously, the analyst made the following assumptions with respect to those trees that did not match:

1. A tree appeared on the FHM plot tree list (1999 or earlier), but there was no record of it when the plot was measured in 2000 or 2001:
   a. If a treatment code indicated that there had been any logging on or adjacent to the plot, the analyst assumed the tree to have been cut.
   b. Otherwise, the analyst assumed the tree to have died.

2. A new tree occurred on the tree list for the phase 3 plot in 2000 or 2001 that was not on the FHM plot:
   a. If the tree d.b.h. was < 5 inches, the analyst assumed that the tree was ingrowth on the microplot.
   b. If the tree d.b.h. was ≥ 5 inches and < 6.5 inches, the analyst assumed that the tree was ingrowth on the subplot.
   c. Otherwise, the analyst considered the tree to have been missed by FHM crews on previous visits and dropped the tree from the analysis. However, in future analyses, the analyst will estimate the diameters of missed trees for the years that they were missed.

On some plots, tree numbers in 2000 and 2001 did not match those used in earlier years. Where that occurred, an analysis of tree locations on the plot was performed to try to match trees. While this procedure is believed to have correctly accounted for most trees on those plots, the analyst may have assumed incorrectly that some trees had died. This introduces additional error into the mortality estimates.

For the analysis of crown condition, tracking of individual trees over time was not required because the percentage of basal area associated with poor crowns is a stand-level variable calculated for each point on the sampling grid. When FHM and FIA plots were not colocated, the plots were usually close together (often the plots had the same center but were not aligned the same way), so they are still sampling the same population. Therefore, even if the plots were not colocated, the FHM and FIA plot data could still be used to track change in stand-level crown condition over time.

Wet deposition—Inverse distance squared weighted interpolation (IDW) was used to estimate values of wet sulfate and nitrate for forested areas identified by Zhu and Evans (1994). The general form of IDW used was:

$$v'_p = \sum_{j=1}^{n\geq 12} d_j^{-2}(v_j) \Big/ \sum_{j=1}^{n\geq 12} d_j^{-2}$$

where

v'_p = the predicted value of sulfate or nitrate for location p
v_j = value of SO_4 or NO_3 measured at monitoring station
p = any forested pixel identified by Zhu and Evans (1994)
d_j = distance from the j^{th} monitoring station to p. Monitoring stations > 500 km away from p were not used, and a minimum of 12 monitoring stations were required to predict v'_p.

v'_p was then averaged across years within each ecoregion section. Data from 1994 through 2001 were used for nitrate and sulfate deposition. Ecoregion sections that had values exceeding the 95th percentile for both variables were discussed.

Ozone biomonitoring—The proportion of leaves with ozone injury and the mean severity of symptoms on injured foliage, which were recorded for 10 to 30 plants of up to 3 species at each biomonitoring site (biosite) (see footnotes 4 and 6; Bechtold and Patterson 2005), were used to calculate a biosite index (Coulston and others 2003, Smith and others 2003) (see footnote 8). Biosite index was defined as:

$$1000(m^{-1}\sum_{j=1}^{m} n_j^{-1} \sum_{i=1}^{n_j\geq 10} a_{ij}s_{ij})$$

where

m = the number of species evaluated
n_j = the number of plants of the j^{th} species
a_{ij} = the proportion of injured leaves on the i^{th} plant of the j^{th} species
s_{ij} = the average severity of injury on the i^{th} plant of the j^{th} species

This index was classified into four risk categories that represent a relative measure of impacts from ambient ozone exposure (table 4). The average biosite index for all measurements (1997 to 2001) within each ecoregion section was used in this analysis.

Tree mortality—MRATIO estimates were made using tree and sapling data from FHM and FIA plots. On FHM plots diameters were measured for all trees in the dataset, but heights were only measured for a number of site trees (dominant or codominant) on each plot. On FIA plots (including former FHM plots) the heights of all trees were measured.

Individual heights were estimated for those trees whose heights were not measured using published, regional height/diameter equations of various forms (e.g., Bechtold and Zarnoch,[2] Ek and others 1984, Garman and others 1995, Moore and others 1996). Greater accuracy in estimation was obtained by conditioning the equation through the measured heights of trees, an approach commonly used in growth and yield models (Clutter and others 1983). If a tree on an FHM plot had been subsequently measured by FIA, the height at the time of measurement by FHM was estimated by conditioning the equation through the measured height and diameter of that same tree. If a tree's height had not been measured by FIA, the equation was conditioned through the measured heights of site trees of the same species.

When a tree occurring on the plot was not represented by a site tree of the same species, the analyst modified the procedure. Height was estimated using the dominant heights and diameters of species present on the plot and then adjusted using site index species conversion factors (e.g., Ek and others 1984). For example, if the site index for the site tree species was 100 and the equivalent site index of the subject tree was 80, the estimated height of the subject tree was reduced by 20 percent (Smith and Conkling 2005).

Once heights had been estimated for each tree, the analyst estimated stem volumes using published volume equations. The particular volume equation used depended on tree species and the region of the country where the plot was located.

Total gross volume was expressed on a per-acre basis for each plot. The gross growth (annual change in gross volume) was then estimated for each ecoregion section using a generalized least squares model. For more details on the generalized least squares model, see

[2] Bechtold, W.A.; Zarnoch, S.J. 1996. FHM mensuration engine. Version 1.5. [Not paged]. On file with: USDA Forest Service, Southern Research Station, P.O. Box 2680, Asheville, NC 28802.

"Forest Health Monitoring 2001 National Technical Report" (Conkling and others 2005).

Using the same procedure, the analyst estimated the volumes of trees that died since plot establishment. Volumes for dead trees were estimated based on the last measurement of the tree when it was alive; no growth was assumed between the time the tree was last measured alive and when the tree was determined to be dead. Mortality was modeled as the annual change in accumulated dead volume using the same generalized least squares procedure used to model growth. The mortality rate was divided by the previously derived gross volume growth rate to give the mortality ratio, MRATIO (Conkling and others 2005; Stolte and others, in press).

The variance of the MRATIO for each ecoregion section was taken to be [Cochran 1977 (section 6.19, equation 6.95)]:

$$v_{mratio} = \frac{m^2}{g^2}\left(\frac{v_m}{m^2} + \frac{v_g}{g^2} - \frac{2r_{mg}\sqrt{v_m v_g}}{mg}\right)$$

where

v_{mratio} = variance of the MRATIO
v_m = variance of the mortality rate
v_g = variance of the gross growth rate
m = mortality rate
g = gross growth rate
r_{mg} = the correlation between the mortality and growth rates

For each plot, a dead diameter/live diameter (DDLD) ratio was calculated using data from the most recent measurement of each plot (Smith and Conkling 2005). The DDLD was calculated as the ratio of the quadratic mean d.b.h. of dead trees to the quadratic mean d.b.h. of live trees on the plot. If there were no live trees on the plot because the area had been logged, the DDLD was calculated as the ratio of the quadratic mean d.b.h. of dead trees to the quadratic mean d.b.h. of cut trees, where cut diameters are taken from previous measurement of the plot.

In the West, if the forest on the plot was of a type dominated by western woodland species (see footnote 5), the DDLD was calculated as the ratio of the quadratic mean root collar diameter of dead trees to the quadratic mean root collar diameter of live trees on the plot. The DDLD also was calculated using root collar diameters if the only observed mortality was of western woodland species, even if the forest type was predominantly nonwoodland species. No DDLD was calculated if all mortality was in woodland species and all survivors on the plot were nonwoodland species, or vice versa.

Integrated look at forest health indicators—We used Hotelling's T^2 statistic [see Johnson and Wichern (2002) for details] to test for differences between mean vectors of plots that had trees with thin crowns (denoted by the subscript 1) versus plots that did not (denoted by the subscript 2). Only variables with correlations < 0.4 were used in this analysis.

We calculated the mean response vector for each population by

$$\mathbf{x}_i=(\mathbf{1X}_i)'/n_i$$

where

n = number of observations
x = mean vector for p variables (number of variables)
$X = n \times p$ data matrix
1 = either a 1 x n or n x 1 vector of ones conforming to multiplication used to compute mean vectors and covariance matrix
i = population 1 or 2 (i.e., healthy or unhealthy)

The covariance matrix was calculated as:

$$\mathbf{S}_i = (\mathbf{X}_i-(\mathbf{1x}_i'))' (\mathbf{X}_i-(\mathbf{1x}_i'))/ (n_i-1)$$

The pooled covariance was:

$$\mathbf{S}_{pool} = \mathbf{S}_1(n_1-1)/(n_1+n_2-2) + \mathbf{S}_2(n_2-1)/(n_1+n_2-2)$$

Hotelling T^2 was calculated by:

$$T^2 = (\mathbf{x}_1 - \mathbf{x}_2)' ((1/n_1 + 1/n_2)\, \mathbf{S}_{pool})^{-1} (\mathbf{x}_1 - \mathbf{x}_2)$$

and the critical value for the T^2 statistic at level (α) was:

$$(n_1+n_2-2)/(n_1+n_2-p-1)\, F_{p,n1+n2-p-1}(\alpha)$$

where

p = the dimension (number of variables)
F = the F-value with p numerator degrees of freedom and $n_1 + n_2 - p - 1$ denominator degrees of freedom

The coefficients of the linear combination most responsible for the difference between $\boldsymbol{x}_1$ and $\boldsymbol{x}_2$ was proportional to:

$$\mathbf{L}_c = \mathbf{S}_{pool}^{-1} (\mathbf{x}_1 - \mathbf{x}_2)$$

The Bonferroni 1-α simultaneous confidence intervals are

$$(\mathbf{x}_1 - \mathbf{x}_2) +\!- t_{n1+n2-2}(\alpha/2p)\ \mathrm{sqrt}\ (((1/n_1)+(1/n_2))\mathrm{diag}(\mathbf{S}_{pool}))$$

where

t = the t-value with $n1 + n2 - 2$ degrees of freedom at level ($\alpha/2p$)

Appendix B

Tree Mortality Summary Statistics

Ecoregion section	Plots	Plots with mortality	Obs.[a]	Mortality	Growth	MRATIO	Standard error of MRATIO	DDLD ratio			
								Mean	Minimum	Maximum	Standard error
				ft³ per acre per year							
212A	13	11	43	31.19	90.25	0.346	0.0877	1.318	0.523	2.491	0.7021
212B	29	26	109	29.52	84.16	0.351	0.0824	0.758	0.287	1.460	0.3155
212C	7	6	25	30.89	78.13	0.395	0.1367	0.919	0.623	1.802	0.4445
212D	19	18	74	33.46	69.06	0.485	0.1336	0.653	0.133	1.478	0.3527
212E	6	4	14	29.68	108.44	0.274	0.0949	1.274	0.367	2.646	0.9978
212F	31	18	51	7.41	95.08	0.078	0.0281	0.667	0.278	3.293	0.7247
212G	11	7	21	39.42	93.74	0.421	0.2790	1.330	0.148	2.987	1.1248
212H	79	60	187	35.48	62.42	0.568	0.1843	1.047	0.206	4.636	0.8627
212J	72	51	166	33.61	68.22	0.493	0.1231	0.897	0.219	2.225	0.5302
212K	21	14	50	16.34	48.97	0.334	0.1086	0.713	0.200	1.376	0.3267
212L	35	13	82	20.89	28.25	0.739	0.2408	1.164	0.192	2.493	0.4045
212M	24	10	53	16.00	34.88	0.459	0.2079	1.049	0.372	3.458	0.5297
212N	50	21	114	17.70	36.96	0.479	0.1681	0.903	0.267	2.974	0.3269
221A	46	42	172	20.53	70.80	0.290	0.0521	0.791	0.171	2.148	0.4659
221C, 221D	18	14	55	24.15	53.93	0.448	0.1969	0.903	0.291	2.612	0.6170
221E, 221F	43	33	138	23.13	89.42	0.259	0.0887	0.798	0.104	3.735	0.7565
221H, 221I	13	11	24	26.45	147.08	0.180	0.0589	0.842	0.315	1.770	0.4720
222C	9	4	15	22.84	329.53	0.069	0.0585	0.890	0.322	2.164	0.8654
222D	6	8	13	85.05	80.96	1.051	0.3596	0.928	0.273	2.249	0.6462
222E, 222F	28	17	54	17.64	152.52	0.116	0.0498	0.630	0.226	2.058	0.4894
222G	8	6	16	114.41	188.86	0.606	0.3872	1.043	0.217	1.781	0.6185
222H	9	8	18	104.78	111.57	0.939	0.4162	1.194	0.257	3.151	0.9787
222I, 222J	26	18	58	17.75	70.93	0.250	0.0855	0.764	0.176	1.548	0.4561

continued

Appendix table B—Tree mortality summary statistics (continued)

Ecoregion section	Plots	Plots with mortality	Obs.[a]	Mortality	Growth	MRATIO	Standard error of MRATIO	DDLD ratio Mean	Minimum	Maximum	Standard error
				ft³ per acre per year							
222K	12	4	27	7.88	62.76	0.126	0.0790	1.341	0.703	2.206	0.6564
222L	15	6	31	18.13	45.90	0.395	0.2421	0.905	0.266	1.741	0.5105
222M, 222N	21	10	53	12.04	54.88	0.219	0.0724	0.788	0.388	1.744	0.2564
231A	168	130	455	28.22	127.46	0.221	0.0314	0.715	0.055	2.498	0.4766
231B	68	58	209	29.76	117.10	0.254	0.0529	0.679	0.115	2.254	0.5222
231C	19	17	60	76.74	87.25	0.880	0.2156	0.805	0.281	2.578	0.5212
231D	12	11	38	40.17	110.64	0.363	0.1487	0.748	0.234	1.370	0.3686
232A	36	28	109	35.21	121.07	0.291	0.0707	0.639	0.121	2.100	0.3482
232B	98	68	270	27.75	118.49	0.234	0.0474	0.634	0.085	3.127	0.4730
232C	45	28	102	24.71	99.91	0.247	0.0774	1.117	0.156	4.744	1.0051
242A	28	11	62	54.72	116.38	0.470	0.3111	0.725	0.274	1.434	0.3493
251C, 251D	17	6	35	39.80	76.36	0.521	0.2826	0.635	0.290	0.939	0.2566
261A, M262A	8	0	18	0.00	26.86	0.000	—	—	—	—	—
263A	7	3	17	5.02	26.15	0.192	0.0988	1.427	0.598	2.924	1.2985
313A	14	2	34	0.93	13.39	0.069	0.0360	1.000	1.000	1.000	0.0000
331A	5	3	12	32.66	65.45	0.499	0.3365	0.861	0.494	1.088	0.3214
331F, 331G	7	1	15	0.03	8.95	0.003	0.0011	3.266	3.266	3.266	0.0000
331I	11	3	28	4.06	20.26	0.200	0.1019	0.791	0.372	1.000	0.3627
341B, 341C	20	5	47	2.68	29.50	0.091	0.0807	1.000	1.000	1.000	0.0000
342A,342E,342F, 342G	10	1	23	3.70	24.53	0.151	0.1503	1.610	1.610	1.610	0.0000
342B	12	6	29	7.76	15.77	0.492	0.1793	1.008	0.483	1.978	0.5063
342C	6	4	13	27.30	47.38	0.576	0.1181	0.952	0.760	1.148	0.1639
342H, 342I	10	3	22	5.03	36.82	0.137	0.1330	0.849	0.498	1.049	0.3051
M212A	70	66	266	38.02	70.07	0.543	0.0739	0.953	0.176	2.798	0.5933
M212B	21	17	88	18.99	82.84	0.229	0.0626	0.754	0.236	2.233	0.4759
M212C	18	18	65	41.80	85.46	0.489	0.1565	1.012	0.191	2.704	0.6357
M221A	62	48	175	36.87	72.04	0.512	0.0849	0.820	0.160	2.546	0.5677
M221B	23	16	83	29.50	89.74	0.329	0.1152	0.730	0.196	1.525	0.4326
M221C	17	14	63	22.28	69.82	0.319	0.0999	0.634	0.273	1.392	0.4133
M221D	43	28	109	42.16	112.83	0.374	0.1071	1.063	0.184	4.737	0.9653

continued

Appendix table B—Tree mortality summary statistics (continued)

Ecoregion section	Plots	Plots with mortality	Obs.[a]	Mortality	Growth	MRATIO	Standard error of MRATIO	DDLD ratio			
								Mean	Minimum	Maximum	Standard error
				ft³ per acre per year							
M242A	46	17	97	27.83	136.63	0.204	0.0847	0.736	0.131	3.371	0.7277
M242B	46	24	100	41.83	173.43	0.241	0.1087	0.627	0.053	1.788	0.4395
M242C	60	24	130	46.83	65.54	0.715	0.2207	0.740	0.245	1.319	0.3330
M261A	48	22	111	11.00	48.96	0.225	0.1150	0.967	0.369	5.020	0.9831
M261B	15	3	33	13.29	17.20	0.773	0.6094	1.903	0.290	4.570	2.3261
M261C, M261F	23	5	52	0.86	10.92	0.079	0.0479	0.619	0.096	1.365	0.5048
M261D	15	4	32	5.26	37.98	0.138	0.0727	0.809	0.153	2.000	0.8449
M261E	45	7	108	1.94	22.12	0.088	0.0405	0.599	0.186	1.012	0.3053
M261G	20	1	45	1.92	13.60	0.141	0.0810	0.361	0.361	0.361	0.0000
M331A	17	6	40	27.53	37.44	0.735	0.3531	1.217	0.654	3.339	1.0529
M331B	5	1	10	23.64	57.33	0.412	0.1049	2.189	2.189	2.189	0.0000
M331D	33	13	77	6.24	37.24	0.168	0.0611	0.725	0.203	1.261	0.4080
M331E	8	4	16	24.62	46.39	0.531	0.4008	0.890	0.558	1.000	0.2209
M331F	10	4	32	2.32	23.08	0.101	0.0294	0.973	0.749	1.142	0.1633
M331G	32	21	90	9.86	30.49	0.323	0.0965	1.058	0.225	3.129	0.6414
M331H	33	21	90	19.72	45.26	0.436	0.1254	0.795	0.303	1.842	0.3406
M331I	33	18	88	8.27	35.88	0.230	0.0839	0.859	0.169	1.671	0.4500
M331J	17	6	40	27.53	37.44	0.735	0.3531	1.217	0.654	3.339	1.0529
M332A	50	23	121	36.15	53.48	0.676	0.2336	0.937	0.193	1.640	0.3792
M332E	7	3	18	13.45	35.73	0.376	0.2623	1.042	0.540	1.909	0.7541
M332F	11	5	27	8.21	13.93	0.589	0.3464	1.771	0.503	5.001	1.8461
M332G	38	14	81	10.51	34.60	0.304	0.1365	0.948	0.099	2.611	0.7001
M333A	36	16	85	54.33	74.98	0.725	0.3247	1.028	0.162	1.802	0.4765

[a]A visit to a single plot in a given year to measure growth and mortality constitutes one observation.
MRATIO = ratio of annual mortality volume to gross volume growth;
– = no mortality recorded

Appendix C

List of Cited Common and Scientific Names

Common name	Scientific name
Tree species	
Black cherry	*Prunus serotina* Ehrh.
Douglas-fir	*Pseudotsuga menziesii* (Mirb.) Franco
Loblolly pine	*Pinus taeda* L.
Lodgepole pine	*P. contorta* var. *latifolia* Engelm.
Northern red oak	*Quercus rubra* L.
Ponderosa pine	*Pinus ponderosa* Dougl. ex Laws. var. *ponderosa*
Shortleaf pine	*P. echinata* Mill.
Other plants	
Common milkweed	*Asclepias* spp.
Dwarf mistletoe	*Arceuthobium* Bieb.
Pests and diseases	
Beech bark disease	*Nectria coccinea* var. *faginata* Lohman, Watson, and Ayers
Butternut canker	*Sirococcus clavigignenti-juglandacearam* Nair, Kostichka, and Kuntz
Douglas-fir beetle	*Dendroctonus pseudotsugae* Hopkins
Forest tent caterpillar	*Malacosoma disstria*
Fusiform rust	*Cronartium quercuum* (Berk.) Miyabe ex Shiari
Gypsy moth	*Lymantria dispar* Linnaeus
Hemlock woolly adelgid	*Adelges tsugae*
Littleleaf disease	*Phytopthora cinnamomi* Rands
Mountain pine beetle	*Dendroctonus ponderosae* Hopkins
Southern pine beetle	*D. frontalis* Zimmermann
Sudden oak death	*Phytopthora ramorum*
Western spruce budworm	*Choristoneura occidentalis* Freeman
White pine blister rust	*Cronartium ribicola* Fisch.

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The Forest Health Monitoring Program's annual national reports present results from forest health data analyses focusing on a national perspective. The Criteria and Indicators for the Conservation and Sustainable Management of Temperate and Boreal Forests are used as a reporting framework. This report has five main sections. The first contains introductory material. The next three sections, "Landscape Structure," "Abiotic and Biotic Factors," and "Forest Conditions," contain results of data analyses. Some of the indicators discussed use data collected from ground plots. These include ozone bioindicator plants; changes in trees (crown condition, mortality, and stand age); and soils (forest floor depth). Other indicators or indicator groups use data about insects and diseases, and remotely sensed or ground-based data about distance to roads, forest edge, interior forest, drought, fire, and air pollution (sulfates, nitrates, and ozone). Identifying patterns and observing possible relationships is an important part of national level analysis and reporting. The fifth section "Integrated Look at Forest Health Indicators" presents results of analyses designed to evaluate whether or not individual indicators or linear combinations of indicators discriminate between crowns in poor condition and crowns not in poor condition.

Keywords: Assessment, bioindicators, criteria and indicators, fragmentation, monitoring, mortality.

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