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Analyzing Forest Health Data

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Cover:

The top photo shows the first detection of sudden oak death caused by *Phytophthora ramorum* near Plaskett Creek, Los Padres National Forest (Monterey County, CA) in the fall of 2003. (Photo by Jeff Mai, USDA Forest Service)

The bottom photo shows an area of severe sudden oak death, primarily on tanoak, in the Big Sur area (Monterey County, CA) in the fall of 2004. (Photo by Susan Frankel, USDA Forest Service)

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Abstract

This report focuses on the Forest Health Monitoring Program's development and use of analytical procedures for monitoring changes in forest health and for expressing the corresponding statistical confidences. The program's assessments of long-term status, changes, and trends in forest ecosystem health use the Santiago Declaration: "Criteria and Indicators for the Conservation and Sustainable Management of Temporate and Boreal Forests" (Montreal Process) as a reporting framework. Procedures used in five aspects of data analysis are presented. The analytical procedures used are based on mixed estimation procedures. Examples using the indicators are included, along with a clear link to the analytical procedures used (1) estimating change over time within groups—estimation of growth, harvest, mortality, and crown condition; (2) testing for differences in change over time among groups—foliar transparency; (3) estimating change using covariates—impact of drought on change in foliar transparency; (4) estimating plot values for unmeasured years—comparison of observed and predicted (Best Linear Unbiased Predictions) values of foliar transparency, dieback, and total volume; and (5) estimating tree heights—examples of using estimated tree heights to estimate tree volume.

Keywords: Assessment, BLUP, change estimation, mixed models, monitoring, tree height.

Executive Summary

In this report we focus primarily on the Forest Health Monitoring (FHM) Program's development and use of analytical procedures for monitoring changes in forest health and for expressing the corresponding statistical confidences. FHM's assessments of long-term status, changes, and trends in forest ecosystem health are based on the Santiago Declaration: "Criteria and Indicators for the Conservation and Sustainable Forest Management of Temporate and Boreal Forests" (U.S. Department of Agriculture Forest Service 1995). The Santiago criteria and indicators characterize the components of sustainable forest management. The FHM forest health indicators are a subset of the Santiago indicators, which are used as an organizational framework for reporting.

Procedures used in five aspects of data analysis are presented in this report: (1) estimating change over time within groups, (2) testing for differences in change over time among groups, (3) estimating change using covariates, (4) estimating plot values for unmeasured years, and (5) estimating tree heights. Example analyses using FHM indicators are then presented with a clear link to the analytical procedure used. Estimates of the annual change in FHM indicators are based on the measurements collected from 1991 through 1996 from the FHM plot grid. Measurements from 1997 for six Colorado plots measured out of sequence are also included.

Estimates of change can be made using a procedure that accounts for the fact that FHM data are often correlated over time. This model is used to estimate change for different groupings, i.e., ecoregion section and forest type, over time. Example analyses include the estimation of growth, harvest, mortality, and crown condition. A specific example is the mixed-conifers forest type in California. The annual net growth of this forest type from 1992 to 1996 was -96.4 cubic feet per acre per year, and mortality was 125.3 cubic feet per acre per year. Drought- and insect-induced mortality has been observed in this forest type, primarily in white (*Abies concolor*) and red fir (*Abies magnifica*) (Dale 1996), which contributed to the negative net growth rate.

By testing for differences among regions or forest types that have distinct attributes (climate, soils, species, etc.) or exposure to stressors, we gain insight into likely causal mechanisms behind the observed changes. Although the estimate of mean change provides this insight, it is essential that the significance of the estimated differences over time and among ecoregions or forest types be tested. Otherwise differences due to random sampling error only can be interpreted as real change. The rate of change in softwood transparency among four sections of the Southern Rocky Mountains Steppe Province in Colorado illustrates this type of analysis. In addition to providing information about transparency changes over time and among sections, the analysis results provide direction for future analyses integrating data such as climate and land use.

Estimating change using covariates provides the analysis needed to integrate data such as climate, precipitation, and ozone exposure. These data are covariates with time. Assessing the impact of drought on change in foliar transparency in California illustrates this procedure. The Palmer Drought Severity Index (PDSI)—an empirically derived index based on total rainfall, the periodicity of the rainfall, and soil characteristics such as water-holding capacity—data are the drought data used. The example analysis suggests that year, and the interaction between year and PDSI, are significant factors in foliar transparency change. However, the demonstrated power of the procedure is most important in this report because it suggests the utility of the procedure in analyzing more subtle factors such as ozone and other pollutants.

In addition to estimating change, making annual assessments of forest health status is a major requirement of FHM. The procedures described result in estimates that can be used to predict the plot or tree values for unmeasured years. These predicted values are referred to as Best Linear Unbiased Predictions (BLUP). In this report, comparing observed and predicted values of transparency, dieback, and total volume illustrates the validity of this process.

Tree height is one of the measures of forest vertical structure that is important in addressing many of the Santiago criteria. Although FHM did not measure tree heights across all diameter classes, the heights of one or two dominant or codominant trees (site trees) were measured on most plots. Until height data are available for all trees, regional height/diameter equations of various forms can be used to estimate individual tree heights. Greater accuracy in estimation is obtained by conditioning the equations through the measured heights of dominant/codominant trees (Clutter and others 1983). Conditioning reparameterizes the equation such that the predicted value calculated using the equation is equal to the measured values. In this report, height estimates used to estimate tree volume for productivity and carbon content were calculated using the site-index-species conversion factors to adjust all heights. Estimates of plot volume were then calculated, with tree heights estimated using the conditioning procedures.

Introduction

Assessing the susceptibility of forests to disturbance from pollution, insects, diseases, climatic change, and other stressors, and the capacity of forests to recover is the cooperative responsibility of several programs within the U.S. Department of Agriculture Forest Service (USDA Forest Service) and other Federal and State agencies. Because a forest is an ecosystem of floral, faunal, and abiotic processes, forest health assessment requires regional expertise in ecology, plant physiology, plant pathology, entomology, and many other disciplines that use data from numerous sampling grids and surveys.

The National FHM Program has been established by several Federal and State agencies to monitor, assess, and report on the long-term status, changes, and trends in forest ecosystem health with known confidence on regional and national scales. National FHM assessments are based on the Santiago Declaration: "Criteria and Indicators for the Conservation and Sustainable Management of Temporate and Boreal Forests" (U.S. Department of Agriculture Forest Service 1995), an international agreement signed by 12 nations that characterizes the components of sustainable forest management. Sustainable forest management requires that the capacity to produce forest products and services, including key ecosystem functions, be maintained. The Santiago criteria have been endorsed by the Chief of the Forest Service, the National Association of State Foresters, the American Forest & Paper Association, and the Ecological Society of America.

This report focuses primarily on FHM's development and use of analytical procedures for monitoring changes in forest health and for expressing the corresponding statistical confidences. The forest health indicators measured by FHM since 1990 are a subset of the indicators presented in the Santiago Declaration. Estimates of the annual change in FHM indicators are based on the measurements collected from 1991 through 1996[1] from the FHM plot grid. Only the States that have completed at least one repeat measurement visit to the plots are included. The FHM plot measurements presented in this report include crown dieback and damage, foliar transparency, diameter at breast height (d.b.h.), and tree species. FHM measurements and published equations were used to derive volume, mortality, and carbon sequestration. Non-FHM plot data, i.e., climate data, and how they fit into the assessment process are discussed**.**

The FHM Program

The FHM Program was originally established by merging the forest component of the U.S. Environmental Protection Agency's (EPA) Environmental Monitoring and Assessment Program (EMAP Forests), the Vegetation Survey Project of the USDA Forest Service's Forest Response Program, and the emerging forest health initiative of the USDA Forest Service's Forest Health Protection (FHP) Program. Currently within the USDA Forest Service, data are collected for monitoring forest health by the National Forest Inventory and Analysis (FIA) Program in Research and Development, and the national Forest Health Monitoring (FHM) Program in State and Private Forestry. Analytical procedures for analyzing forest health data are developed by the National Forest Health Monitoring Research Unit (FS-SRS 4803) and cooperating scientists at North Carolina State University. These procedures are shared with regional and State forest health analysts. The National Association of State Foresters provides essential program

[1] Measurements from 1997 for six Colorado plots that were measured out of sequence are included in the analysis.

support, guidance, and assistance. The EPA; the U.S. Department of the Interior, Bureau of Land Management; the Tennessee Valley Authority; the USDA Natural Resources Conservation Service; and several universities participated in the development of FHM.

The FHM Program from 1991 through the 1999 field season comprised three interrelated monitoring activities: detection monitoring (plot and survey components), evaluation monitoring, and intensive site ecosystem monitoring. Each activity provided a different level of information and had specific, complementary goals. A fourth related activity was research on monitoring techniques.

In 1999, the ground plot activities of detection monitoring were integrated with the USDA Forest Service, FIA Program. A systematic grid was adopted by the enhanced FIA Program that includes some, but not all, former FIA plots. This is the phase 2 grid—the annual survey plots that are designed to be measured on a 5-year rotation such that one-fifth of the plots are measured each year. Most former FHM plot indicators became phase 3 indicators, measured on a subset of phase 2 plots. At least one FHM indicator (damage) became part of the phase 2 measurements.

Through 1999, detection monitoring was the most extensive of FHM's three monitoring activities. The objectives of this activity were to collect information annually on the condition of forest ecosystems, to estimate baseline (current) conditions, and to detect short- and long-term changes. Data from FHM plots and surveys were analyzed with other forest data to determine if changes were within normal bounds, indicated improving conditions, or were cause for concern and warranted additional evaluation. Detection monitoring covered all forested lands (with the exception of riparian forests < 100 feet wide) and had two components: (1) the plot component, a network of permanent plots (approximately 4,600 forested plots for the 50 States); and (2) the survey component, primarily an aerial survey of insect, disease, and other disturbances. Each year a systematic sample of one-third of the permanent plots was measured and most forested acres were aerially surveyed. Figure 1 shows the States participating in both the plot and survey components of detection monitoring through 1997.

The plot component was a systematic sample of permanent, fixed-area plots on a hexagonal base grid, located approximately 22 miles apart. The plots were measured on a 4-year cycle such that one-fourth of the plots systematically

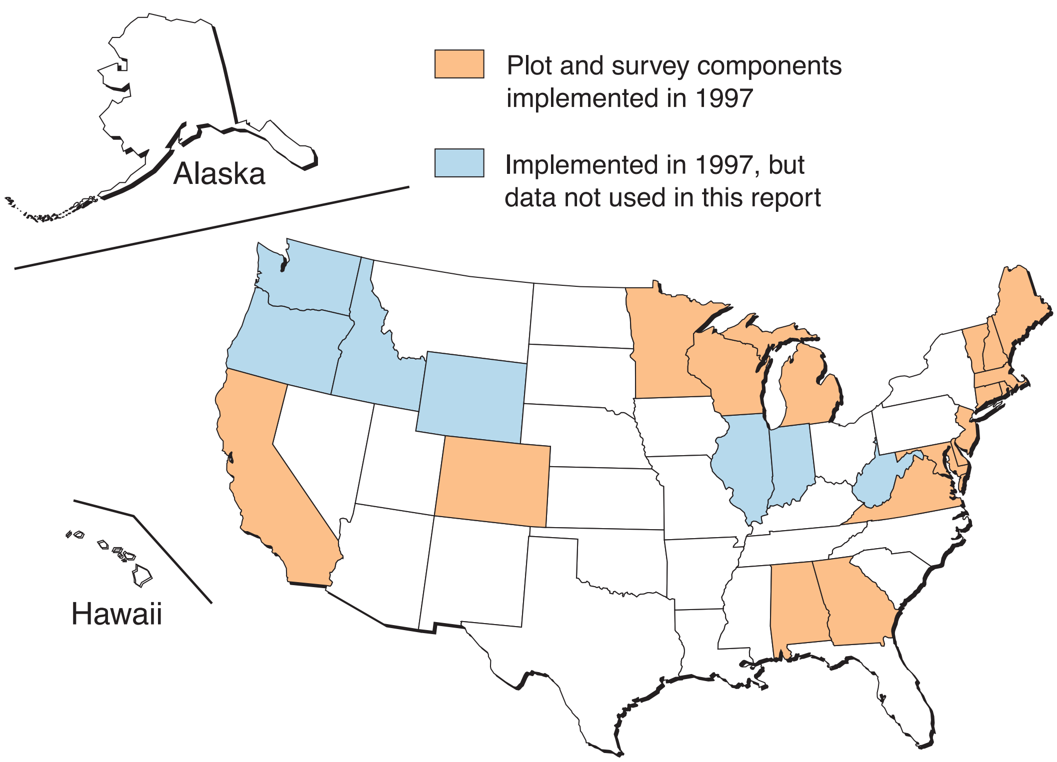

Figure 1—States in which both the plot and survey components of detection monitoring were implemented in 1997; approximately 52 percent of the forest area in the lower 48 States was systematically sampled (States have been added since 1997).

Year ⇒ / Panel ⇓	1	2	3	4	5	6	7	8
0	X	$^x/_3$			X	$^x/_3$		
1	X	X	$^x/_3$			X	$^x/_3$	
2	X		X	$^x/_3$			X	$^x/_3$
3	X			X	$^x/_3$			X

Figure 2—Year-to-year sampling design.

covering the entire State (called a panel) were measured every year. In addition, one-third of the plots systematically covering the entire State in the previous year's panel (called the overlap) were remeasured. This overlap was one-twelfth of the base grid. The rotating panel with overlap was referred to as the FHM rotating panel design. When the design was implemented in a new State, all plots were established and measured the first year. Figure 2 illustrates the year-to-year sampling design.

The objective of the FHM design was to provide precision in estimates of change over short time intervals (temporal) rather than in estimates of change for small geographic areas (spatial). Two to four years was considered a short time interval, and a small geographic area was considered to be < 2 million acres. In making annual assessments, the capacity to update (predict plot values for unmeasured plots) was of particular importance. The overlapping design was developed to allow this updating process.[2]

Each FHM plot had four fixed-area, circular subplots as shown in figure 3. Subplot centers were spaced 120 feet apart. All subplots were 1/24-acre in size and contained a microplot offset 12 feet from the subplot center. The microplots were 1/300-acre in size. The basic plot design could be augmented to meet regional requirements. For example, the West Coast region used a 2.47-acre (1-ha) plot encircling the four subplots to increase the sample of large trees.

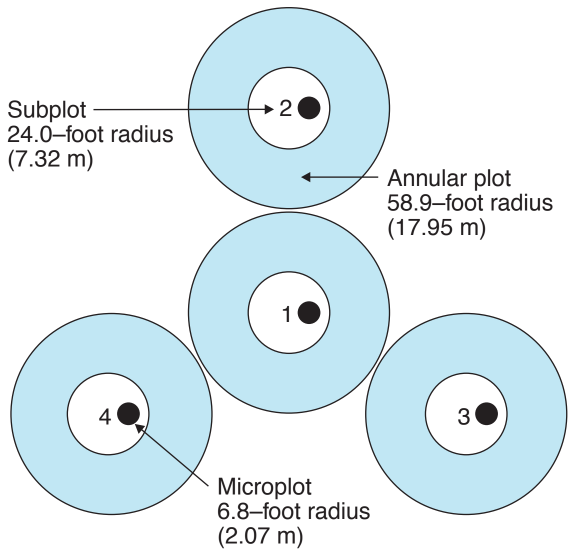

Figure 3—Forest Health Monitoring field plot (drawn to scale).

The survey component provided a record (location and extent) of disturbances from forest insects, diseases, and other change agents. This information was an indicator of forest health, and provided a context for interpreting plot data and for identifying likely factors that contribute to forest health changes. Damage to individual plot trees was indicated and insects, diseases, and other disturbances were identified from the aerial surveys. Without the survey data,

[2] 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. (10/96). Research Triangle Park, NC: U.S. Department of Agriculture, Forest Service, Southern Research Station. 25 p. Administrative report. On file with: Forestry Sciences Laboratory, Southern Research Station, P.O. Box 12254, Research Triangle Park, NC 27709.

the ability to interpret and make management decisions in response to the observed changes in plot variables would be very limited. National standards for the survey component of detection monitoring were developed to address the accuracy of other data associated with digitized, polygonal aerial survey data, e.g., species, damage severity, and causal agent, implement consistent training, quality assurance, and reports across regions, and more fully integrate the plot and survey components, exploiting the strengths of each.

The Santiago Criteria and Indicators of Sustainable Forest Management

Under the Santiago Declaration (U.S. Department of Agriculture Forest Service 1995), a criterion is a category of conditions or processes by which sustainable management can be assessed. It is characterized by a set of indicators that are monitored periodically to assess change. Indicators are quantitative or qualitative variables that can be measured and that demonstrate trends when observed periodically. Changes in the status of forests and related conditions over time, and the direction of those changes, are relevant to assessing sustainability. Given the dynamic nature of forests, it is essential that indicators be assessed as trends over time (U.S. Department of Agriculture Forest Service 1995).

The seven Santiago 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 contributions 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.

Criterion 6 addresses socioeconomic issues that FHM does not assess directly; criterion 7 addresses infrastructure and other factors that FHM cannot or does not address. Sixty-seven indicators are currently associated with the 7 Santiago criteria.

Initially, most of the Santiago criteria and indicators (U.S. Department of Agriculture Forest Service 1995) were stated in terms of change in "area and percent of forest land." For example, the first indicator being addressed by FHM under criterion 3 is:

> Area and percent of forest affected by processes or agents beyond the range of historic variation, e.g., by insects, diseases, competition from exotic species, fire, storm, land clearance, permanent flooding, salinization, and domestic animals (U.S. Department of Agriculture Forest Service 1995).

FHM uses available data to answer questions that reflect the temporal aspects of the indicators. Examples of this type of questions are as follows:

- What is the annual change in crown dieback by ecoregion section and forest type?
- What is the annual change in foliar transparency by ecoregion section and forest type?
- What is the annual change from forest to nonforest use by ecoregion section and forest type?

Assessment of Forest Health

The National FHM assessment process begins with the development of questions relevant to ecological, economic, and political concerns. These issues are addressed in the context of the Santiago criteria. FHM data are being evaluated to determine which FHM measurements can be used to address these criteria and related issues. Analytical procedures for estimating change and the corresponding confidence are currently being applied to FHM plot data. Inferences from the changes observed on the FHM plots are supported with qualitative data from insect and disease surveys. Future developments in the program will include data applications that more explicitly exploit the spatial aspects of plot, survey, and other data sources.

FHM Data Analysis

FHM detection monitoring data and other data are reviewed each year to determine whether forest health conditions of concern are emerging. This review may include analyses of FHM data; other USDA Forest Service data such as FHP survey and plot data, FIA data, National Forest System (NFS) Continuous Vegetation Survey (CVS) data; and data from other agencies such as weather and air quality data. These analyses corroborate whether or not apparent indicator changes are significant and provide insight into problem extent, severity, and likely causal relationships. If these analyses do not satisfactorily explain a situation, an evaluation monitoring project may be needed. Meaningful evaluation requires an integration of FHM plot and survey data, FIA data, NFS data, and other data by biometricians, pathologists, entomologists, plant physiologists, ecologists, and silviculturists knowledgeable about each specific State or region. Because causal agents or stressors are not identified on the plot, the plot data must be related to other information to make meaningful interpretations. Through 1999 in FHM, the survey component of the program

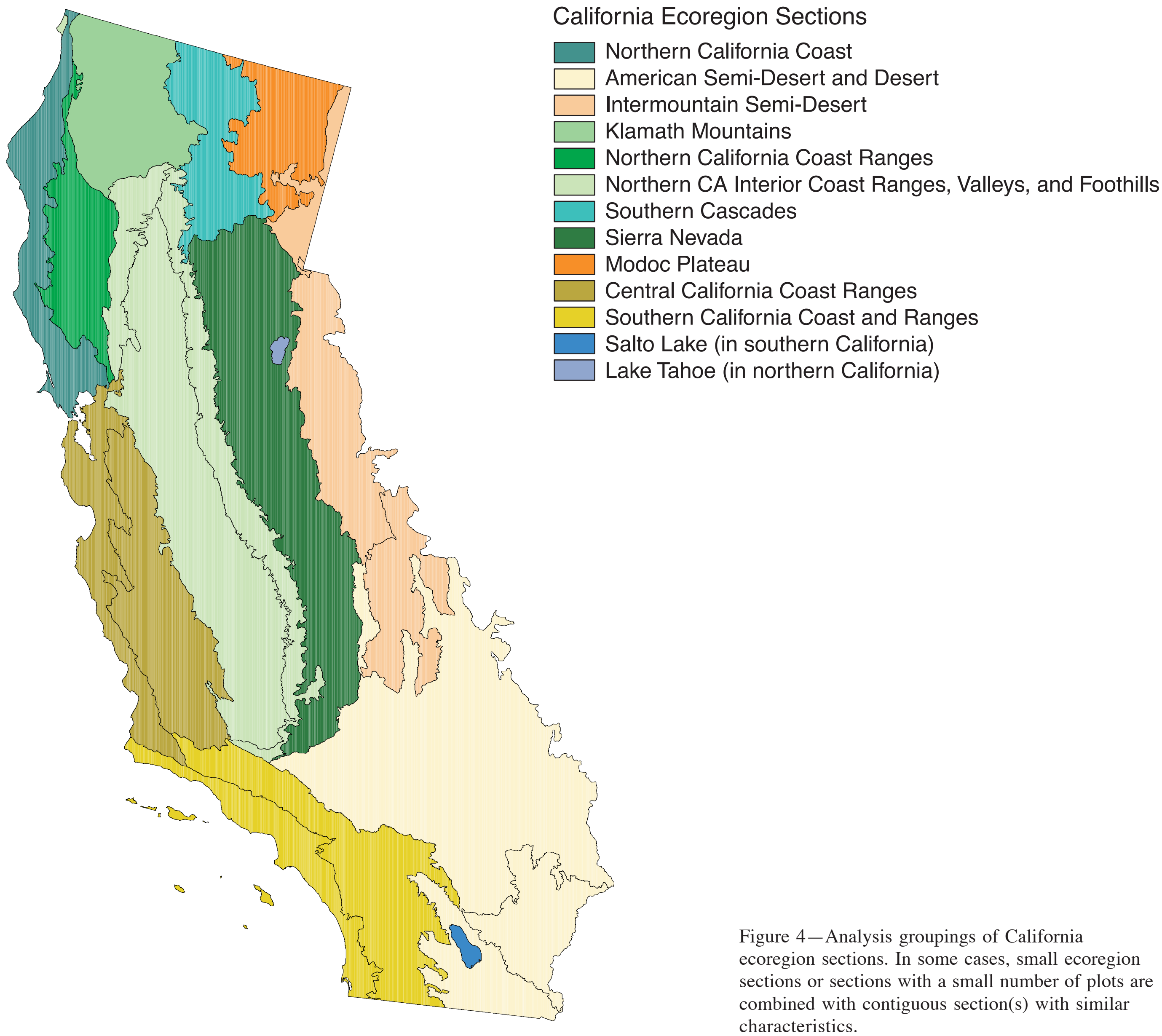

Figure 4—Analysis groupings of California ecoregion sections. In some cases, small ecoregion sections or sections with a small number of plots are combined with contiguous section(s) with similar characteristics.

determined the stress or damaging agent and the plot component determined the magnitude and direction of the forest's response to stresses or damaging agents.

Scale of Analysis

For analyses in this report, FHM plot data were aggregated spatially [plots that are in proximity to one another based on some geographic characteristic such as State or Bailey's (1995) ecoregion section] or by condition (plots are not proximal to one another but are grouped by some common characteristic such as forest type, age, or seral stage). In general, stresses or damaging agents, such as pollution and storms, affect forests on a spatial basis while insects and diseases affect forests on a condition basis (such as host or forest type). The minimum level of analysis in this report is the mean plot value of each variable or indicator by species or species group within some contiguous or noncontiguous grouping of approximately 2 million acres (see footnote 2). In some cases, small ecoregion sections are combined with contiguous sections with similar characteristics. These groupings are presented in figure 4 for California, figure 5 for Colorado, and figure 6 for eastern ecoregions. Some indicators, such as crown dieback, are evaluated by the mean change per plot within each group (ecoregion or forest type), while other indicators, such as tree species richness, are meaningful only over a large geographic area (ecoregion, administrative region, or State).

Analytical Procedures for Estimation from FHM Data

Procedures used in five aspects of data analysis are presented in this section: (1) estimating change over time within groups, (2) testing for differences in change over time among groups, (3) estimating change using covariates, (4) estimating plot values for unmeasured years, and (5) estimating heights. Included with the analytical procedures described are the indicators used as example analyses and a reference to where the analytical results can be found in this report.

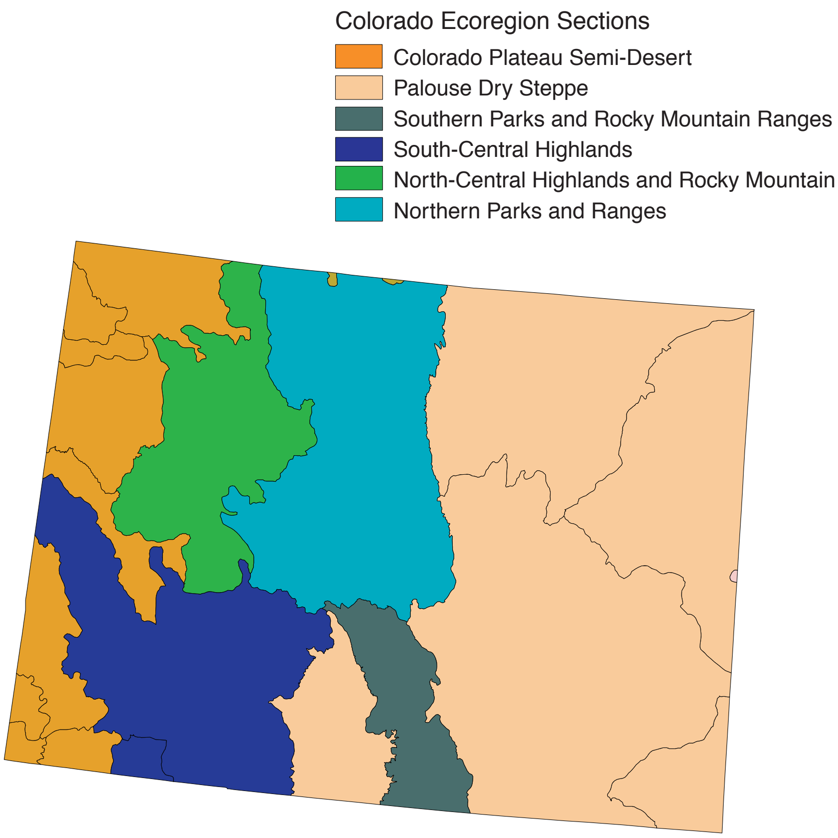

Figure 5—Analysis groupings of Colorado ecoregion sections. In some cases, small ecoregion sections or sections with a small number of plots are combined with contiguous section(s) with similar characteristics.

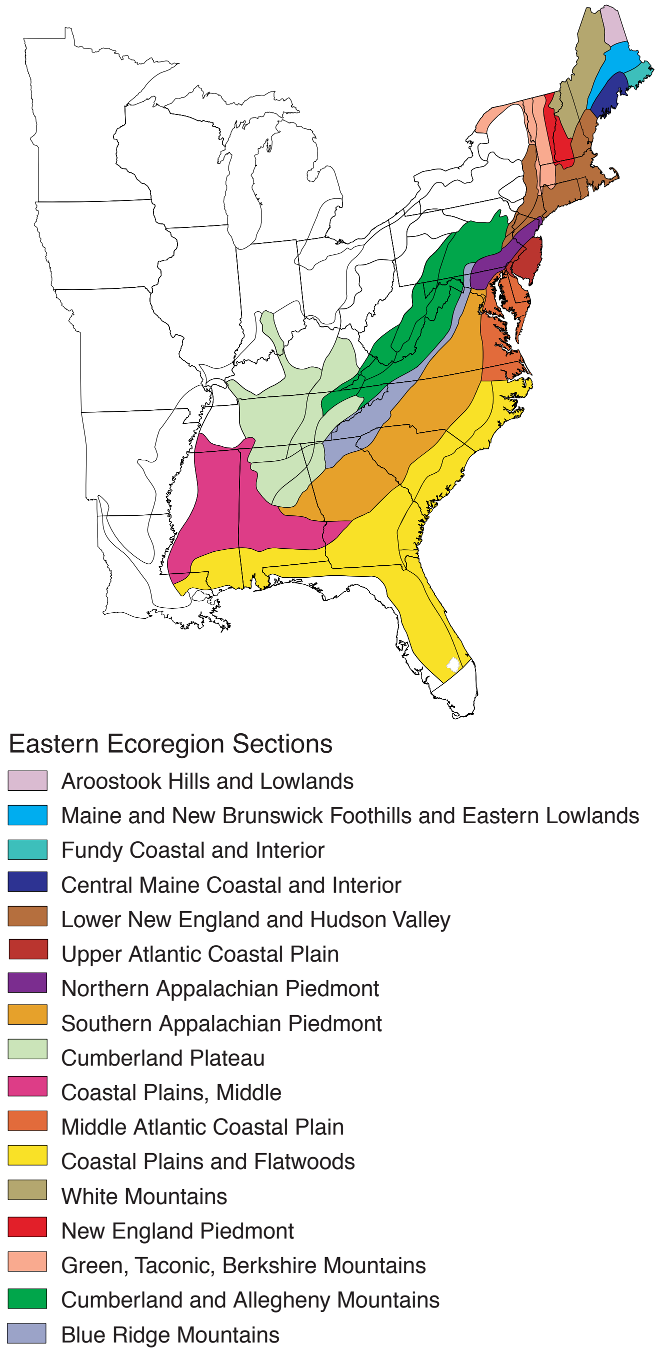

Figure 6—Analysis groupings of eastern ecoregion sections. In some cases, small ecoregion sections or sections with a small number of plots are combined with contiguous section(s) with similar characteristics.

Estimating Change Over Time Within Groups

The analysis for change is based on the general linear model:

$$y_{ij} = b_0 + b_1(t_j - t_0) + \eta_i + \varepsilon_{ij} \qquad \text{model (1)}$$

where

y_{ij} = the value of the indicator on plot *i* at time *j*
b_0 = estimated mean of the value of all plots at year 0
b_1 = estimated change in *y* over time
t_j = time of measurement *j*
t_0 = time of initial measurement
η_i = plot effect (spatial) variability
ε_{ij} = within-plot (temporal) variability

The measurement error, δ, is assumed to be normally distributed with a mean = 0 and variance = σ^2. This assumption is critical to detecting change. This requirement can be relaxed if it can be assumed that a nonzero measurement error (bias) does not change with time. For example, if the error in measurement is of a consistent direction and magnitude, the measurement of change is minimally affected by the measurement error. Because the current analysis method does not partition measurement error from random variation, all standard error, probability estimates, and R^2 statistics reflect both sources of error.

Both *Y* and *b* are estimated using a procedure that accounts for the fact that FHM data are often correlated over time (the value of measurements at time 2 are influenced by the values at time 1). For example, if in response to some stress factor a tree has significant crown dieback at time 1, the same tree is more likely to have crown dieback at time 2 than similar trees not exhibiting crown dieback at time 1 (see footnote 2).

This model is used to estimate mean change of plots within different groupings, such as ecoregion section and forest type, over time. An example of this procedure is presented in the sections "Assessment of Forest Health Based on the Santiago Criteria, Santiago Criterion 2—Maintenance of Productive Capacity of Forest Ecosystems, Estimation of Growth, Harvest, and Mortality" and "Assessment of Forest Health Based on the Santiago Criteria, Santiago Criterion 3—Maintenance of Forest Ecosystem Health and Vitality, FHM Measures of Crown Condition."

Testing for Differences in Change Over Time Among Groups

Insight into likely causal mechanisms behind the observed changes can be obtained by testing for differences among regions or forest types that have distinct attributes (climate, soils, species, etc.) or exposure to stressors. The differences in change over time among ecoregions or forest types can be tested using the following model:

$$Y_{(i+n),j,k} = b_0 + b_1(t_{(i+n),j,k} - t_{i,j,k}) + s_j + b_{1,j}(t_{(i+n),j,k} - t_{i,j,k}) + \eta_{i,j,k} + \varepsilon_{i,j,k} \quad \text{model (2)}$$

where

$Y_{i,j,k}$ = the value of Y at measurement i for plot j in group k

$t_{i,j,k}$ = the year of measurement i on plot j in group k

n = the interval between measurements

b_0 = the initial value of Y

b_1 = the annual change in Y

$b_{1,j}$ = the change in Y per change in unit x

s_j = group effect

$\eta_{i,j,k}$ = random variation among plots

$\varepsilon_{i,j,k}$ = random error over time within plots

An example of this procedure is presented in "Assessment of Forest Health Based on the Santiago Criteria, Santiago Criterion 3—Maintenance of Forest Ecosystem Health and Vitality, Testing for Equality of the Changes in Transparency Among Ecoregion Sections in Colorado."

Estimating Change Using Covariates

In analyses, the FHM Program uses data other than the plot component data, i.e., climate, precipitation, and ozone exposure. Data such as these are covariates to time. A covariate is a variable whose change influences the change in another variable. Adding these data to model 1 can provide insight into the causal mechanism underlying the estimated change in Y and a more precise estimate of the change:

$$Y_{(i+n),j} = b_0 + b_1(t_{(i+n),j} - t_{i,j}) + b_2(x_{(i+n),j} - x_{i,j}) + b_3(t_{(i+n),j} - t_{i,j})(x_{(i+n),j} - x_{i,j}) + \eta_{i,j} + \varepsilon_{i,j} \quad \text{model (3)}$$

where

Y_{ij} = the value of Y at measurement i for plot j

$t_{i,j}$ = the year of measurement i on plot j

x_{ij} = the value of a covariate at measurement i for plot j

n = the interval between measurements

b_0 = the initial value of Y

b_1 = the annual change in Y over time

b_2 = the change in Y per change in unit x

b_3 = the interaction between the change in x and the change in Y

$\eta_{i,j}$ = random variation among plots

$\varepsilon_{i,j}$ = random error over time within plots

In model 3, the value of x is a continuous variable rather than a class variable as in model 2. Examples of continuous variables are precipitation and ozone exposure that change over time. In model 2, S is a discrete class such as ecoregion, State, or forest type.

Model 1 is used to test whether Y changes over time. Model 2 is used to test whether the change over time is different among groups such as ecoregions or forest types. Model 3 is used to test whether the change over time is affected by other factors such as climate, precipitation, or ozone concentration. An example of analysis using model 3 is presented in "Assessment of Forest Health Based on the Santiago Criteria, Santiago Criterion 3—Maintenance of Forest Ecosystem Health and Vitality, Including Climatic Factors in Estimates."

Estimating Plot Values for Unmeasured Years

The parameter estimates resulting from the previous models can be used to predict plot or tree values for unmeasured years. This is particularly useful for displaying data spatially. As more mechanistic models are developed, the procedure can also be used to develop predictive models for future years based on current conditions.

In addition to estimating change, a major requirement of FHM is to make annual assessments of forest health status. Although FHM plots were measured on a 4-year interval, a benefit of the general least squares estimation procedure (model 1) and the FHM rotating panel design is the capacity to estimate plot values for unmeasured years. Although this facilitates spatial display and analysis, predicted values are never used in estimation. An example of this procedure is presented in "Assessment of Forest Health Based on the Santiago Criteria, Santiago Criterion 3—Maintenance of Forest Ecosystem Health and Vitality, Including BLUPs in Spatial Analysis." In addition to estimating plot values for unmeasured years, the procedure can be used to estimate the value of missed trees based on subsequent measurements.

These predicted values are referred to as BLUPs. BLUPs are best in that they have the minimum mean square error, linear in that they are linear functions of the data, unbiased in that the average value of the estimate is equal to the average value of the quantity being estimated, and predictors in that they are predictors of random effects (Robinson 1991). In this report they are used to predict the value of particular plot attributes; i.e., transparency and volume, from a population of random effects. This procedure maximizes the efficiency of unbalanced designs, such as those where not all samples are measured every year (Gregoire and others 1995). BLUPs are commonly used in quantitative genetics, statistical quality control, time series, and geostatistics (Christensen 1991, Robinson 1991). Given linear model 1, the BLUP for predicting the value of plot *i* at time *k* is:

$$blup(y_{ik}) = \underbrace{\hat{y}_{ik}}_{mean} + \underbrace{\frac{n_i\sigma^2_\rho}{\sigma^2_\varepsilon + n_i\sigma^2_\rho}}_{weight}\underbrace{\left(\bar{y}_i - \frac{1}{n_i}\sum_{j=1}^{n_i}\hat{y}_{ij}\right)}_{mean\ deviation}$$

$$= \hat{y}_{ik} + \frac{n_i\sigma^2_\rho}{\sigma^2_\varepsilon + n_i\sigma^2_\rho}\left(\frac{1}{n_i}\sum_{j=1}^{n_i}\left(y_{ij} - \hat{y}_{ij}\right)\right)$$

where

model (4)

y_{ik} = the value of plot *i* at time *k*

$\hat{y}_{ik}$ = the fitted value for plot *i* at time *k*, i.e., the expected value of all plots within an ecoregion

n_i = the number of measurements on plot *i*

y_{ij} = the value of plot *i* at time *j*

$\bar{y}$ = the mean of all measurements of plot *i*

σ^2_ρ = the between-plot variance

σ^2_ε = the residual within-plot (temporal) variance

The BLUP consists of the mean value of all plots within the group measured in year *k*, plus the mean deviation of the predicted values of plot *i* from the actual value in the years the plot was measured. Mean deviation is multiplied by a weight term, which reflects the number of times the plot was measured, and the plot and residual variance. Figure 7 illustrates the relationship between the weight with number of measurements and plot variance. To facilitate understanding, weight is plotted against correlation, *rho*,

where

$$rho = \frac{\sigma_\rho}{\sigma_\varepsilon + \sigma_\rho}$$

The weight increases as the number of measurements increases and/or the correlation over time increases. This reflects the statistical confidence in the estimate. If the estimate is based on very few measurements or the correlation over time is small, the weight approaches 0 and the best estimate of the plot value is the mean of the population.

This procedure contrasts with traditional regression estimates in that the plot factor (s_i) accounts for spatial variation between plots, and the within-plot error (ε_{ij}) reflects the variation over time as well as the mean ($\hat{y}_k$) of all plots within the ecoregion or forest type. The BLUP is composed of two components: (1) an estimate of the mean value of all plots within the group, in this case ecoregion section or forest type; and (2) a component that reflects where the plot fits within the distribution of plots in the group. The procedure can be better understood by examining a few simple numerical examples.

For example, a plot was measured in years 1 and 4 and an estimate of the plot value at year 5 is needed. Assuming the model is $\hat{y}_j = 10 + 2(t_j - t_o)$, the estimate for year 0 is 10 and change over the 5-year interval is 2 units per year. Then the mean value of all plots in the section is 10 + 2(5) or 20. If, in addition, correlation with time is 0.7, and observed and predicted values for the plot are:

Year	0	1	2	3	4	5	mean
Observed	•	3	•	•	5	•	4
Fitted	•	5	•	•	12	•	8.5

then the average deviation from the observed value is 4 - 8.5 = - 4.5; that is, in years when plot *i* was measured, its average was 4.5 units less than the mean of the fitted values. Therefore, the BLUP for year 5 is 20 + weight (-4.5). For this illustration the appropriate weight can be determined from figure 7. A correlation of 0.7 with two measurements gives a weight of 0.8. The best estimate of the value of plot *i* in year 5 is 20 + 0.7(-4.5) = 16.85.

The behavior of this estimate can be better understood by considering some other possible conditions relating to this example:

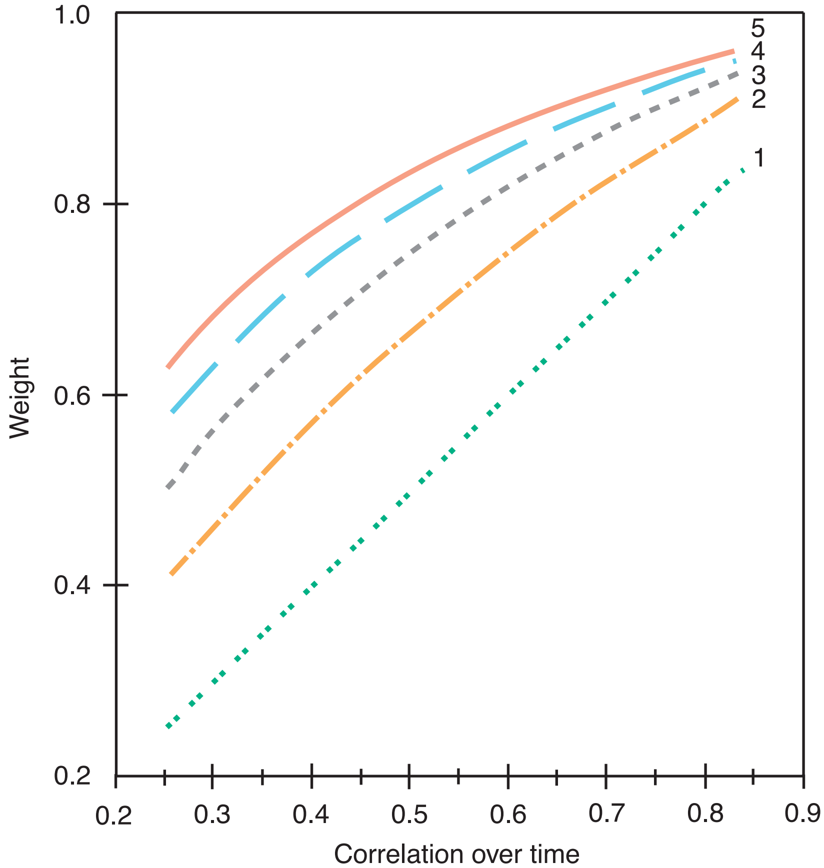

Figure 7—Relationship between correlation over time and number of times a plot has been measured with weight of Best Linear Unbiased Predictions adjustment. The numerical annotation on the graph is the number of times the plot was measured.

1. When predicting the value of a plot that has never been measured, mean deviation is 0 and the best estimate is the mean of all plots in the group (20).
2. If the plot value in the first measurements was 5 greater than the mean, and at the second measurement the value was 5 less than the mean, then mean deviation is 0 and the best estimate for year 5 is again 20, the mean estimate of all plots in the group. The mean deviation of 0.0 indicates that the within-plot variability is probably due to measurement error or seasonal variability, in contrast to the initial example where the plot was consistently lower (-4.5) than the mean of all plots.
3. If the correlation over time was 0.3 instead of 0.7, the weight would be approximately 0.45 instead of 0.8 (fig. 7). This would indicate a high degree of within-plot variability due to measurement error or seasonal variability, and the best estimate is 20 + 0.45(-4.5) = 18.0.

The precision of BLUP estimation was evaluated on FHM plots using data collected in the Northern region from 1991 through 1996. Figure 8 shows the sequence of measurements taken in that region. Prior to 1996, every plot was measured every year in that region. The parameters for model 4 were estimated using FHM data, but omitting the plots measured in 1995, indicated by a “Y” in the figure. The values for those plots were predicted using the BLUP equation described, and compared with the actual values from the plots. This procedure independently tested the precision of the estimates. Table 1 and figure 9 present the results of the test. The goodness-of-fit of the BLUP values is comparable to that when the actual values are used. For

Year⇒ Panel⇓	1991	1992	1993	1994	1995	1996
0	X				X	X/3
1	X				Y	X
2	X				Y	
3	X			X		

Figure 8—Sequence of measurements for the Forest Health Monitoring (FHM) North region. Measurement years consistent with the FHM sampling design (1997–99) are indicated with an "X." The "Y" indicates the years and plots used to test the Best Linear Unbiased Predictions.

example, the R^2 of hardwood dieback for all forest types was 0.65 (table 1) for the BLUPs compared to R^2s that ranged from 0.06 (oak-hickory) to 0.79 (natural yellow pine) for the actual data (table 2). The R^2 of volume was 0.99 (table 1) for the BLUPs compared to R^2s of 0.98 to 0.99 for the actual data (table 3).

Estimating Heights

Addressing many of the Santiago criteria requires a measure of forest vertical structure. This requirement ranges from tree heights for estimating productivity and carbon sequestration, to vertical structure for estimating wildlife habitat suitability, e.g., the presence of a midstory in a forest's vertical structure lowers pine warbler habitat

Table 1—Results of BLUP evaluation using Forest Health Monitoring northern data from 1991 through 1996

Indicators	BLUP R^2	Mean deviation	Mean	Deviation	Measured R^2
				percent	
Hardwood dieback	0.49	0.61	9.92	6.15	0.65
Hardwood transparency	0.20	0.65	13.56	4.82	0.36
Softwood dieback	0.29	0.29	5.79	4.95	0.53
Softwood transparency	0.38	0.61	9.92	6.14	0.48
Volume (ft^3 per acre)	0.99	-12.7	2,217.2	-0.57	0.99
Mortality (ft^3 per acre)	0.16	16.34	129.1	12.66	0.41
Carbon sequestration (pounds per acre)	0.95	740.9	66,702.9	1.11	0.95

BLUP = Best Linear Unbiased Predictions; R^2 = a measure of goodness-of-fit of the estimate.

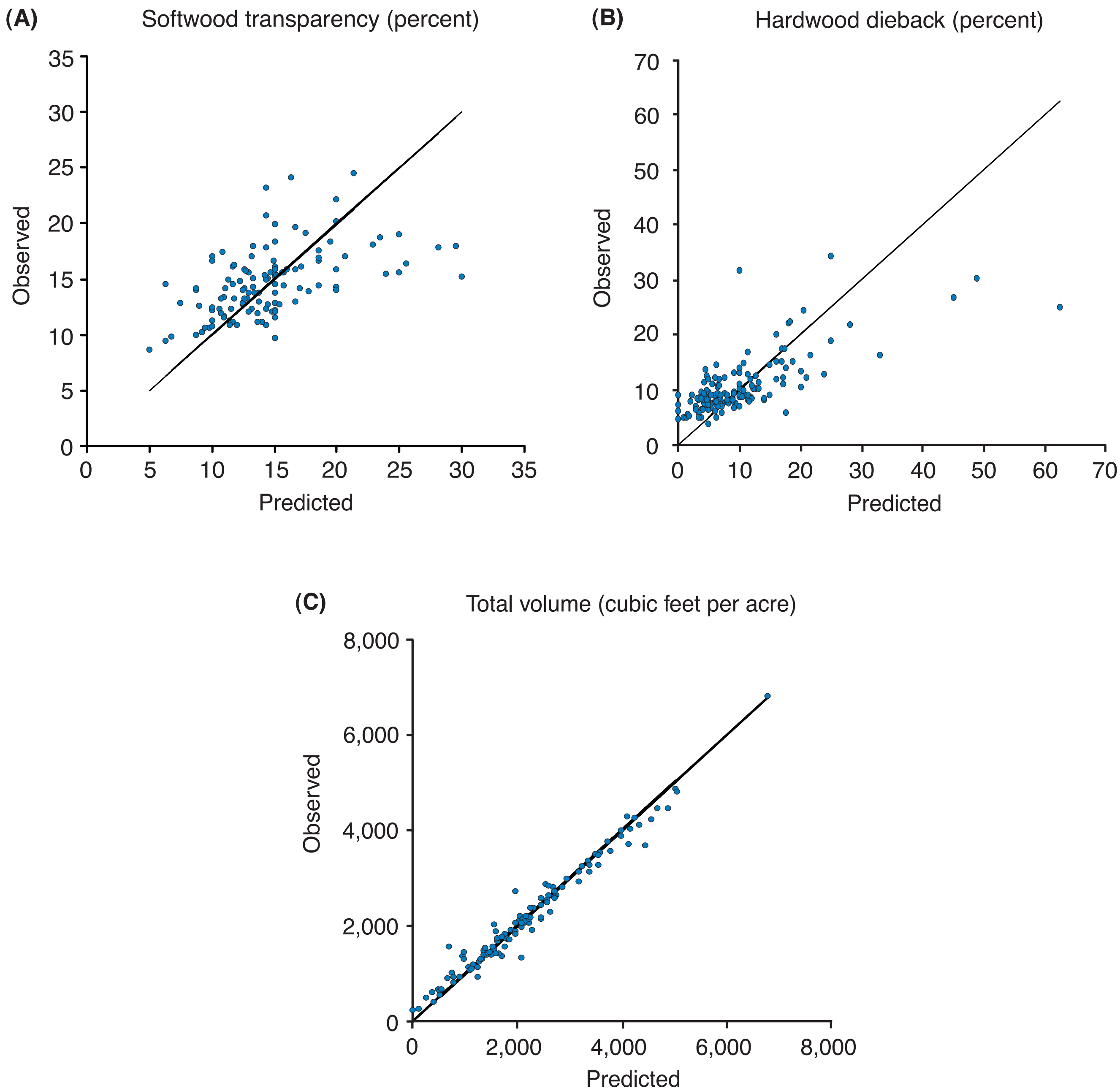

Figure 9—Plots of observed vs. predicted values for northeastern forest types: (A) softwood transparency, (B) hardwood dieback, and (C) total volume. Observed values are actual values for 1995 that would not have been measured under the Forest Health Monitoring design starting in 1997. Predicted values were estimated using the 1997 design, i.e., plots that would not have been measured were deleted for the estimation.

Table 2—Dieback of northeastern hardwood by forest type

Forest type	n	Estimate of value in 1991	Estimate of change	Standard error of estimate	R^2	Degrees of freedom	Value of *t*	Pr > *t*
White-red-jack pine	115	6.21	1.12	0.32	0.667	91	3.51	0.001
Spruce-fir	245	9.56	0.86	0.31	0.669	195	2.80	0.006
Natural yellow pine	20	7.40	0.71	0.44	0.792	15	1.61	0.128
Oak-pine	60	6.24	0.58	0.37	0.167	47	1.58	0.122
Oak-hickory	52	6.29	0.19	0.36	0.059	40	0.53	0.600
Bottomland hardwood	20	7.09	-0.65	0.57	0.089	15	-1.14	0.272
Birch-beech-maple	445	7.47	0.82	0.14	0.754	355	6.06	0.000
Aspen-birch	35	6.68	0.16	0.47	0.109	27	0.33	0.742

n = Total number of measurements over time, including repeat measurements; estimate of value in 1991 = average value at the initial year of measurement; estimate of change = annual change over the time interval; standard error of estimate = a measure of the variability of the data; R^2 = a measure of goodness-of-fit of the estimate; degrees of freedom = number of repeat measurements -2; value of *t* = a measure of the variability of the data relative to the mean; Pr > *t* = probability that the estimated change was due to random chance and that the true change over the interval was 0.

Table 3—Volume growth of softwood and hardwood by forest type in the Northeast

Forest type	n	Estimate of change	Standard error of estimate	R^2	Degrees of freedom	Value of *t*	Pr > *t*
		cubic feet per acre					
White-red-jack pine	71	67.4	12.5	0.987	41	5.38	0.000
Spruce-fir	148	46.1	7.8	0.982	83	5.94	0.000
Natural yellow pine	12	41.8	31.7	0.983	6	1.32	0.235
Oak-pine	35	25.6	18.2	0.996	20	1.40	0.175
Oak-hickory	30	50.4	20.7	0.995	15	2.43	0.028
Bottomland hardwood	9	19.8	37.6	0.997	4	0.53	0.626
Birch-beech-maple	224	45.6	6.6	0.985	127	6.91	0.000
Aspen-birch	20	24.8	26.4	0.977	10	0.94	0.370

n = Total number of measurements over time, including repeat measurements; estimate of change = annual change over the time interval; standard error of estimate = a measure of the variability of the data; R^2 = a measure of goodness-of-fit of the estimate; degrees of freedom = number of repeat measurements -2; value of *t* = a measure of the variability of the data relative to the mean; Pr > *t* = probability that the estimated change was due to random chance and that the true change over the interval was 0.

suitability. Although FHM did not measure tree heights across all diameter classes, the heights of one or two dominant or codominant trees (site trees) were measured on most plots. Since 2000, colocation with FIA/CVS plots has eliminated this limitation.

However, using FHM data through 1999, individual tree heights can be estimated using published, regional height/diameter equations of various forms, e.g., (Bechtold and Zarnoch in an unpublished report[4]), Ek and others (1984), Garman and others (1995), Moore and others (1996).

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

Greater accuracy in estimation is obtained by conditioning the equation through the measured heights of dominant (codominant) trees. This conditioning approach is commonly used in growth and yield models (Clutter and others 1983).

The simplest regional height/diameter equation is of the form:

$$\log(H) = a + b / D$$

where

H = total height

D = d.b.h. (4.5 feet above the ground)

a = species- and region-specific estimate of the intercept

b = species- and region-specific estimate of the slope

This can be conditioned through the dominant height of the stand since

$$\log(H_d) = a + b / D_d$$

where

H_d = the average total height of the dominant trees

D_d = the average d.b.h. of the dominant trees

Combining the two equations results in the following equation:

$$\log(H_i) = \log(H_d) + b(1/D_i - 1/D_d)$$

where

H_i = the predicted height of the i^{th} tree

D_i = the measured diameter of the i^{th} tree

Figure 10 provides an example of this procedure. The model is plotted in the exponential form,

$$H_i = H_d\, e^{(1/D_i - 1/D_d)}$$

In this example the tree heights relative to the tree diameters are greater than the regional average, probably reflecting better site quality or the influence of management. The procedure described adjusts the heights to reflect those differences.

When species occur on the plot that are not represented by a site tree of the same species, the procedure is modified. In this case the height is estimated using dominant heights and diameters of species present on the plot, and then is

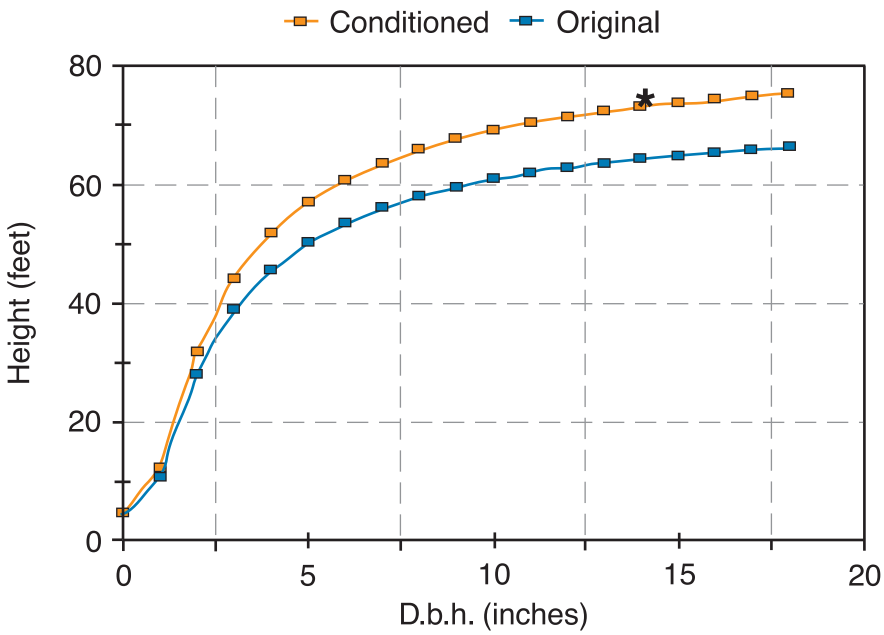

Figure 10—Regional height/diameter model conditioned through measured height (*).

adjusted using site-index-species conversion factors, e.g., Ek and others (1984). For example, if the site index for the site-tree species is 100 and the equivalent site index of the subject tree is 80, then the height of the subject tree is reduced by 20 percent. Height estimates, used to estimate tree volume for the productivity and carbon content in the sections "Assessment of Forest Health Based on the Santiago Criteria, Santiago Criterion 3—Maintenance of Forest Ecosystem Health and Vitality, FHM Measures of Crown Condition" and "Assessment of Forest Health Based on the Santiago Criteria, Santiago Criterion 5—Maintenance of Forest Contribution to Global Carbon Cycles, Sequestration of Atmospheric Carbon in Trees" were calculated using site-index-species conversion factors to adjust all heights.

Estimates of plot volume were calculated with tree heights estimated using the conditioning procedures, and were used in the section "Assessment of Forest Health Based on the Santiago Criteria, Santiago Criterion 2—Maintenance of Productive Capacity of Forest Ecosystems, Estimation of Growth, Harvest, and Mortality." Although harvested trees are recorded on FHM plots, harvest estimates were not included in this report due to lack of robustness in making estimates from severely discontinuous data with small sample sizes.

Assessment of Forest Health Based on the Santiago Criteria

The following sections are organized using the Santiago criteria; they present the results of analyses using the five techniques previously discussed.

Santiago Criterion 1—Conservation of Biological Diversity

Introduction—Biological diversity is considered a key attribute of ecosystem sustainability (Anon. 1995). Both the number of species (richness) and the relative abundance of species (evenness) are of interest when evaluating plant diversity. Overall plant biological diversity is expressed differently in different forest types and seral stages; there may be different woody and nonwoody understory and midstory species as well as different overstory trees. This report focuses on the tree component of biodiversity as expressed by number of tree species.

Number of tree species by ecoregion—Plant diversity, like many other aspects of forest health, is dynamic both temporally and spatially. For example, stand development causes changes in species composition over time, and stand disturbances—including management—can cause changes spatially. For the most part, this dynamic process can be stopped only by urbanization, soil loss through erosion, or physical damage such as compaction.

Table 4 presents the maximum numbers of tree species per plot present in the overstory and the understory, and total tree species richness for each ecoregion section. Richness is defined here as the number of unique species irrespective of structure location (overstory or understory). For example, the Southern Appalachian Piedmont Ecoregion Section (in the South) has 16 species in the overstory, 9 in the understory, and a tree species richness of 20, indicating that 5 species occur in both the understory and overstory. Figure 11 spatially presents tree species richness within ecoregion sections. Comparisons of richness among regions are not as meaningful as richness comparisons over time for individual regions, because climatic and edaphic factors differ among regions. For example, diversity among tree species is expected to be greater in the Southeast than in the West; within the Southeast, tree species diversity is expected to be greater in the mountains than on the coastal plain due to the history of periodic fires on the coastal plain. Diversity changes over time within each region are indicative of relative states of forest health. For example, evidence of changes in plant communities due to climate change is reflected first in woody and nonwoody vegetation in the understory (Devall and Parresol 1994).

Santiago Criterion 2—Maintenance of Productive Capacity of Forest Ecosystems

Introduction—The ultimate measure of health in an ecosystem is its ability to support and sustain plant growth. In the absence of inherent poor site quality, poor plant growth invariably indicates the presence of some biotic or abiotic constraint (Pankhurst 1994).

Estimation of growth, harvest, and mortality—The definition of growth used in this analysis is traditionally used in calculating growth from permanent plots (Beers 1962, Meyer 1953, Society of American Foresters 1984). For a further discussion on the growth calculations used, see appendix B. In this report, net growth is referred to as growth.

Table 5 presents the estimates of growth and mortality for each forest type by FHM region. In California, for example, mixed conifers (last entry in table 5) experienced an annual growth from 1992 to 1996 of -96.4 cubic feet

Table 4—Maximum number of tree species in the overstory and understory, and total tree species richness by province or ecoregion section for each Forest Health Monitoring region in 1997

FHM region	Province or ecoregion section	Overstory	Understory	Tree species richness
		- - - - - - - -	*number*	- - - - - - - -
North	Aroostook Hills and Lowlands Section	12	3	15
	Maine and New Brunswick Foothills and Eastern Lowlands Section	11	4	12
	Fundy Coastal and Interior Section	9	2	9
	Central Maine Coastal and Interior Section	9	6	15
	Lower New England and Hudson Valley Sections	13	6	16
	Upper Atlantic Coastal Plain Section	6	2	7
	Northern Appalachian Piedmont Section	12	1	12
	White Mountains Section	13	8	14
	New England Piedmont Section	11	8	14
	Green, Taconic, Berkshire Mountains Section	12	5	12
South	Southern Appalachian Piedmont Section	16	9	20
	Coastal Plains, Middle Section	16	6	16
	Southern Cumberland Plateau Section	17	7	20
	Middle Atlantic Coastal Plain Section	14	5	15
	Coastal Plains and Flatwoods Sections	14	8	15
	Cumberland and Allegheny Mountains Sections	13	5	15
	Blue Ridge Mountains Section	13	6	17
Interior West	Palouse Dry Steppe Province	3	1	4
	Southern Parks and Rocky Mountain Ranges Section	4	1	5
	South-Central Highlands Section	5	1	5
	North-Central Highlands and Rocky Mountain Sections	5	1	5
	Northern Parks and Ranges Section	6	1	6
	Colorado Plateau Semi-Desert Province	4	0	4
West Coast	Northern California Coast Section	7	1	7
	Intermountain Semi-Desert and Desert Province	3	0	3
	Klamath Mountains Section	6	4	9
	Northern California Coast Ranges Section	6	3	6
	Northern California Interior Coast Ranges, Valleys, and Foothills Section	6	2	6
	Southern Cascades Section	5	2	6
	Sierra Nevada Section	8	2	8
	Modoc Plateau Section	4	1	5
	Southern California Coast and Ranges Section	3	1	3

FHM = Forest Health Monitoring.

per acre per year and mortality of 125.3 cubic feet per acre per year. Drought- and insect-induced mortality has been observed in this forest type, primarily in white and red fir (Dale 1996), which contributed to the negative growth estimate.

Santiago Criterion 3—Maintenance of Forest Ecosystem Health and Vitality

Introduction—An insightful definition of tree health and vitality is presented by Shigo (1996):

- Vitality—the ability to grow under the dynamic conditions present

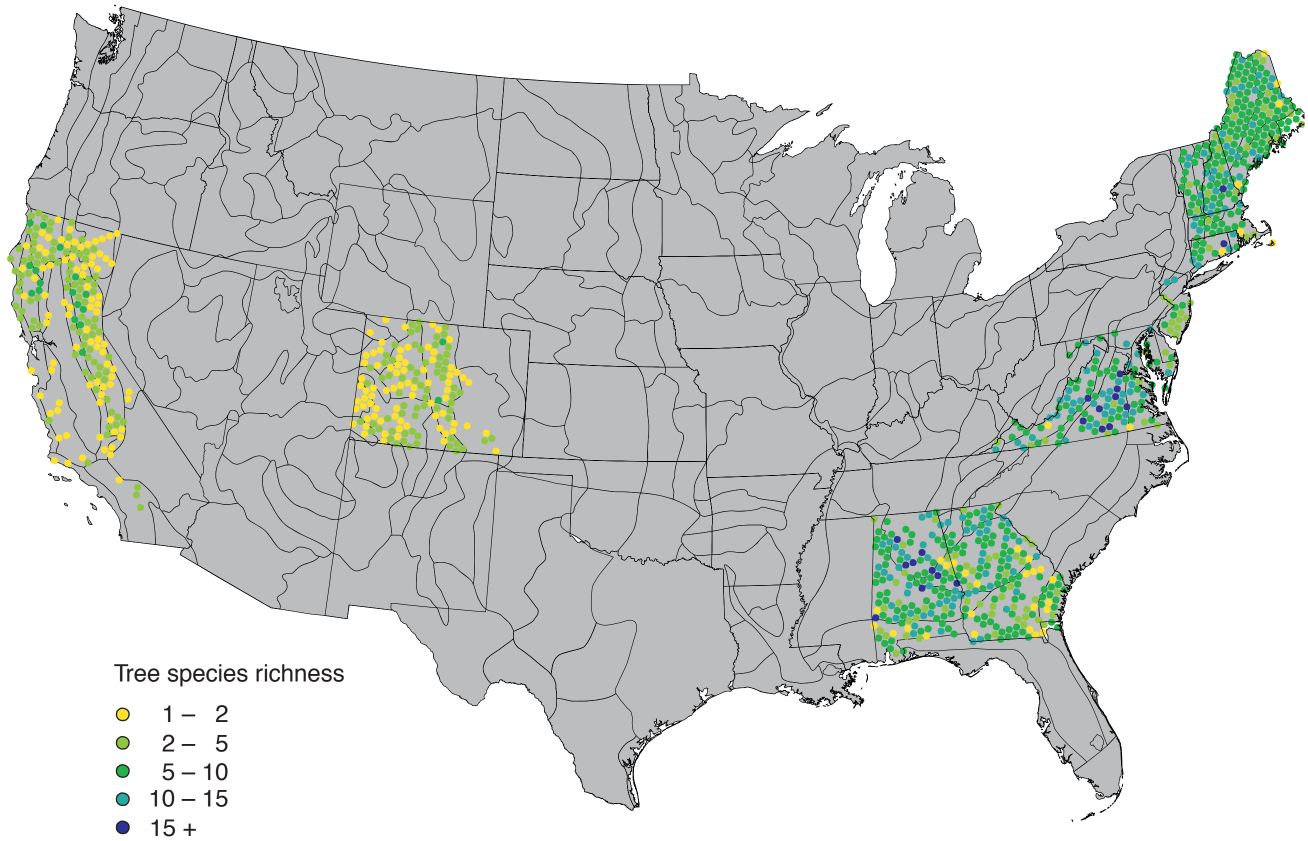

Figure 11—Number of unique tree species by Forest Health Monitoring plot in 1997.

- Stress—a condition wherein a system begins to operate near the limits of its design
- Strain—disruption in a system operated beyond the limits of stress
- Health—the ability to resist strain

Applying these definitions to forests, a healthy and vital forest ecosystem has the capacity to function and grow within the range of historic variation. In response to normal stresses, such as drought, trees have developed adaptations such as dieback and precocious loss of foliage. Pushed beyond stress conditions considered normal, a forest may become unhealthy and lack vitality. For example, a forest that has evolved under a fire disturbance regime can grow with endemic levels of insects and diseases. If fire exclusion results in a dramatic change in tree species composition, the ecosystem balance can be affected. If the fire-resistant species are encroached by fire-susceptible species that are also susceptible to insects and diseases, the insect and disease population can reach epidemic levels. Even resistant tree species can be susceptible at epidemic levels. Similarly, anthropogenic pollutants are by definition beyond the level of historic variation and may affect the forest's capacity to grow or reproduce.

Forest health and vitality were measured on FHM plots using crown dieback, transparency, mortality (dead tree d.b.h./live tree d.b.h. ratio), tree damage, and evidence of specific insect, disease, and abiotic stressors from FHM and FHP survey data.

FHM measures of crown condition—The predominant measure for assessing forest health worldwide has been based on visual assessment of tree crowns and foliage (Innes 1993). Crown dieback is branch mortality that begins at the terminal and proceeds toward the stem in response to biotic or abiotic stressors. In many cases this is an adaptation to local or temporal stressors such as drought or root damage. When the stress is alleviated, the tree grows normally with only a structural change such as

Table 5—Annual growth and mortality of softwood and hardwood by Forest Health Monitoring region or State and forest type from 1992 to 1996

FHM region or State	Forest type	Growth	Standard error of growth	Mortality	Standard error of mortality
		- - - - - - - -	- - - - - - - - *ft*^{3} *per acre*	- - - - - - - -	- - - - - - - -
Northeast[a]	White-red-jack pine	55.5	10.2	28.9	4.3
	Spruce-fir	36.6	6.3	30.1	3.4
	Natural loblolly-shortleaf	35.8	17.3	5.4	1.1
	Oak-pine	18.5	6.0	19.7	3.3
	Oak-hickory	42.6	6.1	14.6	4.0
	Bottomland hardwood	-0.2	11.5	60.8	12.7
	Birch-beech-maple	39.9	5.5	29.8	2.4
	Aspen-birch	16.0	18.7	52.7	16.4
South[b]	White-red-jack pine	92.55	74.02	20.14	14.24
	Natural slash-longleaf pine	63.45	12.63	11.05	5.95
	Planted slash-longleaf pine	75.66	25.72	4.04	1.78
	Natural loblolly-shortleaf pine	55.39	13.55	29.89	8.14
	Planted loblolly-shortleaf pine	173.1	20.57	7.86	2.10
	Oak-pine	54.71	7.04	22.29	4.13
	Oak-hickory	37.96	5.12	20.59	3.70
	Bottomland hardwood	49.28	8.12	15.74	5.00
Colorado	Douglas-fir	30.80	3.22	13.9	9.4
	Lodgepole pine	6.71	8.63	14.9	5.3
	Ponderosa pine	21.54	9.05	0.0	0.0
	Englemann spruce	48.86	14.08	1.6	0.8
	Quaking aspen	16.01	6.65	9.8	2.5
	Gambel oak	13.60	2.98	0.0	0.0
	Pinyon-juniper	0.90	1.21	0.1	0.1
California	Douglas-fir	50.6	36.1	34.31	12.45
	Lodgepole pine	53.3	3.3	0.38	0.29
	Jefferey pine	17.7	10.1	2.41	1.53
	Ponderosa pine	29.3	26.3	25.22	13.38
	White fir	43.4	34.6	73.89	24.55
	California red fir	47.0	22.0	1.00	0.65
	Tanoak	141.8	27.0	10.24	4.07
	Oak–decidious	28.6	27.8	10.32	4.83
	Blue oak	48.3	23.3	5.52	2.74
	Oak–evergreen	35.8	11.8	0.0	—
	Pinyon-juniper	2.3	2.2	0.0	—
	Mixed conifers	-96.4	100.1	125.3	61.97

FHM = Forest Health Monitoring.
— = No mortality occurred in this forest type.
[a] States include: Connecticut, Delaware, Maine, Maryland, Massachusetts, New Hampshire, New Jersey, Rhode Island, Vermont, and West Virginia.
[b] States include: Alabama, Georgia, and Virginia.

the development of crook or forking. Although these structural changes can result in severe loss of a tree's value as a timber product, other ecological processes proceed unabated.

A FHM field measurement related to dieback is loss of apical dominance, dead terminal. If dieback progresses to the point where no branches on the dead part of the stem are < 1 inch, the condition is no longer classified as dieback but as a dead terminal. In this analysis, when trees initially identified with dieback show declining dieback and increasing dead terminal over the same time period, the value assigned to dieback is the maximum of the two measures. In figure 12, the tree on the left represents the initial measurement with no crown dieback. The middle tree represents the same tree with 20 percent dieback at the first remeasurement. The tree on the right represents the same tree at the second remeasurement, and because all the dead branches have dropped off, it would be recorded as having a dead terminal at 20 percent and no dieback. The dieback value alone erroneously implies that the tree recovered from dieback when it had actually worsened. In the analysis for this report, the dieback value remained at 20 percent.

Foliar transparency is the percentage of light visible through the normally foliated portion of the crown. Like dieback, this can be a normal adaptation to climatic stress. An example of an adaptation is needle cast in response to drought or as the result of insect, diseases, or anthropogenic pollutants. Specific stressors related to both dieback and transparency are described in Stolte (1997).[5]

[5] Stolte, K.W. 1997. 1996 national technical report on forest health. [Research Triangle Park, NC]: U.S. Department of Agriculture, Forest Service, Southern Research Station. 47 p. Administrative report FS–605. On file with: Forestry Sciences Laboratory, Southern Research Station, P.O. Box 12254, Research Triangle Park, NC 27709.

Examples of crown dieback and transparency are in tables 2 and 6. Determining whether specific values represent a problem is a function of the magnitude of the change, which is very species specific, and the confidence in the estimate. Although the FHM Program has established a significance probability level of 0.10 as the sampling objective, changes with a lower probability level, e.g., FIA uses 0.33, may be important given the specific forest health issue, value, location, etc., addressed.

Testing for equality of the changes in transparency among ecoregion sections in Colorado—Analyzing the differences in rate of change in softwood transparency among four sections of the Southern Rocky Mountains Steppe Province in Colorado provides an example of how testing among groups can give insight into probable causal mechanisms behind changes over time resulting from differences in climate, soils, species, or exposure to stressors. Table 7 presents the analysis using model 2, while figure 13 graphically illustrates the initial condition and change between 1992 and 1996.

The test of fixed effects in table 7 indicates that a significant change in foliar transparency occurred over time and that the change over time differed among ecoregion sections (indicated by “a” and “b” in figure 13). The Pr > F of 0.0001 in the test of fixed effects means that the probability was 1 in 10,000 that the estimated change was a result of random chance and not some causal mechanism. The CONTRAST statement results (table 7) indicate that the annual increase in the North-Central

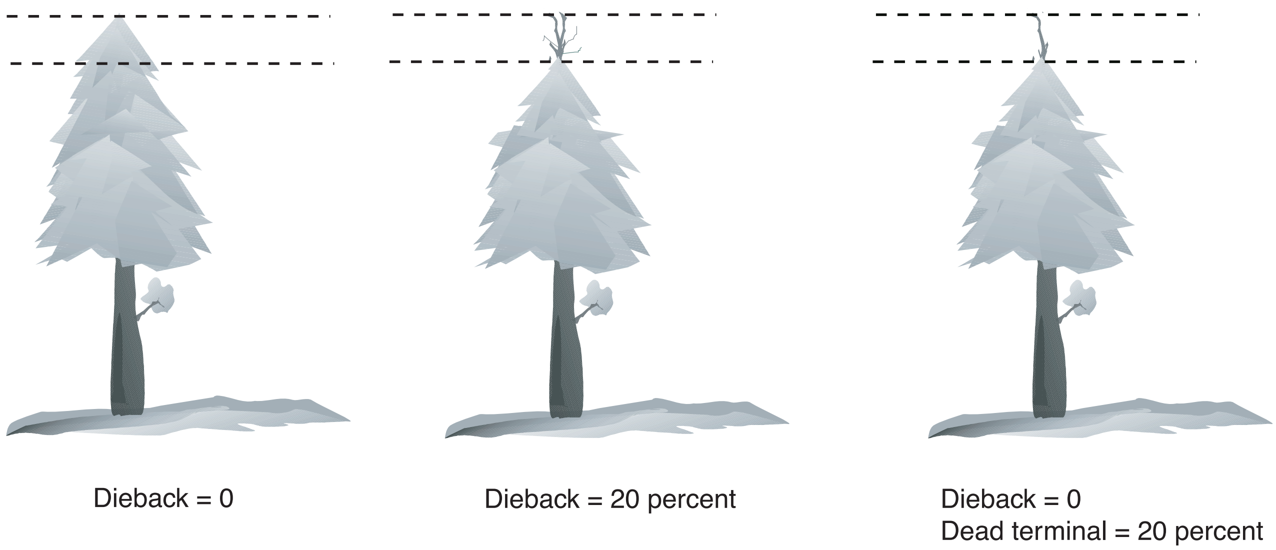

Figure 12—Relationship between dieback and dead terminal.

Table 6—Foliar transparency of Colorado softwood by province or ecoregion section

Province or ecoregion section	n	Estimate of value in 1992	Estimate of change	Standard error of estimate	R^2	Degrees of freedom	Value of *t*	Pr > *t*
Palouse Dry Steppe Province	15	6.30	1.19	0.14	0.985	1	8.39	0.076
Southern Parks and Rocky Mountain Ranges Section	10	4.93	3.12	0.30	0.797	1	10.33	0.061
South-Central Highlands Section	52	6.29	1.36	0.34	0.251	14	4.04	0.001
North-Central Highlands and Rocky Mountain Sections	17	3.92	2.49	0.20	0.919	2	12.54	0.006
Northern Parks and Ranges Section	56	7.02	1.79	0.11	0.908	13	16.50	0.000
Colorado Plateau Semi-Desert Province	18	6.34	1.70	0.63	0.353	3	2.71	0.073

n = Total number of measurements over time, including repeat measurements; estimate of value in 1992 = average value at the initial year of measurement; estimate of change = annual change over the time interval; standard error of estimate = a measure of the variability of the data; R^2 = a measure of goodness-of-fit of the estimate; degrees of freedom = number of repeat measurements -2; value of *t* = a measure of the variability of the data relative to the mean; Pr > *t* = probability that the estimated change was due to random chance and that the true change over the interval was 0.

Table 7—Results of analysis of variance to test the equality of the change in foliar transparency in Colorado softwood among ecoregion sections [PROC MIXED (SAS Institute 1996)]

Source[a]	NDF	DDF	Type III F	Pr > F
		Tests of fixed effects		
Year	1	35	92.28	0.0001
Year * ecosection	3	35	3.22	0.0342
		CONTRAST statement results		
Section A * section B	1	35	1.05	0.3122
Section A * section C	1	35	0.12	0.7341
Section A * section D	1	35	0.56	0.4594
Section B * section C	1	35	3.21	0.0819
Section B * section D	1	35	9.29	0.0044
Section C * section D	1	35	0.21	0.6477

[a] Section A = Southern Parks and Rocky Mountain Ranges; section B = South-Central Highlands; section C = North-Central Highlands and Rocky Mountains; section D = Northern Parks and Ranges.

Highlands and Rocky Mountain (2.49) and Northern Parks and Ranges (1.79) Sections was significantly greater than the increase of 1.36 in the South-Central Highlands Section (table 6). Several characteristics about the sections provide direction for future analysis. Of these three sections, the North-Central Highlands and Rocky Mountain Section showed the greatest increase in transparency, i.e., foliage is getting sparser. A large power plant is located in this section. In addition to increased transparency, a decrease in lichen diversity has been observed. The section with the smallest, although increasing, change of these three sections was the South-Central Highlands, the section with the highest rainfall. The Northern Parks and Ranges Section had the highest population and associated pollution (industry, fireplaces, etc.). As stated earlier, this insight[6] provides direction for future analysis and mitigating measures.

Including climatic factors in estimates—The FHM Program also uses non-USDA Forest Service data in analyses. For example, the PDSI is used in model 3 to assess the impact of drought on change in foliar transparency in California. The PDSI is an empirically derived index based on total rainfall, the periodicity of the rainfall, and soil characteristics such as water-holding capacity. Figure 14 presents the PDSI for seven climatic regions in California and the corresponding values of foliar transparency for the years 1992 and 1996. The foliar transparency was intersected with PDSI to test to what degree the observed change in crown condition can be attributed to the change in PDSI (tables 8 and 9).

[6] Personal communication. 1998. Michael Schomaker, Colorado State Forest Service, 203 Forestry Building, Colorado State University, Fort Collins, CO 80523–5060.

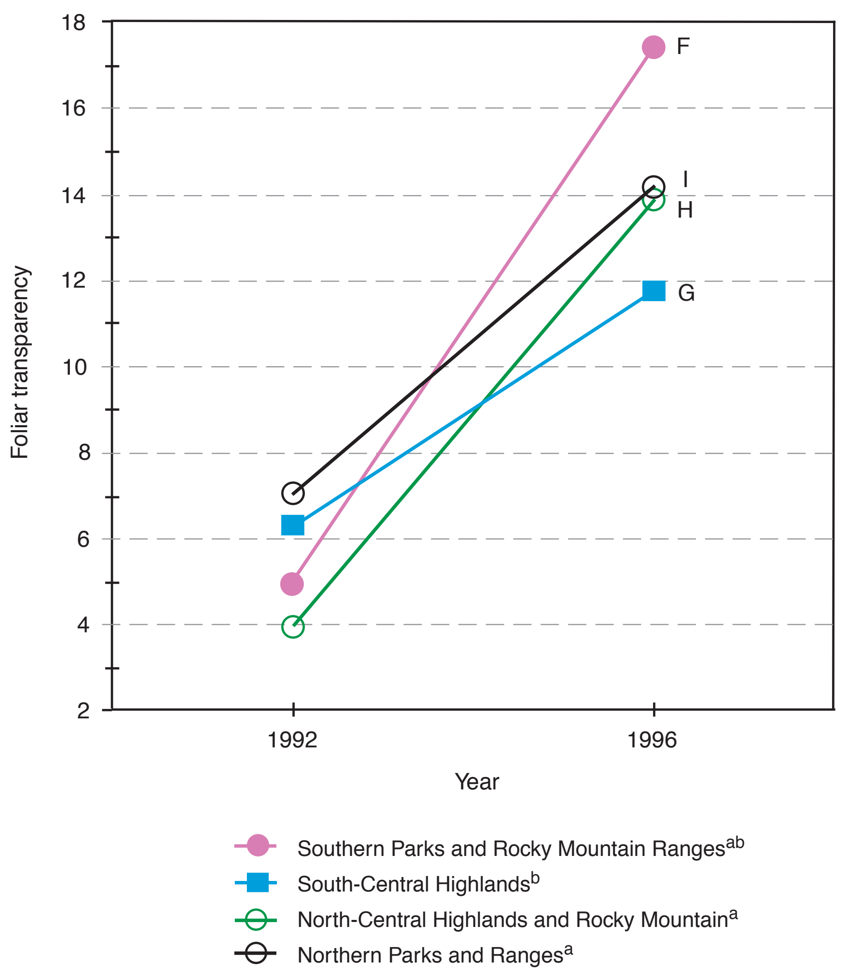

Figure 13—Change in softwood foliar transparency for four ecoregion sections located in the Southern Rocky Mountains Steppe Province in Colorado (1997). Sections with letters in common were not significantly different at the 0.10 probability level.

Analysis suggests that year and the interaction between year and PDSI may be significant factors in the change in foliar transparency. Table 8 indicates that transparency decreased over time, decreased with increasing PDSI, and the Year*PDSI interaction was significant. Table 9 shows that blue oak, oak–evergreen, and mixed-conifer forest types had a significant decrease in transparency over time and with increasing PDSI.

In contrast, Douglas-fir and ponderosa pine decreased in transparency, but the relationship with increasing PDSI was not significant. A cursory analysis suggests that the initial poor transparency in 1992 was not drought related as is indicated in the blue oak, oak–evergreen, and mixed-conifer types. Although this simple analysis does not explain the process itself, it demonstrates the power in the procedure and suggests its usefulness in analyzing more subtle factors such as ozone and other pollutants.

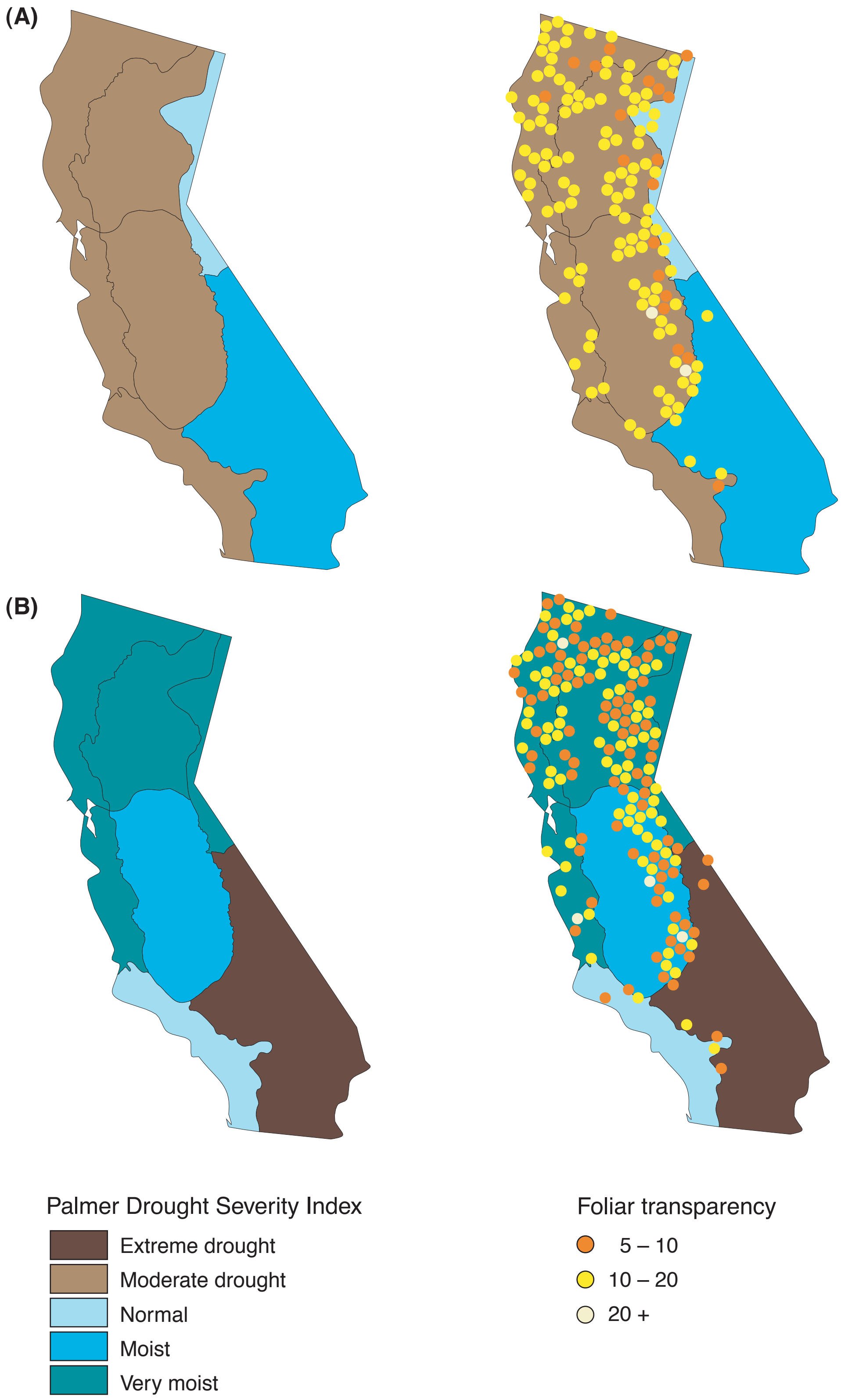

Figure 14—Comparison of Palmer Drought Severity Index and foliar transparency in California in (A) 1992 and (B) 1996.

Table 8—Results of analysis of variance to test significance of change in foliar transparency in California to change in Palmer Drought Severity Index [PROC MIXED (SAS Institute 1996)]

	Solution for fixed effects				
Parameter	Estimate	Standard error	Degrees of freedom	Value of *t*	Pr > *t*
Intercept	13.93981621	0.50116905	168	27.81	0.0001
Year	-1.27370858	0.25366039	53	-5.02	0.0001
PDSI	- 0.42381249	0.26584618	53	-3.30	0.0017
Year * PDSI	0.23836641	0.10288753	53	3.22	0.0022

PDSI = Palmer Drought Severity Index; degrees of freedom = number of repeat measurements -2; value of *t* = a measure of the variability of the data relative to the mean; Pr > *t* = probability that the estimated change was due to random chance and that the true change over the interval was 0.

Table 9—Results of analysis of variance to test significance of change in foliar transparency by forest type in California to change in Palmer Drought Severity Index [PROC MIXED (SAS Institute 1996)]

Parameter	Estimate	Standard error	Degrees of freedom	Value of *t*	Pr > *t*
		Douglas-fir			
Intercept	16.78766120	0.93546449	9	17.95	0.0001
Year	-4.42007989	0.72100990	1	-6.13	0.1029
PDSI	-1.08510212	0.34923821	1	-3.11	0.1982
Year * PDSI	0.80593644	0.17486038	1	4.61	0.1360
		Lodgepole pine			
Intercept	10.43072545	1.61618715	4	6.45	0.0030
Year	-0.14547244	0.45234293	0	-0.32	—
PDSI	0.13923832	0.57031957	0	0.24	—
Year * PDSI	-0.01091106	0.16474579	0	-0.07	—
		Jeffrey pine			
Intercept	11.19010980	3.41683302	5	3.27	0.0221
Year	3.51280668	1.94643187	0	1.80	—
PDSI	-1.31407184	1.49945396	0	-0.88	—
Year * PDSI	-0.20290791	0.53965409	0	-0.38	—
		Ponderosa pine			
Intercept	14.40996203	1.09218854	12	13.19	0.0001
Year	-2.33336064	0.93585584	4	-2.49	0.0672
PDSI	-0.16755919	0.41990673	4	-0.40	0.7103
Year * PDSI	0.28029481	0.20574172	4	1.36	0.2447
		White fir			
Intercept	6.23110158	1.65610312	11	3.76	0.0031
Year	1.56456571	0.85272008	0	1.83	—
PDSI	0.82073571	0.72994874	0	1.12	—
Year * PDSI	-0.41380309	0.26623328	0	-1.55	—

(continued)

Table 9—Results of analysis of variance to test significance of change in foliar transparency by forest type in California to change in Palmer Drought Severity Index [PROC MIXED (SAS Institute 1996)] (continued)

Parameter	Estimate	Standard error	Degrees of freedom	Value of *t*	Pr > *t*
California red fir					
Intercept	11.87348178	1.48086567	7	8.02	0.0001
Year	-1.63858286	2.53061496	2	-0.65	0.5837
PDSI	-0.72063537	0.52523306	2	-1.37	0.3037
Year * PDSI	0.38342295	0.50636533	2	0.76	0.5280
Tanoak					
Intercept	13.53924557	1.43523951	6	9.43	0.0001
Year	-0.46545367	3.31550260	5	-0.14	0.8938
PDSI	-0.97943545	0.72869723	5	-1.34	0.2367
Year * PDSI	0.21083092	0.70546794	5	0.30	0.7771
Oak–deciduous					
Intercept	17.12126497	2.68575164	6	6.37	0.0007
Year	-2.83476979	1.64234355	1	-1.73	0.3343
PDSI	-1.96286207	1.77768703	1	-1.10	0.4685
Year * PDSI	0.77370159	0.61230748	1	1.26	0.4262
Blue oak					
Intercept	17.06350213	1.34180898	19	12.72	0.0001
Year	-3.03316617	1.03607430	5	-2.93	0.0327
PDSI	-1.78170568	0.68448076	5	-2.60	0.0481
Year * PDSI	0.67541451	0.25963152	5	2.60	0.0482
Oak–evergreen					
Intercept	16.89438632	1.77780313	24	9.50	0.0001
Year	-1.61712203	0.57863387	3	-2.79	0.0682
PDSI	-1.46727088	0.73019200	3	-2.01	0.1381
Year * PDSI	0.47978064	0.22267746	3	2.15	0.1202
Pinyon-juniper					
Intercept	10.73759529	1.73602316	16	6.19	0.0001
Year	-0.58961533	0.70256678	2	-0.84	0.4897
PDSI	0.64492988	0.65147120	2	0.99	0.4265
Year * PDSI	-0.23278898	0.22062881	2	-1.06	0.4020
Mixed conifers					
Intercept	13.53400976	0.65617231	30	20.63	0.0001
Year	-1.34167446	0.37345714	5	-3.59	0.0157
PDSI	-0.77074669	0.28249972	5	-2.73	0.0414
Year * PDSI	0.33028711	0.12580859	5	2.63	0.0468

PDSI = Palmer Drought Severity Index; degrees of freedom = number of repeat measurements -2; value of *t* = a measure of the variability of the data relative to the mean; Pr > *t* = probability that the estimated change was due to random chance and that the true change over the interval was 0.
— = Insufficient sample size.

Including BLUPs in spatial analysis—In figure 15, a display of the status of hardwood dieback using only the measured plots (panel 0 and overlap from panel 3) is compared with a display that includes the predicted values of all unmeasured plots (panels 1, 2, and 3) in addition to the measured plots. The comparison illustrates the benefit of using the BLUP procedure. In figure 15 the map on the left displays only the plots measured in 1995. All the plots in New Jersey are in the 0 to 5 dieback class. By random chance the plots measured in that year had minimal dieback, implying good health. In contrast, the map on the right includes the predicted values of all plots not measured in 1995. Four of the 14 plots in the State are in the 2 most severe dieback classes, which implies that approximately one-third of the State is in poor health (concentrated in the southern part).

Mortality—Tree mortality is a natural and essential process in normal stand dynamics. In fact, the absence of mortality can be a useful indicator of poor stand vigor, which often leads to catastrophic conditions of forest health.

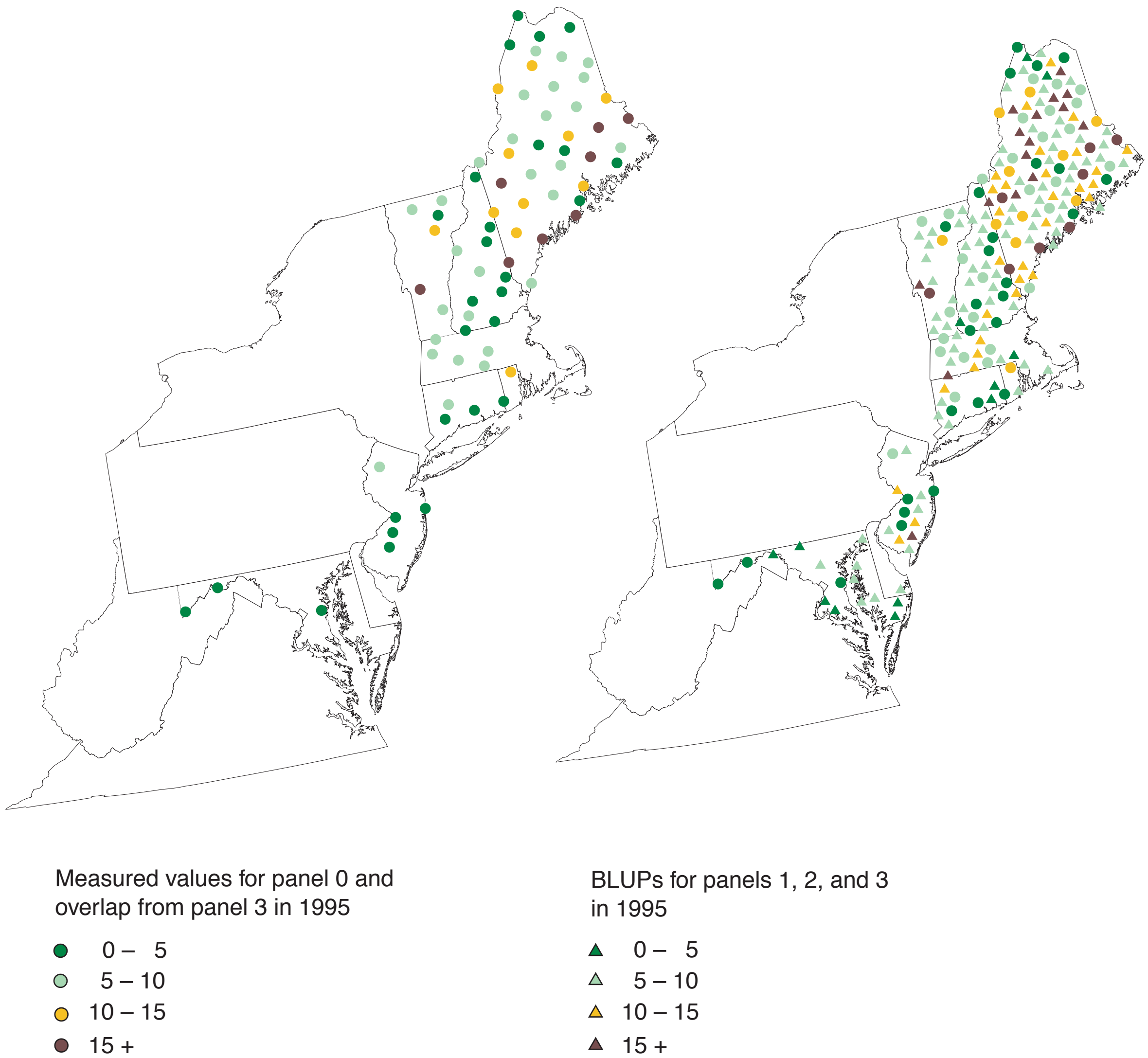

Figure 15—Status of hardwood dieback in the Forest Health Monitoring (FHM) North region using only measured plots compared with the status of hardwood dieback in the FHM North region including the predicted values [Best Linear Unbiased Predictions (BLUP) estimation procedure of all nonmeasured plots].

An informative indicator of mortality relative to forest health is the ratio of the diameter of dead trees to the diameter of live trees (MD/LD). The dead trees in this ratio are the trees that have died since the previous diameter measurement. A low ratio (much less than 1) indicates that the mortality observed is composed primarily of smaller trees that are probably part of the natural self-thinning development of the forest. A higher ratio (much greater than 1) indicates that mortality is due to senescence or some external factor such as insects or diseases. Figure 16 illustrates the plot level average of MD/LD. In California, the Sierra Nevada Section shows an MD/LD ratio of 1.4. Although FHM did not identify causal agents on the plots, the mortality of large trees [red fir (*A. magnifica*)] in that section was associated with attacks by fir engravers (*Scolytus ventralis)* (Dale 1996).

Santiago Criterion 5—Maintenance of Forest Contribution to Global Carbon Cycles

Introduction—It is widely suggested that the increased concentration of greenhouse gases, including carbon dioxide, will result in climate change in most regions of the World. There are many ways of mitigating this effect that relate to trees and forests. Tree- and forest-based methods include increasing forest growth, planting trees, minimizing loss of carbon to the atmosphere through catastrophic mortality, and making efficient use of harvested material and salvaged mortality.

Sequestration of atmospheric carbon in trees—Carbon storage is an important factor affecting the increase of carbon dioxide concentrations in the atmosphere and the

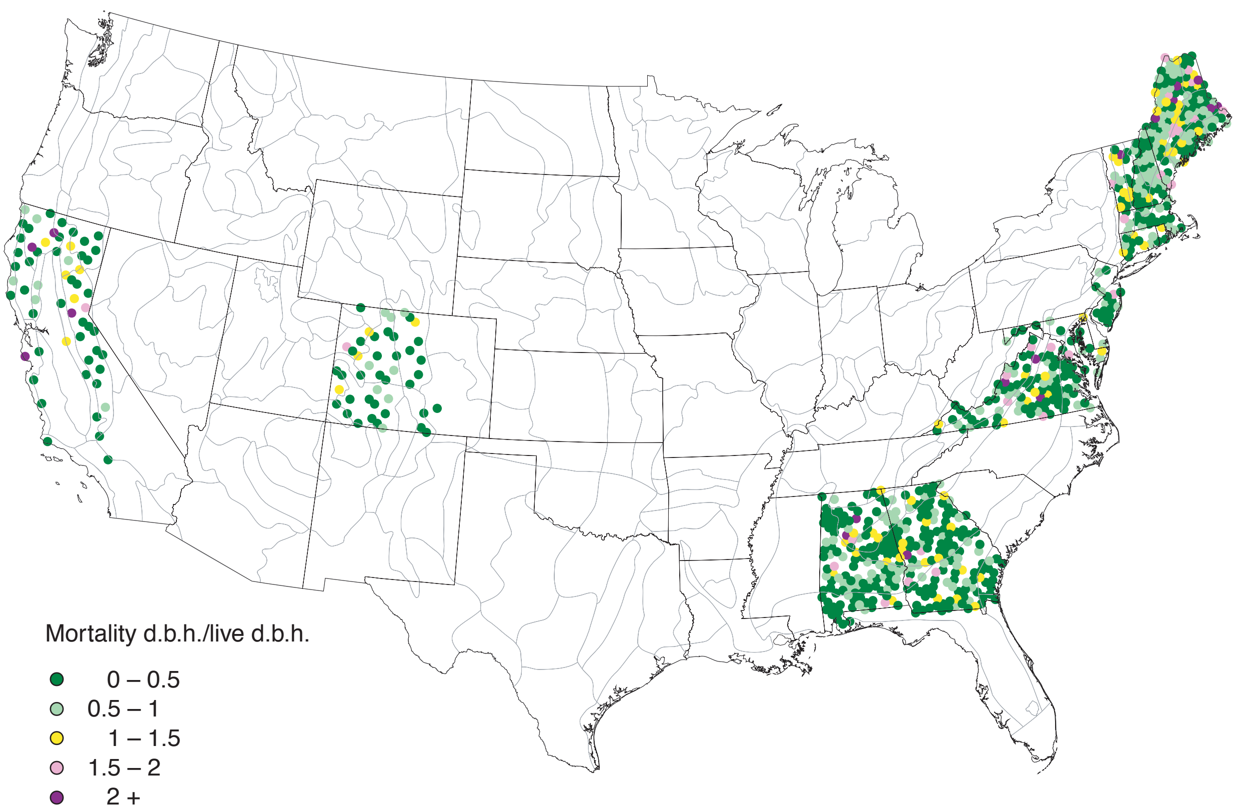

Figure 16—Spatial pattern of the ratio of the diameter of trees that died from 1992 to 1996 to the diameter of trees still living in 1996.

resulting global warming. Trees use carbon from the atmosphere as they grow. Dead trees lose carbon to the atmosphere as they decay. Approximately one-half of the carbon harvested as biomass is stored for long periods as wood products. The amount of carbon stored or lost annually from FHM plots was estimated for variable time periods from 1990 to 1996. Carbon sequestration rates are determined using tree volume data from FHM plots and estimates of other carbon (belowground, downed woody debris) from published information (Birdsey 1996). Carbon storage was estimated by determining the biomass of the living boles and roots of all trees and saplings and then subtracting (1) the biomass of the trees that died, and (2) approximately one-half of the biomass of the trees that were harvested over the same time period. This one-half represents the proportion of harvested biomass that is used in a durable form, e.g., bound books, wooden structures, etc. (Birdsey 1996). A net gain is the result of increased stand growth and the efficient utilization of harvest trees and salvaging of mortality. Figure 17 presents the spatial distribution of estimated net annual carbon sequestration or storage for each FHM plot.

Several regions showed significant losses in carbon. In California most of the losses were in the Sierra Nevada Section, where mortality was substantial due to drought and other contributing factors (table 10). The Coastal Plains and Flatwoods Section of the Southeast showed a net gain in carbon, primarily in planted loblolly pine (*P. taeda*) (table 11).

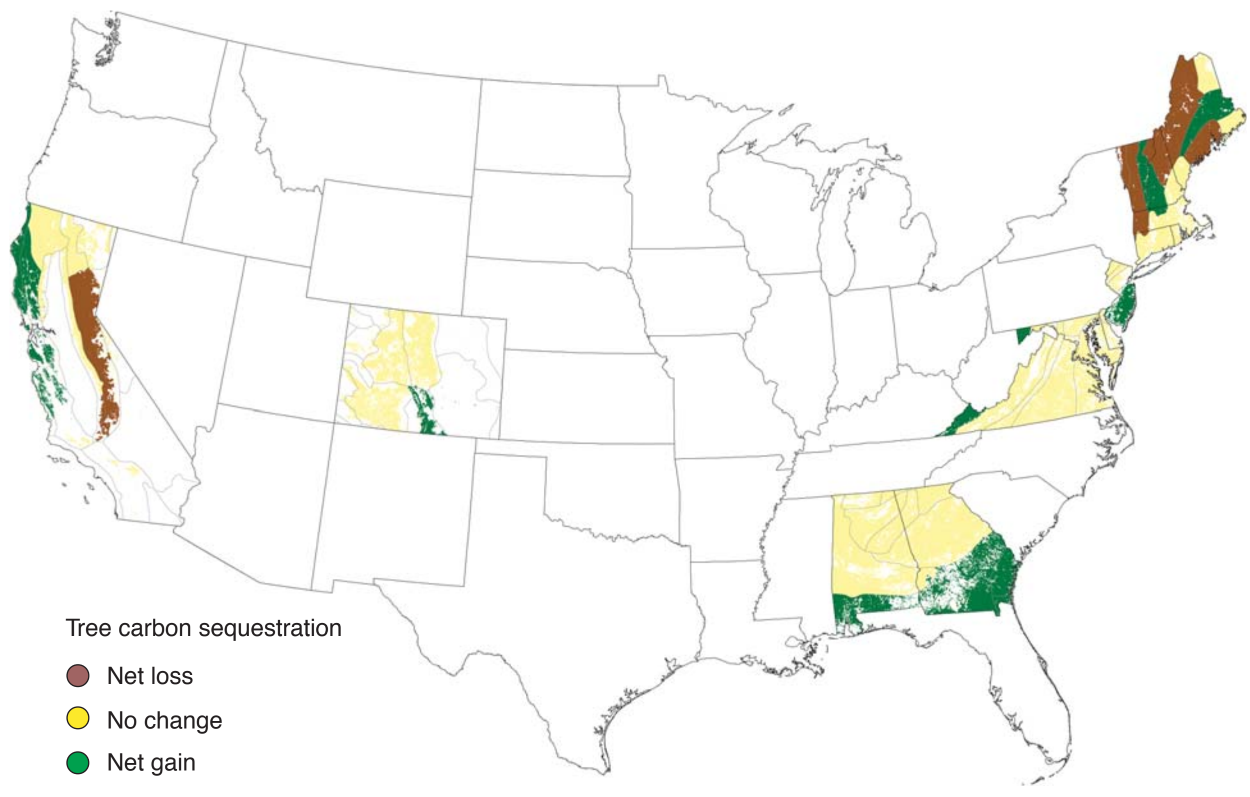

Figure 17—Rate of carbon sequestration in all tree species from 1992 to 1996 by ecoregion section.

Table 10—Tree carbon of softwood and hardwood by province or ecoregion section in California

Province or ecoregion section	n	Estimate of change	Standard error of estimate	R^2	Degrees of freedom	Value of t	Pr > t
		- - - *pounds per acre* - - -					
Northern California Coast Section	21	4,050.74	1,184.75	0.9974	5	3.42	0.019
American Semi-Desert and Desert Province	10	180.07	170.37	0.9999	1	1.06	0.482
Klamath Mountains Section	34	-1222.5	1,683.78	0.9901	8	-0.73	0.488
Northern California Coast Ranges Section	17	2,363.43	596.45	0.9995	3	3.96	0.029
Northern California Interior Coast Ranges, Valleys, and Foothills Section	26	253.07	360.79	0.9968	5	0.70	0.514
Southern Cascades Section	24	206.29	430.75	0.9987	6	0.48	0.649
Sierra Nevada Section	74	-1776.7	1,530.35	0.9825	16	-1.16	0.263
Modoc Plateau Section	17	164.06	151.47	0.9998	3	1.08	0.358
Central California Coast Ranges Section	13	2,417.45	1,143.97	0.9908	2	2.11	0.169
Southern California Coast and Ranges Section	9	873.51	678.38	0.9998	1	1.29	0.420

n = Total number of measurements over time, including repeat measurements; estimate of change = annual change over the time interval; standard error of estimate = a measure of the variability of the data; R^2 = a measure of goodness-of-fit of the estimate; degrees of freedom = number of repeat measurements -2; value of t = a measure of the variability of the data relative to the mean; Pr > t = probability that the estimated change was due to random chance and that the true change over the interval was 0.

Table 11—Tree carbon of softwood and hardwood by province or ecoregion section in the East

Province or ecoregion section	n	Estimate of change	Standard error of estimate	R^2	Degrees of freedom	Value of t	Pr > t
		- - - *pounds per acre* - - -					
Aroostook Hills and Lowlands Section	28	318.2	772.7	0.961	14	0.41	0.687
Maine and New Brunswick Foothills and Eastern Lowlands Section	66	889.6	604.5	0.942	37	1.47	0.150
Fundy Coastal and Interior Section	15	335.3	973.1	0.985	7	0.34	0.741
Central Maine Coastal and Interior Section	45	-1,128.2	746.9	0.945	25	-1.51	0.144
Lower New England and Hudson Valley Sections	106	-413.1	610.5	0.949	60	-0.68	0.501
Upper Atlantic Coastal Plain Section	27	849.2	284.7	0.994	14	2.98	0.001
Northern Appalachian Piedmont Section	7	-3,814.8	3,606.6	0.808	3	-1.06	0.368
White Mountains Section	164	-1,210.7	475.7	0.951	93	-2.54	0.013
New England Piedmont Section	44	3,094.7	673.4	0.978	24	4.60	0.000
Green, Taconic, Berkshire Mountains Section	47	-1,196.0	1,132.7	0.897	27	-1.06	0.300
Southern Appalachian Piedmont Section	218	-166.4	661.3	0.927	108	-0.25	0.802
Coastal Plains, Middle Section	124	336.4	737.2	0.883	61	0.46	0.650
Cumberland Plateau Sections	72	237.7	897.8	0.922	35	0.26	0.793
Middle Atlantic Coastal Plain Section	58	-300.6	1,006.6	0.973	30	-0.30	0.767
Coastal Plains and Flatwoods Sections	165	701.2	525.8	0.970	81	1.33	0.186
Cumberland and Allegheny Mountains Sections	56	771.2	850.5	0.948	27	0.91	0.373
Blue Ridge Mountains Section	40	1,019.3	1,185.4	0.952	19	0.86	0.401

n = Total number of measurements over time, including repeat measurements; estimate of change = annual change over the time interval; standard error of estimate = a measure of the variability of the data; R^2 = a measure of goodness-of-fit of the estimate; degrees of freedom = number of repeat measurements -2; value of t = a measure of the variability of the data relative to the mean; Pr > t = probability that the estimated change was due to random chance and that the true change over the interval was 0.

Summary and Future Assessments

After completing at least one 4-year cycle measurement in some regions, the FHM Program can reliably estimate change in forest health. National FHM assessments are based on the Santiago Declaration: "Criteria and Indicators for the Conservation and Sustainable Forest Management of Temporate and Boreal Forests." Through 1999, FHM measured indicators that contribute information to address four of the seven Santiago criteria: (1) conservation of biological diversity, (2) maintenance of productive capacity of forest ecosystems, (3) maintenance of forest ecosystem health and vitality, and (5) maintenance of forest contributions to global carbon cycles.

In addition to data collected directly as part of the plot and survey components of detection monitoring, FHM uses data from other sources such as other FHP data, FIA data, NFS data, and other related weather and air quality data. These ancillary data are vital to the interpretation of plot data and the assessment process.

The data and data analysis procedures presented in this report show that FHM data are useful in assessing the status and change of forest health. Several data gaps that must be addressed are also identified. The lack of complete vegetative structure information or plant counts in all height components of the forest ecosystem represents a vital data gap. Although collocation of FHM, FIA, and NFS/CVS plots has helped fill this data gap that could be used to assess biodiversity, both FIA (phase 2) and NFS must measure plots during all seasons, increasing the difficulty in detecting and identifying nonwoody plants. As of 1999, FHM was the only program that logistically could measure only during the growing season. In addition to the tree species diversity information collected by FHM, other indicators, such as lichen communities, contributed plant biodiversity information.

More complete tree-height data from ground plots are also needed to improve determination of growth. Growth information is important to assessing the maintenance of forest ecosystem productive capacity. Although at present, tree volumes must be calculated using estimated tree heights, the resulting growth information is useful on a regional scale.

Other FHM data that contribute to the productive capacity assessment are tree mortality, crown dieback, and crown foliar transparency. The data on these indicators can also be used in the procedures presented in this report to predict plot values for unmeasured years. These prediction procedures highlight one of the benefits of the FHM rotating panel sampling design.

FHM assessments are at the point of integrating nonplot data and the data collected as part of the ground plot system. An example of nonplot data presented in this report is climate data (PDSI). In addition, preliminary inferences on causal agents and processes are suggested from insect and disease survey reports (Dale 1996). This step provides the framework for more meaningful interpretation of information. Other kinds of ancillary data, such as remotely sensed landscape data, are being investigated for inclusion in future assessments.

Carbon sequestration is an important part of monitoring the forest contribution to global carbon cycles. FHM data used to determine tree volume could be combined with published information to estimate carbon sequestration rates.

Acknowledgments

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Appendix A

Interpreting FHM Tables

All estimates for the following tables were derived using PROC MIXED (SAS Institute 1996).
Definitions of table output:

Dieback	branch mortality that begins at the terminal and proceeds toward the stem
Foliar transparency	percentage of light visible through the normally foliated portion of the crown
Volume growth	increase in volume of trees living at the initial measure, including those harvested plus ingrowth
Tree mortality	volume of trees living at the initial measurement that were dead at the following measurement
Tree carbon	total aboveground and belowground carbon sequestered since the initial measurement, including that utilized into durable products.
Ecoregion	the ecoregion section based on Bailey's (1995) ecoregions
n	the total number of measurements over time, including repeat measurements
Estimate of value in 1991	the average value at the initial year of measurement
Estimate of change	annual change over the time interval
Standard error of estimate	a measure of the variability of the data
R^2	a measure of goodness-of-fit of the estimate
Degrees of freedom	n - 2
Value of *t*	a measure of the variability of the data relative to the mean
Pr > *t*	the probability that the estimated change was due to random chance and that the true change over the interval was 0

Interpretation—The significance of an estimate of change is a function of the magnitude of the change and the confidence in the estimate. For example, in the Aroostook Hills and Lowlands Ecoregion Section, the mean change in dieback was 0.93 with a standard error of 0.26. The probability is 0.001 of a greater *t* value if the true change is 0.0. This means the odds are 1 in 1,000 that the FHM plots had a change in dieback by random chance equal to 0.93, even though the mean change of all trees in the section was 0.0. Therefore, the change probably occurred.

Appendix table A.1—Example of dieback of eastern softwoods by ecoregion

Ecoregion	n	Estimate of value in 1991	Estimate of change	Standard error of estimate	R^2	Degrees of freedom	Value of *t*	Pr > *t*
Aroostook Hills and Lowlands	55	2.51	0.93	0.26	0.556	43	3.63	0.001
Maine and New Brunswick Foothills and Eastern Lowlands	120	3.27	0.54	0.20	0.721	95	2.74	0.007
Fundy Coastal and Interior	35	4.88	3.54	1.12	0.600	27	3.16	0.004

Appendix B
Measures of Tree Growth

Three measures of growth relevant to forest health follow:

Gross growth = $(V_2 + M + C - V_1) / (t_2 - t_1)$
Net growth = $(V_2 + C - V_1) / (t_2 - t_1)$
Net change = $(V_2 - V_1) / (t_2 - t_1)$

where

V_1 = volume of trees at initial measurement
V_2 = volume of trees at remeasurement
M = initial volume of trees that died since initial measurement
C = initial volume of trees removed since initial measurement
t_1 = year of initial measurement
t_2 = year of remeasurement

Consistent with common usage (Beers 1962), the inclusion of ingrowth, i.e., trees that were below the threshold diameter at time t_1, in V_2 is implied.

Gross growth is the change in volume from period t_1 to t_2 including trees that died during the interval. Net growth is the change in volume from period t_1 to t_2 minus the initial volume of trees that died during the interval. Both gross growth and net growth include volume harvested during the period. Gross growth and net growth are measures of productivity. Net growth is commonly, and in this document, referred to as simply growth.

A related term that can be confused with net growth is net change. Net change is sometimes referred to as net increase or actual change in growing stock (Beers 1962). Net change is equal to growth minus cut.

Smith, William D.; Conkling, Barbara L. 2004. Analyzing forest health data. Gen. Tech. Rep. SRS–77. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southern Research Station. 33 p.

This report focuses on the Forest Health Monitoring Program's development and use of analytical procedures for monitoring changes in forest health and for expressing the corresponding statistical confidences. The program's assessments of long-term status, changes, and trends in forest ecosystem health use the Santiago Declaration: "Criteria and Indicators for the Conservation and Sustainable Forest Management of Temporate and Boreal Forests" (Montreal Process) as a reporting framework. Procedures used in five aspects of data analysis are presented. The analytical procedures used are based on mixed estimation procedures. Examples using the indicators are included, along with a clear link to the analytical procedures used (1) estimating change over time within groups—estimation of growth, harvest, mortality, and crown condition; (2) testing for differences in change over time among groups—foliar transparency; (3) estimating change using covariates—impact of drought on change in foliar transparency; (4) estimating plot values for unmeasured years—comparison of observed and predicted (Best Linear Unbiased Predictions) values of foliar transparency, dieback, and total volume; and (5) estimating tree heights—examples of using estimated tree heights to estimate tree volume.

Keywords: Assessment, BLUP, change estimation, mixed models, monitoring, tree height.