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Crown-Condition Classification: A Guide to Data Collection and Analysis

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Abstract

The Forest Inventory and Analysis (FIA) Program of the Forest Service, U.S. Department of Agriculture, conducts a national inventory of forests across the United States. A systematic subset of permanent inventory plots in 45 States is currently sampled every year for numerous forest health indicators. One of these indicators, crown-condition classification, is designed to estimate tree crown dimensions and assess the impact of crown stressors. The indicator features eight tree-level field measurements in addition to variables traditionally measured in conjunction with FIA inventories: vigor class, uncompacted live crown ratio, crown light exposure, crown position, crown density, crown dieback, foliage transparency, and crown diameter. Indicators of crown health derived from the crown data are intended for analyses at the State, regional, and national levels, and contribute to the core tabular output in standard FIA reports. Crown-condition measurements were originally implemented as part of the Forest Health Monitoring (FHM) Program in 1990. Except for crown diameter, these measurements were continued when the FIA Program assumed responsibility for FHM plot-based detection monitoring in 2000. This report describes in detail the data collection and analytical techniques recommended for crown-condition classification.

Keywords: Forest health indicators, tree crown condition, tree crown health, tree crown measurement, tree health indicators.

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1 Introduction

Tree crowns convert solar radiation into the photosynthate required for tree growth, repair, and maintenance. It logically follows that these functions are correlated with tree crown dimensions. The crown-condition classification procedures described herein have been developed to facilitate monitoring of spatial and temporal trends associated with tree crown health at the ecosystem, State, and regional levels. The forest health related indicators associated with crown-condition classification range from measures of single crown dimensions to composite estimates of crown volume and surface area. They also include descriptive information about light interception and competitive position. The intent of this report is to provide a reference that documents all aspects of crown-condition classification as implemented by the Forest Inventory and Analysis (FIA) Program of the Forest Service, U.S. Department of Agriculture. Specifically, it covers topics associated with crown-indicator definitions, measurement units, field protocols, training requirements, data quality assurance, estimation methods, and analytical methods. Although tailored to FIA applications, this information may also be of use to other researchers interested in adopting these or similar protocols.

The indicators of crown health listed below were originally developed and implemented by the U.S. Forest Service, Forest Health Monitoring (FHM) Program between 1990 and 1999. The first of these (vigor class) was designed for saplings 1.0 to 4.9 inches in diameter, and the latter seven for live trees at least 5.0 inches in diameter.

1. **Vigor class** is a visual assessment of the crown vigor of saplings. The purpose of this classification is to distinguish between excellent saplings with superior crowns and stressed individuals with poor crowns.
2. **Uncompacted live crown ratio** is the ratio of live crown length to aboveground tree length.[1] The term “uncompacted” means that crown length is not reduced to compensate for gaps between the base of the live crown and the live top of the tree. Crown length is one of the dimensions needed to compute crown volume and biomass.
3. **Crown light exposure** estimates the amount of direct sunlight that reaches the live crown.

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[1] An estimate of tree length is required to compute crown length from uncompacted live crown ratio. Tree length is not listed as a crown indicator because it is considered a standard mensuration variable, i.e., one not measured specifically for the purpose of crown-condition classification. The tree length used in the denominator of this ratio is “actual tree length” as defined by FIA (see footnote 1, page 5).

4. **Crown position** establishes the location of an individual live crown in relation to the surrounding overstory canopy.
5. **Crown density** estimates the proportion of crown volume that contains biomass, which includes foliage, branches, and reproductive structures.
6. **Crown dieback** measures the proportion of the crown that has experienced recent dieback, primarily in the upper and outer edges. Crown dieback is often an early indication of stress.
7. **Foliage transparency** estimates the absence of foliage where foliage normally occurs. Foliage transparency is negatively correlated with tree health.
8. **Crown diameter** is one of the dimensions needed to compute crown volume and biomass. It can also be used to measure canopy closure and competition among trees.

The FHM plot network was merged with the FIA Program in 2000, resulting in the "phase 3" subset of the FIA plot system, which is dedicated to monitoring forest health (Stolte 2001). With the exception of crown diameter, FIA adopted the entire set of crown-condition measurements listed above, adding them to the standard mensuration data recorded for trees encountered on FIA phase 3 plots. The national sampling design and estimation procedures for phases 1 and 2 of the FIA Program, including information about how phases 1 and 2 relate to phase 3, are documented by Bechtold and Patterson (2005).

1.1 Justification of Crown Indicators Used to Assess Forest Health

A multitude of abiotic and biotic factors determine the relative vigor of forest trees. These include both physiological and external factors such as age, stand density, genetics, pest problems, climatic trends, light, water, nutrient availability, and management practices. The effects of these factors often manifest themselves in the physical appearance of tree crowns. When natural or anthropogenic stresses impact a forest, the first signs of deterioration are often observed in the tree crowns. Because tree crowns form a part of the basic structural architecture of a forest ecosystem, they also influence the composition, processes, and vigor of understory flora and fauna.

Tree crown dimensions are a major determinant of net primary production. Trees with high ratings for crown diameter, uncompacted live crown ratio, and crown density together with low crown dieback and foliage transparency ratings have increased potential for carbon fixation, nutrient storage, growth, and survival. Large, densely foliated crowns are associated with vigorous growth rates, while trees with small, sparsely foliated crowns may be in a state of decline, growing little or not at all. The condition of a tree crown affects tree survival (Kramer 1966) and volume increment (Hamilton 1969). Maximum radial growth occurs in close proximity to the live crown base (Duff and Nolan 1953, Labyak and Schumacher 1954, Shreve 1924, Young and Kramer 1952). Several studies of southern species have reinforced these concepts by relating crown diameter to the size of bottomland hardwood trees (Francis 1986) and Fraser fir (Jett and others 1993) and crown density to the growth of loblolly pines (Anderson and Belanger 1987, Anderson and others 1992, Belanger and Anderson 1992, Grano 1957). Uncompacted live crown ratio and crown density are related to the growth and survival of western conifers (Dolph 1988). Crown density, dieback, and transparency can be related to insect defoliation and subsequent growth and survival (Kulman 1971). Allen and others (1992) related sugar maple health to annual changes in crown dieback and transparency. Kolb and others (1992) showed that sugar maples affected by pear thrips had thinner crowns. Nash and others (1992) developed a computer-based diagnostic system for assessing crown health of northern hardwoods.

Interpreting the relationship between tree crown dimensions and vigor is complicated by the influence of forest dynamics and stand structure. For example, live crown ratio of red oak (Ward 1964) and crown width of lodgepole pine (Bonner 1964) are related to stand density. Thinning slows the recession of crown length in loblolly pine (Kramer 1966), and affects crown structure (Siemon and others 1976) and crown position (Lamson and others 1990). Models have been developed that relate crown dynamics to stand attributes for unthinned loblolly pine plantations (Dyer and Burkhart 1987, Feduccia and others 1979, Short and Burkhart 1992, Sprinz and Burkhart 1987), open-grown loblolly and shortleaf pine (Smith and others 1992), unthinned slash pine plantations (Dell and others 1979), Douglas-fir stands (Maguire and Hann 1990), and Lake States forest species (Holdaway 1986). The effects of thinning have also been incorporated into loblolly pine crown-height increment models (Dyer and Burkhart 1987, Short and Burkhart 1992) and Scots pine crown-ratio models (Hynynen 1995).

Recent research has been directed at the effects of tree diseases and global climate change stresses on tree crowns. Studies have demonstrated the association of crown condition with basal-area growth of loblolly pine (Jacobi and others 1988, Oak and Tainter 1988) and shortleaf pine (Zarnoch and others 1994) growing on littleleaf disease sites. Young loblolly pine needle production, which directly affects crown condition, is related to stand basal area. It has been observed that needle retention can be reduced by as much as 2 months in abnormally dry years (Dougherty and others 1990, 1995; Hennessey and others 1992). Similarly, peak needle fall of Monterey pine in Australia occurred 3 to 6 months sooner under summer drought conditions (Raison and others 1992). Another study found that ozone has a significant effect on the timing and rate of foliage abscission (Stow and others 1992).

The effect of stress on crown condition is expressed by foliage mass and distribution. Using the Weibull distribution to quantify the crown profile, Schreuder and Swank (1974) found that vertical distribution of foliage within the crown is related to stand and site conditions. Models have been developed for vertical crown development in lodgepole pine (Cole and Jensen 1982). Crown profile models were fitted to plantation loblolly pines growing under various nitrogen and phosphorus fertilizer regimes (Vose 1988). It is conceivable that alterations in crown profiles can affect canopy architecture and consequently influence individual tree growth, stand growth, survival, and community dynamics. Kuuluvainen (1988) discussed the relationship of crown architecture to stemwood production in Norway spruce.

2 Field Procedures and Methods

To the extent possible, the various crown measurements must be based on objective standardized definitions. This section defines the tree crown and its various parts and highlights critical points for crown-condition measurements. Each crown measurement contributes to the comprehensive rating for each tree. Crown measurements should be considered individually and collectively when evaluating a tree. All measurements are based on appearance at the time of measurement.

The complete crown classification field manual[1] can be downloaded from the Web site http://socrates.lv-hrc.nevada.edu/fia/dab/databandindex.html#4.%20%20Current%20National%20Core%20Field.

2.1 General Crown Evaluation Procedures

All crown rating procedures except crown diameter are based on two-dimensional sideviews of each crown, usually from two different vantage points. Two people are needed to view and evaluate each crown. The most accurate measurements are achieved when crew members occupy the recommended vantage points, which may not always be possible.

Variation between crew members is reduced by requiring them to record the average of their individual estimates. Discussion and negotiation between crew members are likely to reduce errors and measurement extremes. Consistency and quality are improved by changing observation points and repeating estimates. This reduces the likelihood of rating an adjoining tree, using incorrect crown outlines, or overlooking damage or dieback.

All crown variables, with the exception of vigor class, are measured for all live trees at least 5.0 inches in diameter at breast height (d.b.h.). For shrublike species designated by FIA as woodland species, the minimum is 5.0 inches diameter at root collar (d.r.c.). For saplings, the variables measured are vigor class, uncompacted live crown ratio, crown light exposure, and crown position. The recommended measurement window begins when leaves of deciduous trees are expanded to full size, and ends before

[1] U.S. Department of Agriculture Forest Service. 2005. Crowns: measurements and sampling. In: Forest inventory and analysis national core field guide: field data collection procedures for phase 3 plots. Version 3.0. Section 12, 1–21. Internal report. On file with: U.S. Department of Agriculture Forest Service, Forest Inventory and Analysis, Rosslyn Plaza, 1620 North Kent Street, Arlington, VA 22209.

fall leaf drop starts. All crown variables are recorded for each candidate tree during initial plot establishment and in subsequent inventories when these variables are remeasured. Measurements are recorded on field tally forms or on portable data recorders (PDRs). PDRs are preferred because they can be programmed with realtime range and logic checks. Coding summaries are provided in appendix A.

The suggested order of data collection for each tree is:

1. Vigor class
2. Uncompacted live crown ratio
3. Crown light exposure
4. Crown position
5. Crown density
6. Crown dieback
7. Foliage transparency
8. Crown diameter

2.2 Crown Rating Precautions

The following circumstances should be considered when rating tree crowns in the field:

- Distance from the tree—visibility of the tree top usually improves with distance from the tree, but competing vegetation can obscure visibility as distance increases. Crews should attempt to stay at least one-half tree length from the tree being evaluated.
- Crew position—crew members should attempt to evaluate trees while standing at an angle of 90 degrees from each other (using the tree as the angle vertex). They should not stand directly opposite or beside each other unless this is unavoidable. Crew members should also try to position themselves on approximately the same slope contour. Fulfilling the distance and grade requirements is not possible in all situations, so adjustment may be required to obtain the best view of the tree. Trees should not be evaluated from the downhill side unless absolutely necessary (fig. 2.1). Overlapping branches, background trees, and lack of a good viewing area can cause problems, but the view can often be improved with small lateral movements once the prescribed viewing positions are attained.
- Weather conditions—cloudy or overcast skies, fog, rain, wind, and poor sun angles may affect estimates. Uncompacted live crown ratio

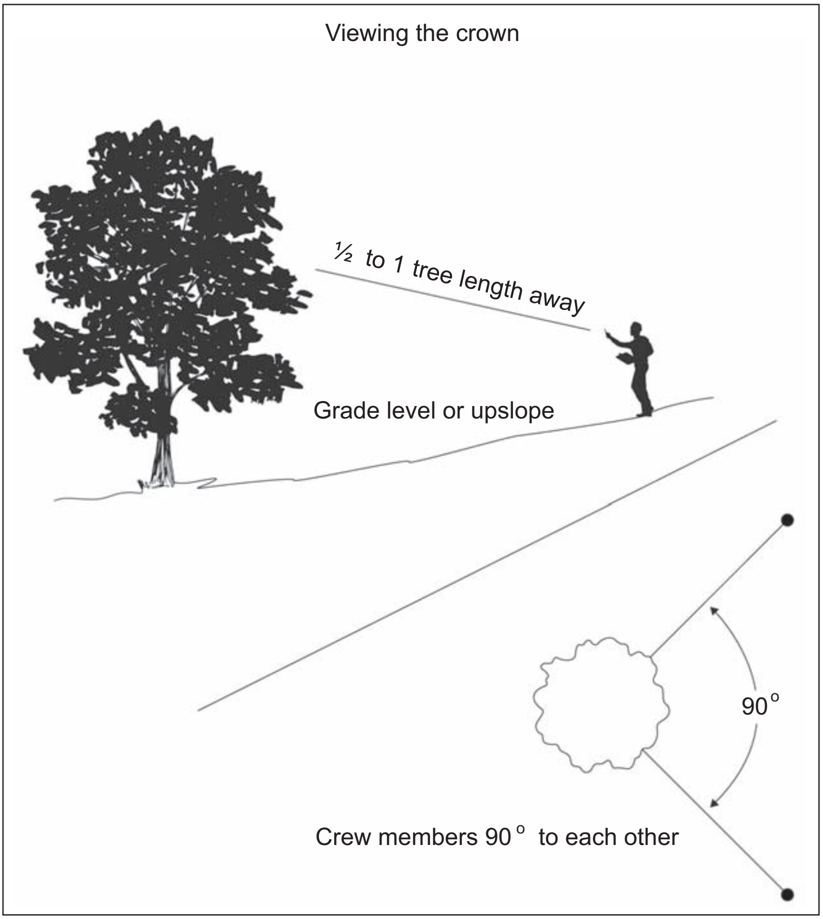

Figure 2.1—Optimal viewpoints for rating tree crowns.

and crown diameter measurements are less affected by adverse weather conditions than other crown indicators. Crown density tends to be overestimated when light is blocked by background foliage, but in open situations the light may be too bright for a good estimate. Crown dieback may be underestimated because it is difficult to see dead twigs or to differentiate defoliated twigs from dead twigs, or both. Foliage transparency estimates could be affected in either direction when it is hard to discern foliage from branches. Crews need to be especially careful during poor lighting conditions and may need to move around more than usual to get the best view, even when a view appears adequate at a specific location.

- Heavy defoliation—during heavy defoliation, crown dieback may be overestimated and foliage transparency may be underestimated because of difficulty distinguishing dead twigs from defoliated ones. The use of binoculars will help in separating dead twigs from defoliated twigs.

- Epicormic branches—trees and saplings that do not have any live foliage except epicormic branches are rated as follows: uncompacted live crown ratio = 0, crown light exposure = 0, crown position = 3, crown density = 0, crown dieback = 100 percent, foliage transparency = 100 percent, and crown diameter = 0.

2.3 Descriptions of Crown Indicators

2.3.1 Vigor Class

2.3.1.1 Definition

Vigor class is a measure of sapling crown vigor. Saplings are classified as vigorous, moderate vigor, or low vigor. The moderate vigor class has been made large because the objective is to distinguish between extremely good and poor crowns, while placing average saplings in the middle.

2.3.1.2 Measurement

- Units—vigor class is recorded in three classes: 1 = vigorous, 2 = moderate vigor, and 3 = poor vigor.
- Method of determination—the easiest way to classify vigor is to see if a sapling meets the criteria for vigor class 1 or 3. Saplings that qualify for neither of these classes are assigned to class 2 (fig. 2.2).

Vigor class 1 saplings must have an uncompacted live crown ratio of at least 35 percent and < 5 percent dieback. (Note that damage caused by browsing mammals is classified as missing foliage, and not as dieback, and that twigs and branches that have died as a result of normal shading are not included in dieback.) Also, 80 percent or more of the leaves present must be undamaged. Damaged foliage is defined as leaves with more than 50 percent of their original surface area chewed, discolored, missing, or otherwise damaged.

Vigor class 2 saplings do not meet class 1 or 3 criteria. They may have any uncompacted live crown ratio, may or may not have dieback, and 21 to 100 percent of their foliage is classified as normal.

Vigor class 3 saplings may have any uncompacted live crown ratio. Less than 20 percent of their leaves are undamaged. Leaves of twigs and branches that have died as a result of normal shading are not considered missing or damaged.

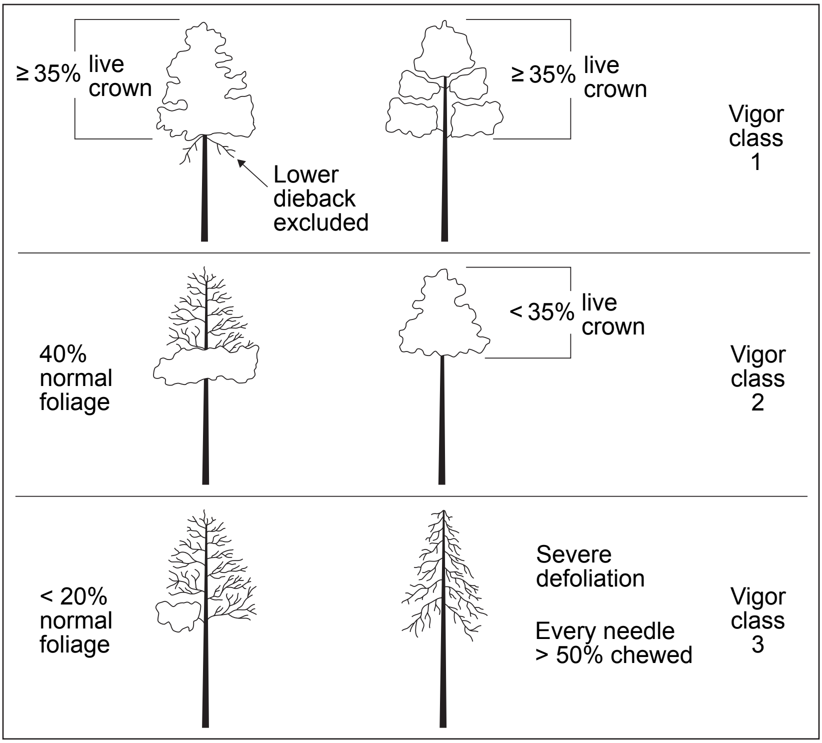

Figure 2.2—Sapling vigor rating criteria.

- Limitations—dieback may be difficult to distinguish from recent defoliation. Estimating normal foliage when the percent damaged or missing is very close to 50 percent may cause errors in ratings.

2.3.1.3 Causes of Change

- Increase—species shade tolerance may cause positive reactions to changes in canopy structure. Many species will respond favorably to release. Discolored foliage may also recover over time, and dieback may be shed or obscured.

- Decrease—species shade tolerance may cause negative reactions to changes in canopy structure. The base of the crown may move upward or portions of the top may be lost, thus decreasing the live crown length. Common causes are:
  - Shading by neighboring trees due to crown closure
  - Mechanical damage caused by animal browsing
  - Defoliation with associated dieback or death of lower branches or tree tops

- Loss of tree tops or lower branches resulting from breakage or mortality
- Competition with other vegetation for water and nutrients

- Persistence—vigor class can change slowly or rapidy depending on events that change stand structure. Mechanical injury, other damage, or dieback in the stand may expedite this change.

2.3.1.4 Intended Use

Vigor class ratings may be used to determine growth potential and future stand stocking levels. The ability to determine this potential depends upon an analyst's knowledge of individual species within a forest type or stand. Generally, greater numbers of vigorous saplings are indicative of healthier, faster growing stands while more saplings of low vigor may indicate stand decline.

2.3.1.5 Attributes Shared with Other Indicators

Vigor classes are determined partly on the basis of uncompacted live crown ratio. Crown light exposure and position affect vigor class ratings.

2.3.2 Uncompacted Live Crown Ratio

2.3.2.1 Definition

Uncompacted live crown ratio is the length of a tree that supports live foliage relative to "actual tree length" as defined by FIA.[2] Dead lower branches are not included as part of the live crown. The ratio is determined by dividing the uncompacted live crown length by the actual tree length, then multiplying by 100 to express the ratio as a percentage (fig. 2.3).

2.3.2.2 Measurement

- Units—uncompacted live crown ratio is recorded in 5-percent classes and coded as 0, 05, 10, 15, . . . , 100, where the code represents the upper limit of the class, e.g., 1 to 5 percent is code 05.

- Method of determination—determine uncompacted live crown ratio by first establishing the live crown top, which is the live foliage nearest the top of the tree. Exclude dieback and dead branches. Next, determine the base of the live crown. This is located at the point of the lowest live foliage of the "obvious live crown." Typically, this location will be easily

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[2] U.S. Department of Agriculture Forest Service. 2005. Forest inventory and analysis national core field guide: field data collection procedures for phase 2 plots. Version 3.0. Vol. 1. Internal report. On file with: U.S. Department of Agriculture Forest Service, Forest Inventory and Analysis, Rosslyn Plaza, 1620 North Kent Street, Arlington, VA 22209.

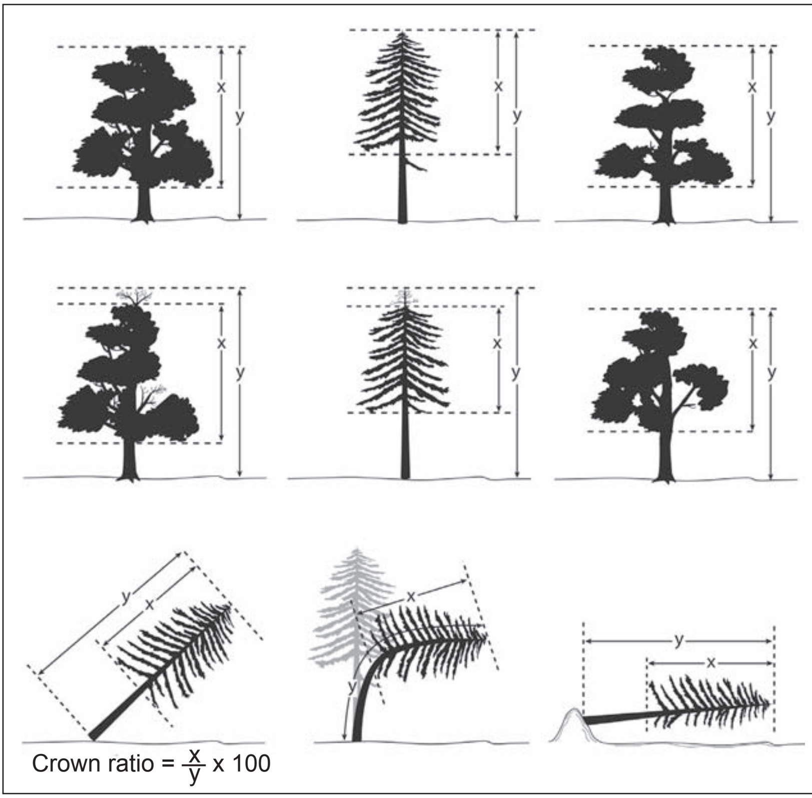

Figure 2.3—Uncompacted live crown ratio is expressed as a percentage of actual tree length.

recognizable. However, there will be occasions where branches extend beyond what would normally be considered the obvious live crown. When this occurs, apply the 5-foot rule (see appendix B) to establish the base (fig. 2.4).

An individual can use the scale on the back of the crown density-foliage transparency card to help estimate ratios (fig. 2.5). To use the scale, hold the card in one hand parallel to the tree and move the card closer or farther from your eye until the zero is at the live top of the tree and the 99 is at the base of the tree (ground). Then place your finger on the card at the base of the live crown. The number on the scale is the uncompacted live crown ratio. Interpolate to the nearest 5 percent if the point is between two values on the scale. A clinometer can also be used to measure uncompacted live crown ratio.

When individuals disagree by more than 10 percent (two classes) on a rating, they should discuss the reasons for their rating. If neither

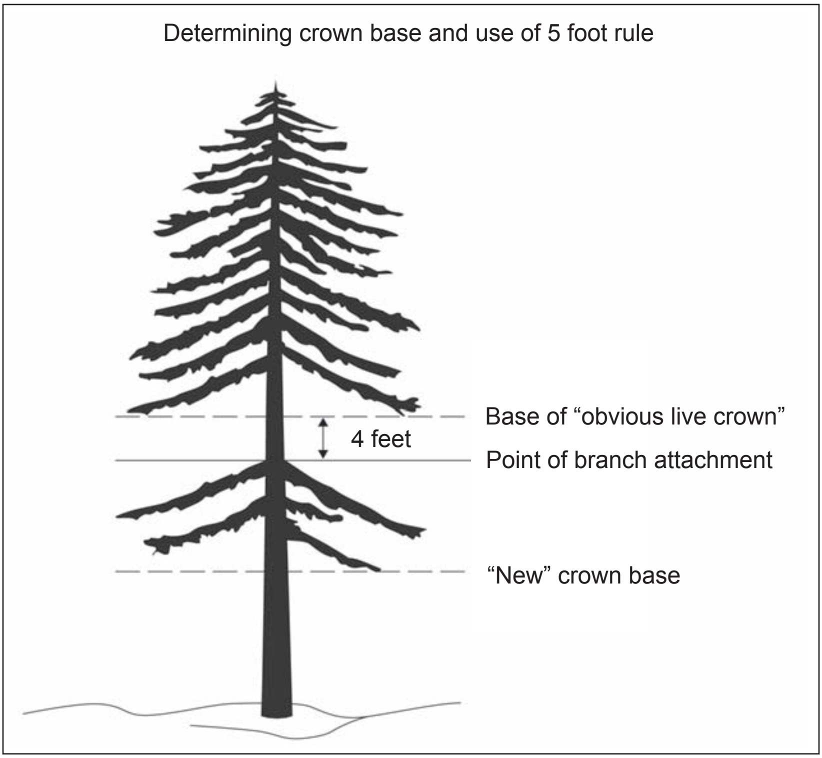

Figure 2.4—Identifying the obvious live-crown base with the 5-foot rule.

individual is willing to change an estimate, then the two ratings are averaged. Disagreement may result from differences in opinion or viewing angle.

- Limitations—views of tree tops may be obstructed. Tree tops may not be clearly identifiable for species such as oaks that have rounded crowns. Branch structure of some trees is such that an obvious live crown base is difficult to establish. Defoliation of tree tops by insects may be mistakenly interpreted as dieback. Binoculars are used to confirm dieback.

2.3.2.3 Causes of Change

- Increase—epicormic branches below the live crown base may grow and mature, lowering the base of the live crown. Annual terminal growth increases live crown length. Insect defoliated tops may recover and not be counted as dieback in subsequent measurements. Release from thinning may increase vigor and consequently live crown growth.

Density of tree present

Percent of tree missing	5	15	25	35	45	55	65	75	85	95
10	5	15	25	35	45	50	60	70	80	90
20	5	15	20	30	40	45	55	60	70	80
30	5	15	20	25	35	40	50	55	60	70
40	5	10	15	25	30	35	40	45	55	60
50	5	10	15	20	25	30	35	40	45	50
60	5	10	10	15	20	25	30	30	35	40
70	5	5	10	15	15	20	20	25	30	30
80	5	5	5	10	10	15	15	15	20	20
90	5	5	5	5	5	10	10	10	10	10

Scale to estimate live crown ratio

99 90 80 70 60 50 40 30 20 10 00

Figure 2.5—The scales on the back of the density-transparency card may be used to determine live crown ratio and to adjust density ratings when part of the crown is missing.

- Decrease—the base of the crown may move upward or portions of the top may be lost, decreasing the live crown length. Common causes are:
  - Self pruning with increasing age
  - Shading by neighboring trees as a result of crown closure
  - Mechanical damage done by branches of neighboring trees
  - Defoliation with associated dieback or death of lower branches or tree tops
  - Loss of tree tops or lower branches through breakage or mortality
  - Competition with other vegetation for water and nutrients
- Persistence—uncompacted live crown ratio normally changes slowly and usually declines after trees reach maturity. Mechanical injury, damage, or dieback may expedite change in uncompacted live crown ratio.

2.3.2.4 Intended Use

Uncompacted live crown ratio is used to calculate crown volume and biomass. Generally, larger ratios are indicative of healthier, faster growing trees. As the base of the live crown progresses toward the top of a tree, i.e., as the uncompacted live crown ratio declines, stem growth tends to decline. Uncompacted live crown ratio, in combination with tree length, crown diameter, and crown-density measurements, can be used as a basis for estimates of crown biomass.

2.3.2.5 Attributes Shared with Other Indicators

Uncompacted live crown ratio is used to obtain crown light exposure ratings. The live crown base for uncompacted live crown ratio is the same base used for crown density, crown dieback, and foliage transparency measurements.

2.3.3 Crown Light Exposure

2.3.3.1 Definition

Crown light exposure measures the amount of direct sunlight a tree receives when the sun is directly overhead. Determining crown light exposure involves dividing the tree crown into five sections: four equal vertical quarters, i.e., faces, and the top (fig. 2.6).

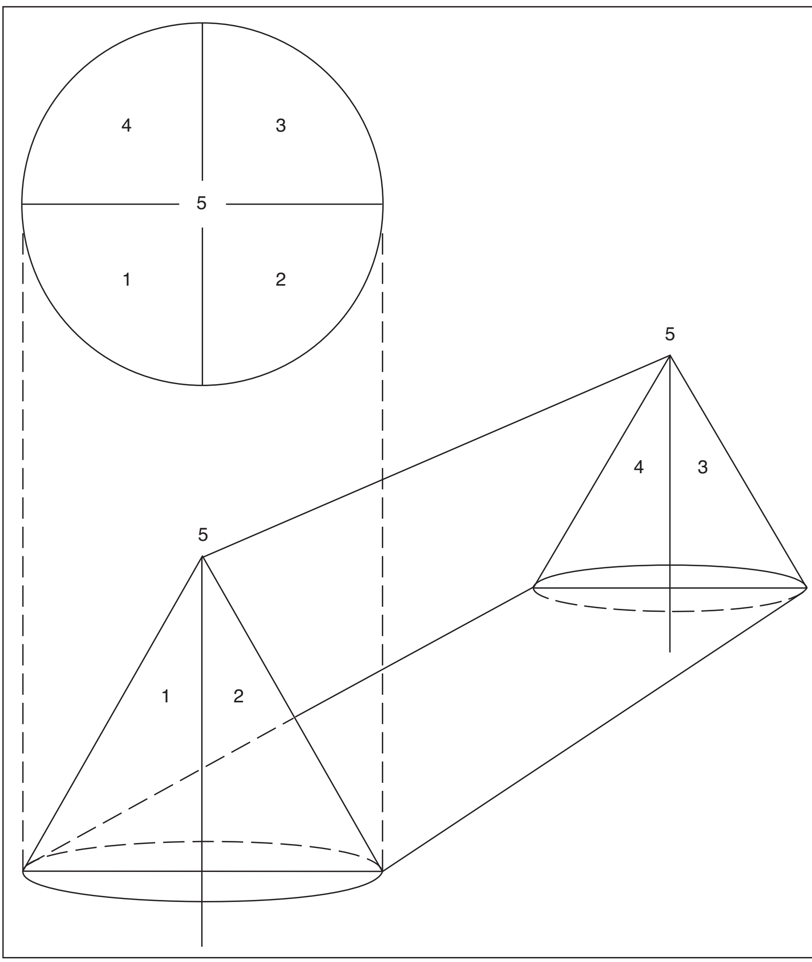

Figure 2.6—Dividing the crown into the five sections necessary to rate crown exposure.

2.3.3.2 Measurement

- Units—crowns are rated from zero to five, depending on the number of crown sections exposed to direct sunlight.

- Method of determination—mentally divide the crown into four equal vertical quarters (faces) and the top (five sections total). Then observe the uncompacted live crown ratio of each of the four vertical quarters. Any quarter with an uncompacted live crown ratio rating of 35 or greater has the potential to be counted as receiving full light. Trees having an overall uncompacted live crown ratio of < 35 may have a maximum exposure rating of 1 (if their tops have sun exposure).

  For a vertical quarter to count as receiving full light, that section of the tree must be at least 35-percent foliated with leaves exposed to direct sunlight. The top section qualifies if any portion of the top of the tree receives light. A top does not need to receive light on its entirety as do the quarter sections (fig. 2.7). Add up the total number of sections exposed to full light, including the top if receiving any light, and record the appropriate number.

- Limitations—visibility and viewing angle of the crown can cause evaluation problems. In dense stands it can be difficult to divide the crown accurately into quarters or see the crown top. Trying to establish uncompacted live crown ratios for each quarter may be a challenge and make it hard to determine whether each entire quarter is receiving light.

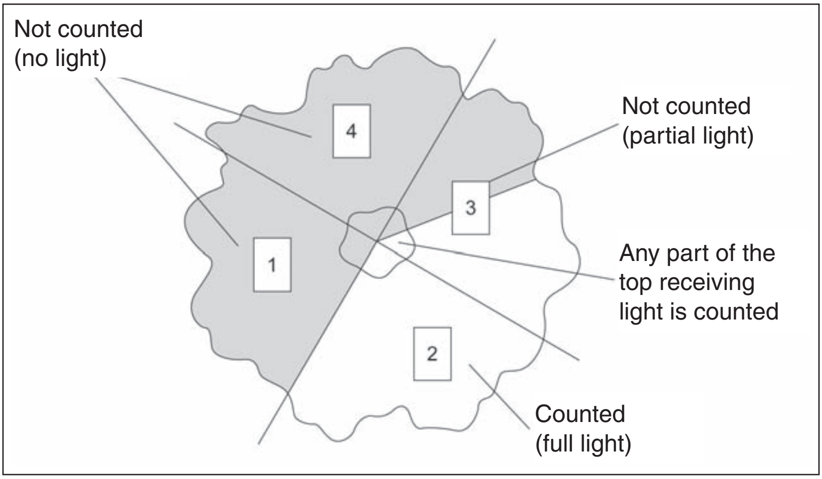

Figure 2.7—When rating crown exposure, count only those sides that receive full light.

2.3.3.3 Causes of Change

- Increase—crown light exposure, or the number of sections receiving light, may increase due to:
  - Removal or mortality of adjacent trees
  - Increase in uncompacted live crown ratio
- Decrease—the number of crown sections receiving light may be reduced because of:
  - Decrease in uncompacted live crown ratio
  - Competition from adjacent trees or other vegetation
  - Dieback or loss of branches
- Persistence—changes in crown light exposure commonly occur gradually over long periods. Significant or rapid change should only result from a disturbance that immediately alters canopy structure.

2.3.3.4 Intended Use

Crown light exposure estimates the amount of direct sunlight to which a tree is exposed. It provides information about stand structure and competition, tree and stand vigor, and growth potential. A tree receiving more light typically has less direct competition, thereby increasing its vigor and growth potential.

2.3.3.5 Attributes Shared with Other Indicators

Crown light exposure rating is designed to be used with crown position rating. Ratings for these two indicators can be used to compute Kraft crown classes (Bechtold 2003b). Changes in crown light exposure should not have a direct effect on other crown indicators. However, changes in other crown indicators may affect the crown light exposure rating.

2.3.4 Crown Position

2.3.4.1 Definition

Crown position refers to the relative position of an individual crown in relation to the overstory canopy zone. This crown indicator provides information regarding stand structure and competition.

2.3.4.2 Measurement

- Units—a crown position code is assigned to each tree individually, except in open-grown stands. Codes 1 to 4 represent the superstory, overstory, understory, and open-grown crown positions, respectively.

- Method of determination—to make a crown position assessment, first establish the average live crown height for the entire stand. This defines the "overstory canopy zone." Next, separate the overstory canopy zone horizontally into halves with an imaginary line through the middle. Finally, compare each individual tree's live crown top to this midpoint line. The location of the live crown top relative to this line determines the tree's crown position code (fig. 2.8).

  For a tree to qualify as a superstory tree (code 1), the live crown top must be twice the height of the top of the overstory canopy zone. To be coded as an overstory tree (code 2), the live crown top needs to extend past the midline of the overstory canopy zone. An understory crown (code 3) will have its top at or below the midline of the overstory canopy zone. The open canopy code (code 4) is used for every tree in the stand when an overstory zone is not discernable due to lack of canopy cover and competition. This code is used if the tree is located in an opening (at least 1 acre in size) that has < 50-percent crown cover, or when the overall forest condition consists of a patchwork of clumps and open spaces that are < 1 acre in size.

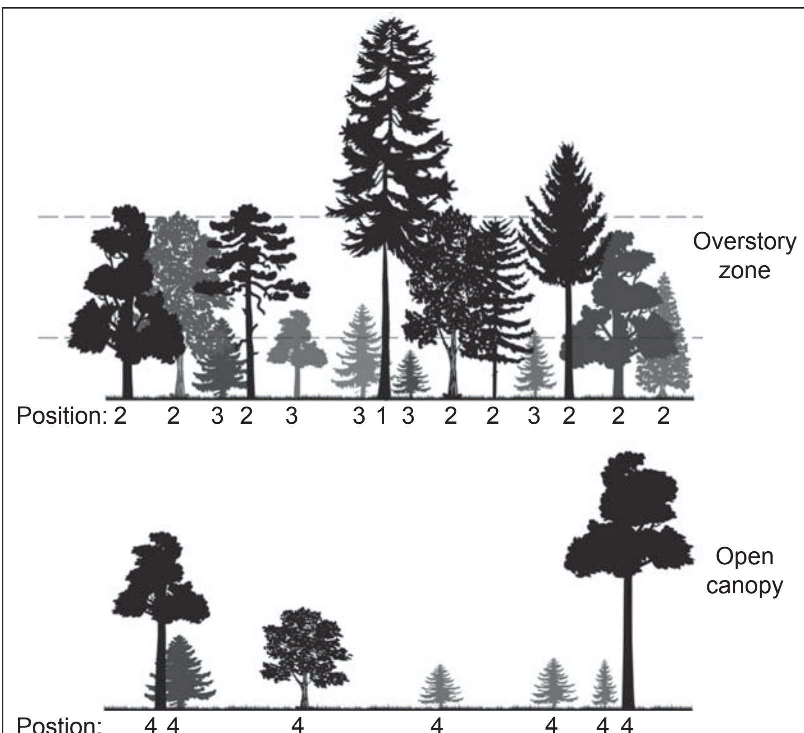

Figure 2.8—Crown position ratings are determined relative to the prevailing overstory canopy zone of the stand.

- Limitations—competing foliage or lower portions of a crown that is being evaluated can obstruct the view of tree tops. In dense stands this makes it difficult to establish not only the overstory canopy zone, but also where individual crowns begin or end. A steep slope can make it hard to define the overstory canopy zone because it can make the crown heights of identical trees seem unequal. To avoid these problems, perform crown evaluations from a position on the same slope contour as the tree base whenever possible.

2.3.4.3 Causes of Change

- Increase or decrease can be caused by:
  - Removal of overstory trees
  - Removal of understory trees
  - Environmental stress such as drought, disease, fire, ice, and wind
  - Tree-to-tree differences in growth rates
  - Stand succession
- Persistence—crown position is a relatively stable and slowly evolving measurement. There should be no drastic changes in crown positions of a stand unless there is some manmade or natural catastrophic disturbance.

2.3.4.4 Intended Use

Crown position represents the location of each individual crown in relation to the overstory canopy zone. When considered on a large scale rather than on an individual tree basis, crown position provides information about stand structure and forest health. Trees with favorable crown position may have higher vigor and survivability as well as reproductive and growth potential. Trees with unfavorable crown positions are more likely to exhibit less vigor, survivability, reproductive potential, and growth potential.

2.3.4.5 Attributes Shared with Other Indicators

Crown position in conjunction with crown light exposure can be used to compute Kraft crown classes (Bechtold 2003b). Changes in crown position can directly affect crown light exposure. While this measurement does not have a direct effect on the other crown indicators, changes in the other crown indicators may affect crown position. For example, a change in uncompacted live crown ratio or dieback measurements could cause changes in crown position.

2.3.5 Crown Density

2.3.5.1 Definition

Crown density is the amount of crown stem, branches, twigs, shoots, buds, foliage, and reproductive structures that block light penetration through the crown. Dead branches and dead tops are part of the crown. Live and dead branches below the live crown base are excluded. Broken or missing tops are visually reconstructed when forming this crown outline by comparing tops of adjacent healthy trees of the same species and stem diameter (fig. 2.9).

2.3.5.2 Measurement

- Units—crown density is recorded in 5-percent classes and coded as 0, 05, 10, 15, . . . , 100, where the code represents the upper limit of the class, e.g., 1 to 5 percent is code 05.

Figure 2.9—Missing portions of a tree crown are reconstructed to determine the crown density outline.

- Method of determination—establish the crown outline by selecting the point on the stem used as the base for uncompacted live crown ratio and visualize a normal, expected crown that encompasses the branch tips for that tree. Exclude any foliage below the crown base (fig. 2.10).

  If there is a broken or missing top, reconstruct the missing portion by using other trees of the same size, species, and growing condition as

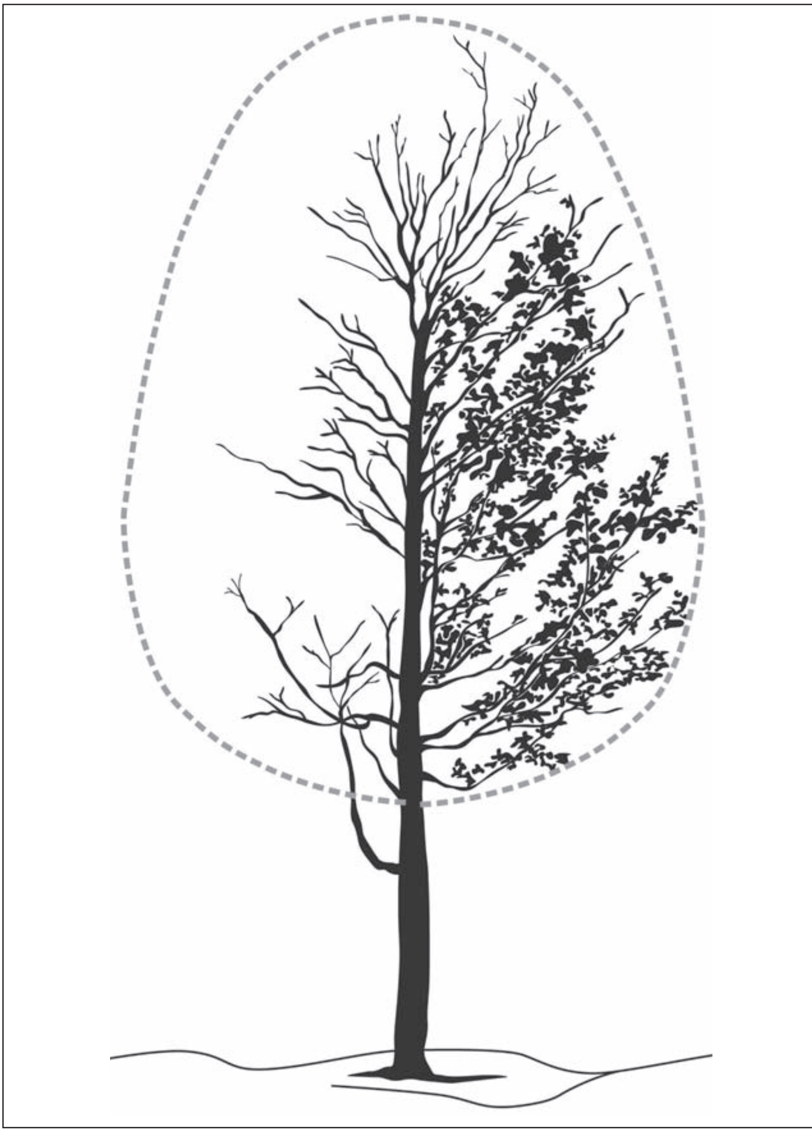

Figure 2.10—Establishing a crown outline for the crown density rating.

a guide. After determining the outline, each crew member should hold the crown density-foliage transparency card (fig. 2.11) along the line of sight and estimate what percentage of the outlined area is blocking sunlight.

Crowns with portions missing and half-sided trees are rated as if they have full symmetrical crowns. Include crown dieback and open areas in the crown density outline. In these situations it may be easier to determine the percent of the tree missing and the crown density of the tree's remaining portion. Then use the table on the back of the crown density-foliage transparency card to arrive at the final crown density for that tree. The reverse side of this card provides a table of percentages for various combinations of density and percent missing ratings (fig. 2.5).

When individuals disagree by more than 10 percent (two classes) on a rating, they should discuss the reasons for their ratings. If neither individual is willing to change an estimate, then the two ratings are averaged. Disagreement may result from differences in opinion, or viewing angle, or both.

- Limitations—identifying the crown outline of the tree correctly is the key to determining crown density. Sources of variation include identification of the crown outline, and estimating the missing crown area within that outline. Tops or sides of trees may not be clearly visible at the same time and errors may result from "piecing the crown together" from various viewing points. Branch structure of some trees may make determining the base of the crown difficult. If the selected live crown base is wrong, this may affect crown density greatly.

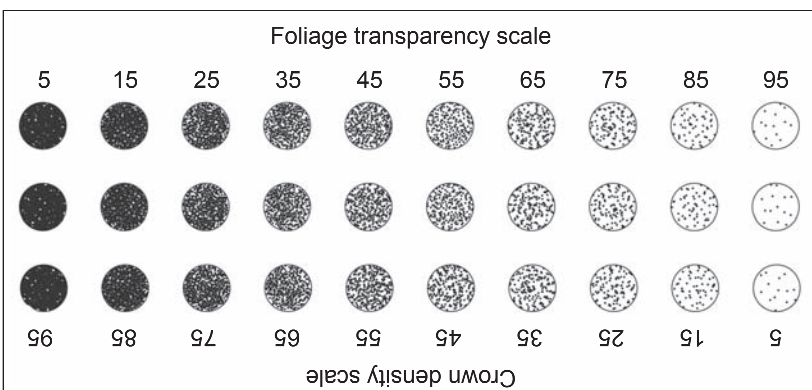

Figure 2.11—The front side of the density-transparency card can be used to assist with crown density and foliage transparency ratings.

2.3.5.3 Causes of Change

- Increase—crown density may increase for reasons such as:
  - Increased growing space as a result of death or removal of neighboring trees
  - Rebuilding crown structure after loss of major branches
  - Recovery after defoliation by insects, diseases, or environmental stress
  - Loss of branches causing a change in the crown outline
  - Recovery or regrowth of a broken or missing top or side
- Decrease—normally, crown density declines over time as a result of competition and aging. Crown density also declines because of:
  - Stress that causes loss of branches and creates gaps in the live crown
  - Stress that increases transparency as a result of poor foliage production or defoliation
  - Stress that stunts foliage
  - Crown form changes as a result of increased stand density
  - Broken or missing tops or sides
- Persistence—crown density usually changes slowly as stand density changes. Defoliation may change crown density within a growing season, but repeated defoliation followed by branch dieback is needed for permanent change. Branch mortality, such as that caused by wind and ice damage, creates rapid change in crown density.

2.3.5.4 Intended Use

Crown density is used to estimate the percentage of crown volume that contains biomass. Trees with below average crown densities are expected to have reduced growth compared to trees with full, symmetrical crowns (Anderson and Belanger 1987).

2.3.5.5 Attributes Shared with Other Indicators

Crown density includes other crown characteristics that are measured separately. These include:

- Foliage transparency as influenced by changes in foliage abundance
- Crown dieback as reflected by complete absence of foliage
- Crown diameter as influenced by competition from adjacent trees

2.3.6 Crown Dieback

2.3.6.1 Definition

Crown dieback is recent mortality of branches with fine twigs that begins at the terminal portion of a branch and proceeds toward the trunk. Dieback is considered only when it occurs in the upper and outer portions of the tree. When whole branches are dead in the upper crown, without obvious signs of damage such as breaks or animal injury, assume that the branches died from the terminal portion of the branch. Dead branches in the lower live crown are not considered as part of crown dieback unless there is continuous dieback from the upper and outer crown down to those branches.

2.3.6.2 Measurement

- Units—crown dieback is recorded in 5-percent classes and coded as 0, 05, 10, 15, . . . , 100, where the code represents the upper limit of the class, e.g., 1 to 5 percent is code 05.

- Method of determination—live crown base for crown dieback determination is the same as that for the uncompacted live crown ratio estimate. Assume that the perimeter of the crown is a two-dimensional outline from branch tip to branch tip. Missing tops, sides, or portions of the tree are not included in this estimate.

  First, each crew member should mentally draw a two-dimensional crown outline. Second, block in the affected area (fig. 2.12). Third, the proportion of the affected area is estimated in 5-percent classes and recorded as a percentage of the total live crown area outline including the estimated dieback area. When individuals disagree by > 10 percent (or two classes) on a rating, they should discuss the reasons for their ratings. If neither individual is willing to change an estimate, then the two ratings are averaged. Disagreement may result from differences in opinion or viewing angle.

- Limitations—tree tops may not be clearly visible due to an obstruction or may not be clearly identifiable for species that have rounded crowns, e.g., oaks. The branch structure of some trees makes it difficult to establish an obvious live crown base. Heavy defoliation or transparency > 50 percent makes it difficult to separate recently dead twigs and branches from living, defoliated branches.

2.3.6.3 Causes of Change

- Increase—crown dieback is an indication of severe stress and increases with damage to the roots, stem damage that interferes with moisture and nutrient transport to the crown, direct injury in the crown, severe defoliation, excessive seed production, or scorch due to sudden release from competition.

- Decrease—crown dieback decreases through loss of dead twigs and branches. Also, trees frequently rebuild their crowns after the stressing agent is removed.

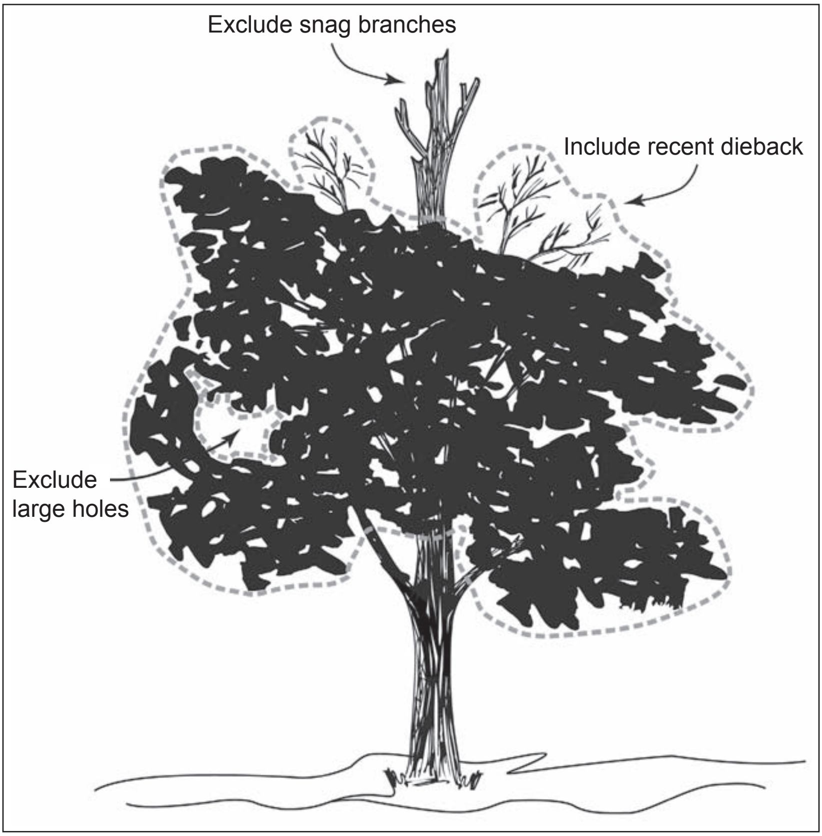

Figure 2.12—The dotted line represents the crown silhouette used to rate crown dieback.

- Persistence—small dead twigs do not persist very long and may drop annually. Larger dead branches persist longer. Therefore, annual fluctuations of dieback are expected.

2.3.6.4 Intended Use

Crown dieback estimates the severity of recent stresses on trees. Increased dieback reduces growth. The measurement serves as an early indicator of loss of vigor and growth potential in response to stresses or damage. High crown dieback indicates defoliating agents or other stressors such as drought, root rots, canker diseases, and root mortality due to deep frosts. However, some crown dieback results from normal tree processes, such as excessive seed production. Thus minor crown dieback probably does not indicate an abnormal condition. Some species of trees, particularly conifers, do not exhibit crown dieback unless something is seriously wrong with the root system.

2.3.6.5 Attributes Shared with Other Indicators

Crown dieback reduces the crown density measurement. Crown dieback may affect the uncompacted live crown ratio and crown diameters by killing a portion of the tree top or sides.

2.3.7 Foliage Transparency

2.3.7.1 Definition

Foliage transparency is the amount of skylight visible through microholes in the live portion of the crown, i.e., where foliage or remnants of foliage occur. Recently defoliated branches are included in foliage transparency measurements. Macroholes are excluded unless they are the result of recent defoliation. Dieback and dead branches are always excluded from the estimate. Foliage transparency is different from crown density because it emphasizes foliage and ignores stems, branches, fruits, and holes in the crown (fig. 2.13).

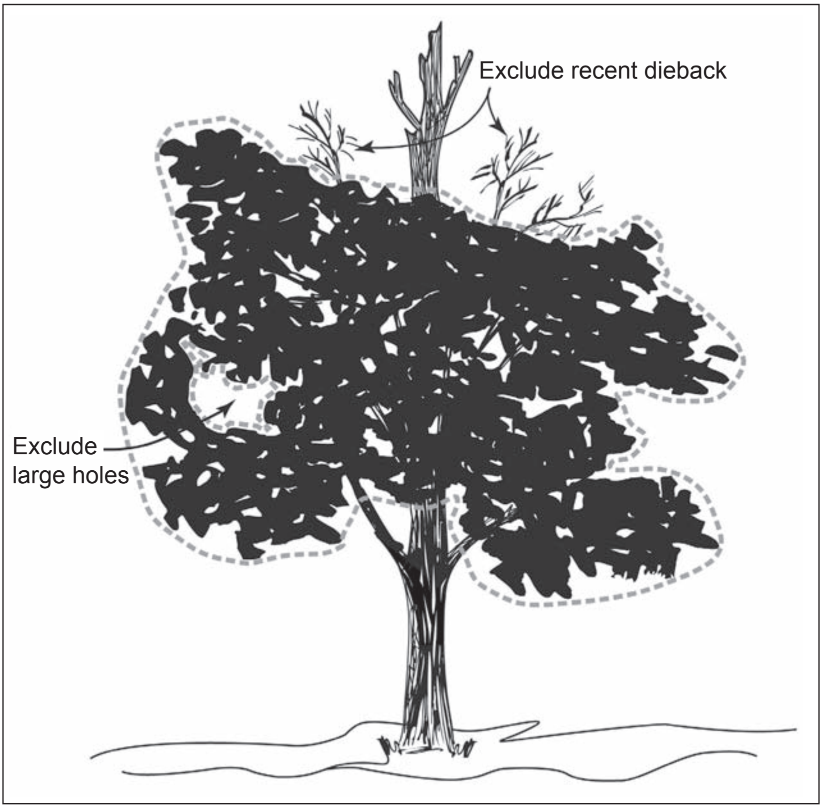

Figure 2.13—The dotted foliage transparency outline excludes dieback, snag branches, and areas where foliage is not expected to occur.

2.3.7.2 Measurement

- Units—foliage transparency is recorded in 5-percent classes and coded as 0, 05, 10, 15, . . . , 100, where the code represents the upper limit of the class, e.g., 1 to 5 percent is code 05.
- Method of determination—when defoliation is severe, branches alone will screen the light, but crews should exclude the branches from foliage as best they can and rate the area as if the light were penetrating the branches. For example, an almost completely defoliated dense spruce may have < 20-percent skylight coming through the crown, but it will be rated as highly transparent because of the missing foliage.

  Old trees and some hardwood species have crowns with densely foliated branches that are spaced far apart. The spaces between clumps of foliage should not be included in the foliage transparency rating (fig. 2.14).

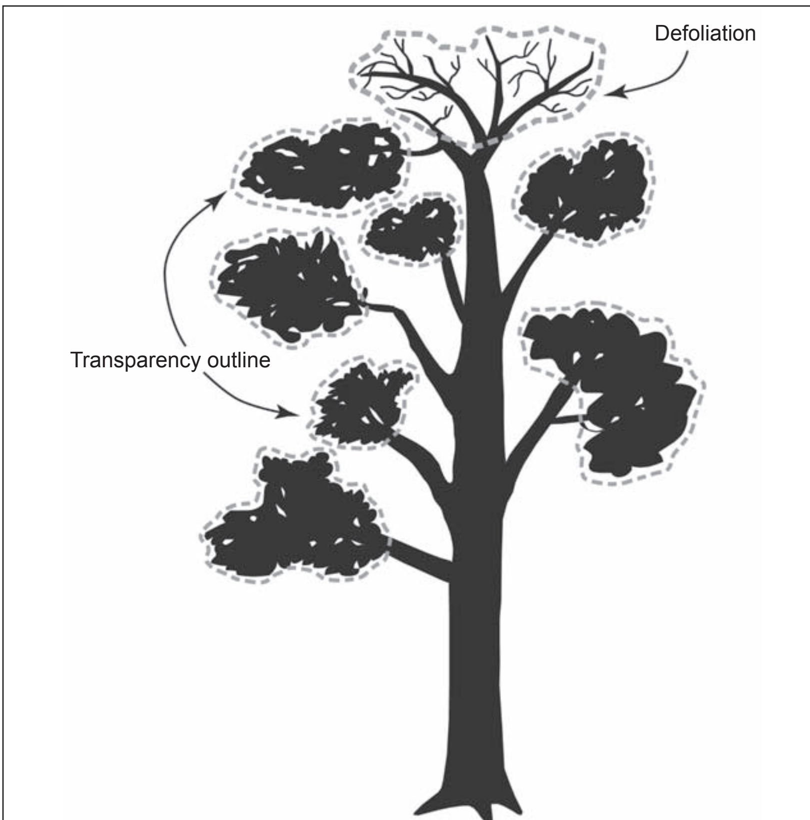

Figure 2.14—The transparency rating of trees with clumped foliage is accomplished by averaging (and weighting by relative area) the transparencies of the individual clumps.

When foliage transparency in one section of the crown differs from that in other sections, the estimate is made by averaging the weighted (by area) transparencies of each section.

Foliage transparency is rated by two people using the crown density-foliage transparency card (fig. 2.11). First, each individual mentally draws a two-dimensional crown outline. Second, the foliated area is blocked into the crown outline (fig. 2.15). Third, each individual estimates the amount of skylight that penetrates the foliated crown as a percentage of the total area of the foliated crown outline. The measurement is then recorded as a 5-percent class.

Figure 2.15—The dotted line shows the crown outline used when rating the transparency of a uniformly foliated tree.

When individuals disagree by more than 10 percent (two classes) on a rating, they should discuss the reasons for their ratings. Either an individual changes his or her estimate or the ratings are averaged. Disagreement may be due to differences in viewing angle, differences in judgment, or both.

- Limitations—estimates of foliage transparency for individual trees are quite variable because portions of the crown may not be clearly visible. As defoliation increases, branches and reproductive structures may interfere with foliage estimates. Personal judgment about including or excluding portions of the live crown can affect estimates. Distinguishing defoliated live branches from dead branches becomes difficult with increasing amounts of defoliation.

2.3.7.3 Causes of Change

- Increase—foliage transparency increases when foliage is reduced by:
  - Insect defoliation
  - Diseases
  - Environmental stresses
  - Increased seed production that may reduce the amount of foliage production
  - Declining tree vigor
  - Decreased needle retention of conifers caused by defoliating events like insect outbreaks or drought
  - Decreased size of leaves or needles
  - Loss of branches that decreases foliage overlap
  - Loss of adjacent trees that may have been unintentionally included in previous estimates
- Decrease—foliage transparency decreases when foliage is added by:
  - Control or collapse of insect or disease defoliation events
  - Recovery from environmental stresses
  - Improved tree vigor
  - Increased needle retention of conifers caused by improved growing conditions
  - Increased size of leaves or needles
  - Addition of branches, which increases foliage overlap
  - Growth of adjacent trees that may affect the estimate
- Persistence—foliage transparency is the most rapidly changing variable measured in tree crowns. Wind, frost, and hail can change foliage transparency in a short time. Changes caused by insect defoliation may

be measurable days apart. Diseases may contribute to steady decline of foliage during a growing season. Defoliation of evergreens may contribute to foliage transparency changes for more than a year. Poor site conditions that cause higher foliage transparency may persist for the life of the tree.

2.3.7.4 Intended Use

Foliage transparency is used as a measurement of defoliation or stress. The amount of foliage in a crown is related to tree growth. A tree with more foliage is expected to have higher growth potential, vigor, survivability, and reproductive potential than a tree of the same species with less foliage. High foliage transparency indicates a loss of vigor and growth potential. Usually, serious effects are not expected until a tree loses half of its foliage or unless significant defoliation persists over multiple seasons. The average foliage transparency of healthy trees tends to be species-specific.

2.3.7.5 Attributes Shared with Other Indicators

Foliage is included in all crown measurements. It is used to determine crown diameter, to identify the uncompacted live crown, and as part of the denominator in determining crown dieback. Since foliage blocks transmission of light through the crown, the attribute measured in crown density, it contributes heavily to the density measurement.

2.3.8 Crown Diameter

2.3.8.1 Definition

Crown diameter is the average of two diameter measurements: (1) widest distance anywhere in the crown between the driplines (fig. 2.16) of two live branches, and (2) the distance perpendicular to the widest measurement. Abnormally long branches, on one side of a tree, that extend beyond the edge of the crown outline are excluded from the measurement on that side (fig. 2.17).

2.3.8.2 Measurement

- Units—crown diameter is measured to the nearest foot.
- Method of determination—a logger's tape is used to measure crown width at the widest point. A second measurement of crown width is then taken at 90 degrees from the widest point. Both measurements are recorded.

  Each crew member stands directly beneath the dripline of the crown and estimates where the dripline intersects a logger's tape. The dripline is

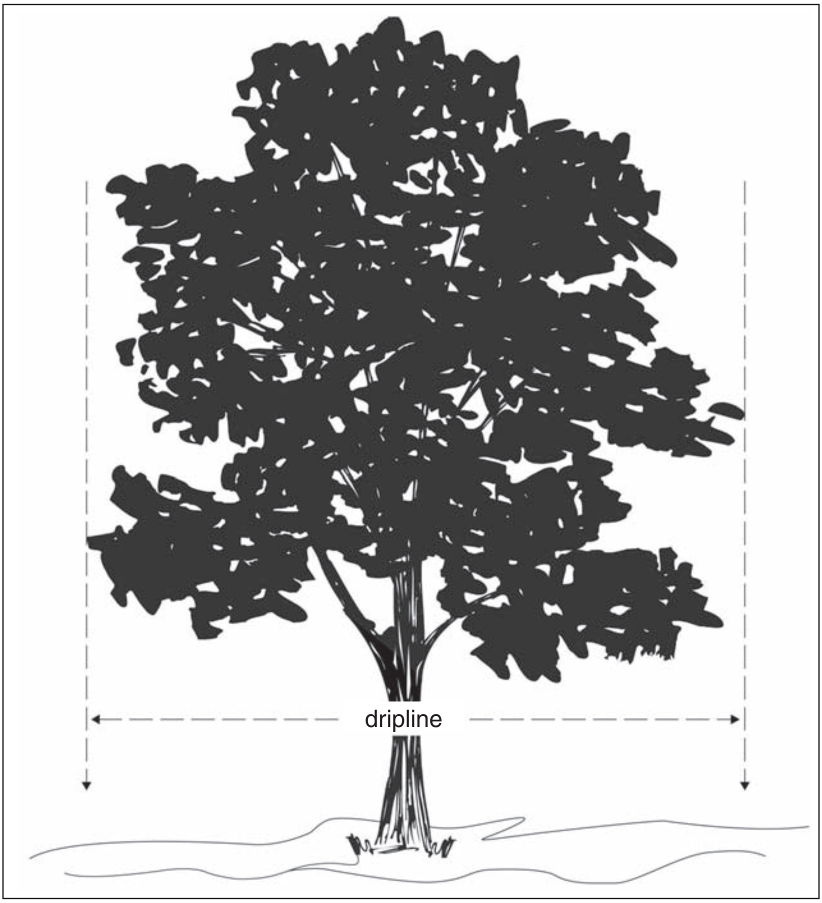

Figure 2.16—Establishing the dripline of a tree crown.

established by projecting a vertical line upward from the ground to the branch tip above. Branches infrequently protrude well beyond the normal outline of a tree. These abnormal branches are excluded from crown diameter measurements. Occasionally it is helpful to use a device such as a clinometer to ensure that a crew member is directly beneath the crown edge. Such devices are used for training and data quality control checks. If the branch tips cannot be seen from beneath the tree, then both crew members should move outward an equal distance away from the tree until they both can see well enough to make the measurement.

- Limitations—the most common causes of error are improper location of the crown edge (dripline) and improper selection of the widest crown axis. Branches may be intermingled with neighboring trees or shielded by the lower canopy, making it difficult to see the branch tips.

Key points of crown diameter measurement

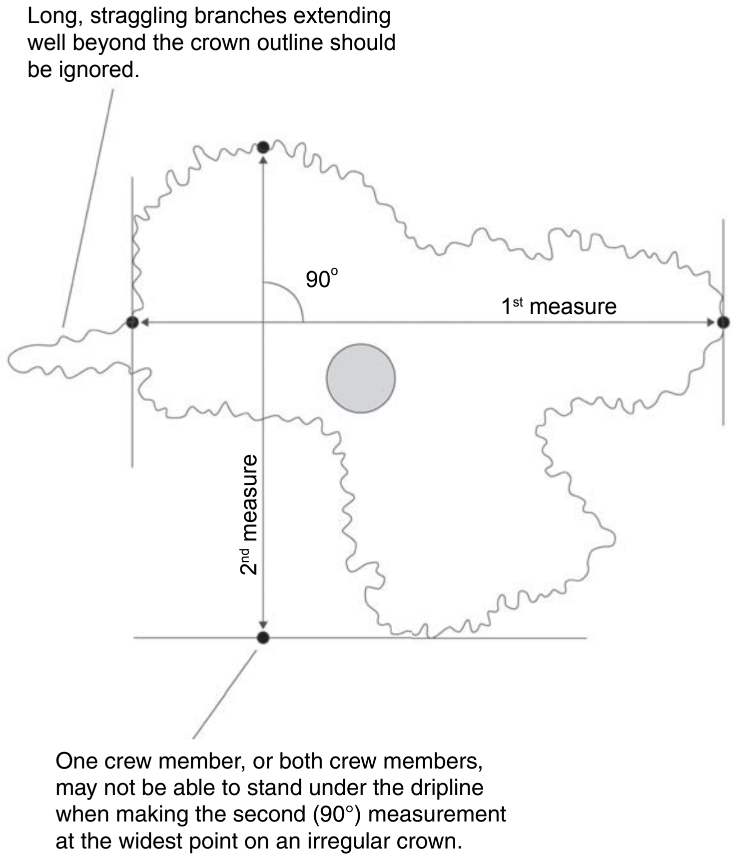

Figure 2.17—The first crown diameter measurement is taken at the widest diameter, and the second is taken 90° from the first.

2.3.8.3 Causes of Change

- Increase—crown diameters are likely to increase as a tree assumes higher canopy positions. Decreasing stand density will make more space available for lateral branch growth and larger diameters.
- Decrease—crown diameters decline with increased competition from neighboring trees. Mortality of lower branches as a result of competition, snow and ice damage, or insect or disease damage reduces crown diameter. Shock response after logging or similar disturbance may result in loss of large branches and decreased crown widths.

- Persistence—crown diameters are not likely to change from one year to the next unless some major injury has occurred. Significant changes may not be detected before 5 to 10 years of measurements have been recorded.

2.3.8.4 Intended Use

Crown diameters are associated with vigor, stand stocking, and the stem diameters of most species. Trees with large crown diameters are expected to have greater growth than trees of the same species with small crown diameters. Trees with large crown diameters have more foliage and surface area for photosynthesis and have a greater potential for carbon fixation. This may be offset by higher respiration costs for large mature crowns. Mature and overmature trees may have slower growth, wider crowns, and lower uncompacted live crown ratios than younger trees. Because crown diameters of open-grown trees tend to differ from species to species, stand-level growth predictions for multispecies stands should not be based on crown diameter alone.

2.3.8.5 Attributes Shared with Other Indicators

Crown diameter measurements are sometimes reflected in crown density measurements. When two trees are close together, their crowns are often reduced or missing on the side where they are in closest proximity. A similar reduction is recorded in crown density for the missing portion of the crown. Lateral dieback of branches can cause a reduction in crown diameter.

2.4 Limitations and Assumptions Associated with Crown Indicators

Remeasurements of crown variables by quality control experts demonstrate that observer-to-observer variation in measurements can result from differences in regional training and interpretation of terminology. Annual training and certification sessions for both regional trainers and crews are critical to reducing such variation.

Combining crown indicators across species must be done cautiously because most tree stresses are species-specific and the effect of a particular stress may be obscured. For instance, averaging crown data across both loblolly pines and oaks may mask an important forest health problem that affects only the loblolly pine, e.g., the southern pine beetle. Unless properly adjusted for species differences, subsequent analyses of crown condition are highly influenced by species distribution. Crown indicators must either be adjusted with models or otherwise stratified by species to overcome this problem.

The composite crown indicators described later in this report are defined as functions of live crown length, crown diameter, and crown density. Calculation of crown length requires a measure of tree length, which was not recorded on FHM plots between 1990 and 1999. Tree length is a standard mensuration variable recorded by FIA, and is, therefore, available in subsequent datasets. At this writing FIA has concluded that crown-diameter measurements are prohibitively expensive, so field measurements of crown diameter are not available in most post-1999 FIA datasets (although they are available in the previous FHM datasets). Models will have to be substituted for field measurements if tree length or crown diameters are not available in a given dataset.

3 Training

The primary goal of training is to ensure that all field crews assess crown conditions in a consistent and standard way. Training for crown measurements is done in two sessions. The first, an indoor session, covers the methods, terms, and requirements for each measurement. The second provides hands-on outdoor demonstration and practice for students. The training then concludes with a written exam and field test that qualifies crews for field data collection. Successful completion of the written exam and field exam is required before a crew member or student can be certified as qualified to collect crown classification data for the current year. Certification must be renewed on an annual basis.

To promote consistency from one training session to the next, a detailed training and certification plan has been prepared to provide trainers with step-by-step guidance. The training package and training visual aids will eventually be available from the Internet; until then a training package and CD may be obtained from:

Forest Inventory and Analysis National Office
Forest Service, U.S. Department of Agriculture, SPPII
4th Floor, RP–C
1601 North Kent Street
Arlington, VA 22209
(703) 605–4189

Crown-condition classification training is structured to proceed in the following order:

1. Classroom and field instruction
2. Practice
3. Evaluation and certification
4. Retraining, evaluation, and certification if necessary

Each training session must be designed to accommodate the experience level of all trainees. New trainees are provided with complete information about methods and objectives. Experienced observers may only require a refresher course with updates on changes to field methods. The training and certification process is repeated every year, and trainees must be tested, regardless of experience. Those who fail to meet the measurement quality objectives (table 3.1) are retrained and retested prior to certification.

Table 3.1—Measurement quality objectives for the crown rating system

Crown indicator	Reporting units	Measurement quality objectives[a]
Vigor class	3 classes	90 percent agreement
Uncompacted live crown ratio	21 classes	90 percent agreement @ ± 10 percent (two classes)
Crown light exposure	5 classes	85 percent agreement within one class if > 0
Crown position	4 classes	85 percent agreement
Crown density	21 classes	90 percent agreement @ ± 10 percent (two classes)
Crown dieback	21 classes	90 percent agreement @ ± 10 percent (two classes)
Foliage transparency	21 classes	90 percent agreement @ ± 10 percent (two classes)
Crown diameter	1 foot	90 percent @ ± 5 feet of the mean[b] or 90 percent @ ± 10 percent of the mean[b c]

[a] Percentage of field crew observations that are in agreement with field auditors.
[b] The arithmetic mean of the two crown diameter measurements for each tree.
[c] Plus or minus 10 percent is used for crowns with mean diameters larger than 50 feet.

3.1 Prerequisites for Trainers and Trainees

Crown classification trainers should have the following background and skills:

- Previous crown-condition classification training and certification (FIA curriculum or equivalent)
- Field experience in crown-condition classification
- Ability to work and communicate effectively with a broad range of students in both indoor and outdoor settings

Trainees are assumed to have the following skills. If not, these skills must be acquired through additional training:

- Ability to use basic forestry field equipment
- Ability to interpret aerial photographs
- Ability to identify tree species common in the region
- Ability to work effectively under arduous field conditions with a crew partner
- Good or corrected vision within the normal color range

3.2 Training Site Requirements and Materials

Training involves a mixture of indoor and outdoor activities. The indoor training site must include a room that is large enough to accommodate all trainees and suitable for viewing overheads, slides, and portable computer presentations. Indoor training equipment should include:

- Slide and overhead projectors or LCD projector
- Projection screen or suitable wall surface

The outdoor site should be a forested area with trails or roads for mobility and with tree species representative of the region where crews will be working. The following materials are needed to set up the outdoor training course:

- Index cards or paper, metal, or fabric tags for marking trees
- Permanent markers
- Plastic flagging in at least three colors (not green, stripes, or polka dots)
- Staple gun, staple hammer, or hammer and nails

In addition to the standard equipment used for forest inventory, all trainees must be equipped with the following:

- Clinometer
- Logger's tape or other 50- to 100-foot tape (at least one per training group)
- Binoculars
- Density-and-transparency cards
- Data sheets for practice and testing
- Maps of the practice and test courses
- Clipboards
- Pencils
- Field guides (see footnote 1, page 5)

4 Data Quality Control

Quality assurance (QA) encompasses all activities performed to ensure that the field data achieve the desired quality. The QA program focuses on identification and documentation of operations and procedures that affect data quality. Quality control (QC) describes the specific actions required to maintain data quality within an acceptable range.

The goal of any QA program is to ensure that data attain the minimum specified standards. Data collected for QA purposes can also provide the feedback that is necessary to develop realistic measurement quality objectives (MQOs), revise methods to reduce errors, improve training, and aid in the interpretation of results. The main criteria used to interpret the level of data quality in the FIA Program are:

1. Precision—the ability of a method to reproduce the same value
2. Accuracy—the ability of a method to yield the “true” value
3. Completeness—the amount of valid, usable data produced by a method
4. Comparability—the ability to combine data collected by different methods, in different locations, and by different data collectors

An effective QA program provides for prevention of data quality problems, assessment and appraisal, and correction.

4.1 Prevention of Data Quality Problems

Activities designed to prevent data quality problems:

- Development and documentation of standardized definitions and field methods
- Sufficient training and calibration of field crews
- Establishment of realistic MQOs

For crown-condition classification, the first of these has been addressed by production of the field manual. The second includes not only the successful execution of training, but also a feedback loop designed to query trainees about the effectiveness of each training session. This can be accomplished by a training evaluation survey, debriefing trainees, or both. Evaluation topics should include the facilities, instructors, general organization, and certification procedures. Maintaining records on the following aspects of training will improve future training, as well as the interpretation of QC data:

- Time and place of training
- A list of trainers
- A list of individuals trained and certified
- A list of problems noted and proposed resolutions
- Certification results
- Trainee feedback

Field audits, which are conducted as an extension of training, are another important source of feedback. These audits are conducted by trainers who visit and interact with field crews as they gather field data. Audits should be conducted soon after training is concluded so that potential problems are corrected early. These interactions also provide an additional opportunity for crew feedback about the methodology and training, as well as any logistical problems that may have been encountered. A short report should be completed for future reference; it should list the personnel involved, location of the audit, problems and questions encountered with resolutions and answers, and followup action items. This information is filed with other program documentation.

The measurement quality objectives listed for crown-condition classification in table 3.1 represent the precision with which field crews are expected to measure each crown indicator. These MQOs have been determined from more than a decade of field experience. Trainee certification, as well as assessments and appraisals of field crew performance and data quality, are based on comparisons with these measurement quality objectives.

4.2 Assessment and Appraisal

QA assessment and appraisal activities include the remeasurement of field data by "audit crews," data validation, and a debriefing of field crews at the end of the field season. Topics covered at the debriefing should include the training session, methodology, logistics, and data collection techniques.

"Blind checks" are the preferred method for acquiring remeasured data for QA purposes. Audit crews are sent to sites originally sampled by production crews, where they independently remeasure the trees on those sites. The checks are blind in that the audit crew does not have access to the original data, and production crews do not know which sites will be checked. The two datasets are then compared to develop estimates of precision and to check compliance with measurement quality objectives. The target remeasurement intensity is approximately 5 percent of all trees sampled, but the percentage within a given region may vary depending on the availability of resources. Note that data collected by the audit crew should not be used to replace the original data from the production crew because this would disrupt the error structure of the production data.

Data validation ensures that the recorded data do not violate any range or logic checks. A range check is a comparison of recorded values with a list of valid codes; a logic check is a comparison of entries in two or more data fields. For example, if the crown position is superstory, then crown light exposure should be greater than zero. Ideally, all range and logic checks are accomplished during the data collection process by using PDRs with software equipped to perform realtime checks.

4.3 Correction

Correction is modification of training, field protocols, and or the QA program to improve data quality. The need for correction and the effect of previous corrections are most objectively evaluated through analysis of blind check data. This is usually done at the end of the field season, although field audits and training feedback make it possible to implement corrective actions sooner.

Any modification to the methodology is done with extreme caution, because of its potential effect on trend analysis. The need for corrective action decreases over time as the numbers of veteran trainers and experienced crew personnel increase. The level of experience with crown classification in FIA is now at the point where changes to field methodology are rare. Most recent changes have focused on opportunities to improve training.

5 Data Analysis

Many analytical techniques may be used to interpret the crown indicator data. Choosing the best approach requires careful attention to the following before the analysis is initiated:

1. Specify the objectives.
2. Identify the variables of interest.
3. Structure the analysis to accommodate the data and objectives.

Here we present information related to these topics that can facilitate and expedite the analysis of crown condition and guide future research. We discuss methods that have already been applied and others that have yet to be attempted. Although several potential avenues of analysis are discussed, it should be recognized that this does not represent the full range of possibilities.

5.1 Analytical Objectives

The success of any analysis depends on proper specification of the objectives. Analyses of crown condition usually proceed along four major analytical themes: description, detection, evaluation, and intensive site monitoring. To date, some experience has been gained with all but the last of these.

The crown-condition indicators have recently become part of the FIA phase 3 plot network (Stolte 2001). Thus, analyses of crown data are being incorporated into regular FIA reports, which have traditionally favored a descriptive approach to analysis. This descriptive approach usually involves the presentation and discussion of tabular and graphic summaries of population statistics. These data summaries are useful for establishing baselines and pointing to gross differences among sets of observations, but are not designed to identify forest health problems. Auxiliary analyses based on statistical inference are necessary for that.

The FHM Program has promoted a three-tiered approach to analysis, which includes detection monitoring, evaluation monitoring, and intensive site monitoring (Riitters and Tkacz 2004). Detection monitoring is designed to scan the available data for unusual or suspicious trends. If a potential problem surfaces, then an evaluation monitoring project is initiated to further investigate the available data in an attempt to explain the situation. If evaluation monitoring fails to yield a satisfactory explanation and the potential problem is not a false signal, intensive site monitoring may then be implemented to further study the problem. Successful implementation of each tier requires the judicious use of rigorous statistical methods. While evaluation and intensive site monitoring are beyond the scope of regular FIA reports, it would be prudent to incorporate some of the techniques developed for detection monitoring into the FIA processing system.

5.2 Variables of Interest

5.2.1 Absolute and Composite Crown Indicators

This section defines two levels of crown indicators. Absolute indicators are simply the individual crown variables recorded in the field (table 5.1). Although absolute indicators have the advantage of simplicity, they have the disadvantage that each represents only a single aspect of crown structure. Composite indicators formulated using multiple crown dimensions better represent a tree's potential to capture and utilize solar energy. For this reason, composite indicators are generally favored for detection monitoring. The absolute indicators are better suited for further evaluation of any unusual trends that may be identified.

Measures of uncompacted crown ratio, crown density, crown diameter, and tree length are used to compute a variety of composite crown indicators. Composite crown volume (*CCV*) can be calculated for each sampled tree as follows:

$$CCV = \left(0.5\pi R^2 (CL)\right)\left(\frac{CDEN}{100}\right) \tag{5.1}$$

where

$R = CDIA / 2$

$CL = TL\ (ULCR/100)$ = crown length (feet)

TL = total tree length (feet), and *CDIA, ULCR,* and *CDEN* are as defined in table 5.1

Note that the first portion of this equation $\left(0.5\pi R^2 (CL)\right)$ approximates the three-dimensional volume of a parabola, and the second part (*CDEN/100*) estimates the portion of the parabola filled with crown biomass. The estimation of crown volume can be fine tuned to accommodate other crown shapes. For example, the parabola specified by equation 5.1 can be modified to a cone by changing the 0.5 to 0.33. The latter would be more precise for species such as spruce and fir. Highly tuned estimates of individual crown volumes are not possible in the absence of field classification of crown shape, but crude species-level adjustments are possible if desired.

Table 5.1—Summary of crown indicator levels and their associated indicators

Indicator level	Indicator name	Acronym	Bounds	Scale
Absolute	Vigor class	CVIG	$1 \leq CVIG \leq 3$	Ordinal
	Uncompacted live crown ratio	ULCR	$0 \leq ULCR \leq 100$	Ratio
	Crown light exposure	CEXP	$0 \leq CEXP \leq 5$	Ordinal
	Crown position	CPOS	$1 \leq CPOS \leq 4$	Nominal[b]
	Crown diameter[a]	CDIA	$CDIA \geq 0$	Ratio
	Crown density	CDEN	$0 \leq CDEN \leq 100$	Ratio
	Crown dieback	CDBK	$0 \leq CDBK \leq 100$	Ratio
	Foliage transparency	FTRAN	$0 \leq FTRAN \leq 100$	Ratio
Composite	Composite crown volume	CCV	$CCV \geq 0$	Ratio
	Composite crown surface area	CCSA	$CCSA \geq 0$	Ratio
	Crown shape ratio	CSHAPE	$CSHAPE \geq 0$	Ratio
	Crown production efficiency	CEFF	$CEFF \geq 0$	Ratio

[a] Crown diameter measurements may not be available for some Forest Inventory and Analysis Program datasets.
[b] Crown position can be converted to an ordinal variable by combining the open-grown and overstory categories.

Additional equations for the volumes and surface areas of geometric forms common in tree crowns can be found in Husch and others (1982). Again, the analyst has the option of further adjusting alternative volume equations with the *CDEN* term as was done in equation 5.1.

Tree length (*TL*) is not listed among the crown indicators because tree length is a standard mensuration variable measured on all FIA plots. In fact, for trees with broken tops, FIA crews measure both actual tree length and total tree length (which includes the broken top). Note that some adjustment for the calculation of crown length (*CL*) in equation 5.1 may be necessary for trees with broken tops because *ULCR* and *CDEN* are measured differently. When *CDEN* for a broken tree is estimated in the field, the crown outline upon which *CDEN* is based includes the broken top, i.e., the *CDEN* estimate is reduced to account for the missing biomass. *ULCR* is based on the ratio of live crown to actual tree length, i.e., not the total tree length that includes the broken top. If the analyst wants to utilize the *CDEN* specified in the second part of equation 5.1, *CL* must be adjusted for trees with broken tops to retain the proper relationship between *CDEN* and *CL*. Since the missing top is included in the *CDEN* field estimate, the missing top should also be included in the estimate of crown length:

$$CL = AL(ULCR/100) + (TL - AL) \tag{5.2}$$

where

AL = actual tree length (feet)

If the term for *CDEN* is to be omitted from equation 5.1, then the crown lengths of trees with broken tops would be calculated as follows:

$$CL = AL(ULCR/100) \tag{5.3}$$

At this writing FIA has concluded that crown diameter measurements are prohibitively expensive, so field measurements of *CD* are not available in most FIA datasets. Bechtold (2003b, 2004) has developed crown diameter prediction models for numerous species in the Eastern and Western United States, which may be used when *CD* field measurements are not available. Analyses of indicators involving model-based estimates of crown diameter must be interpreted cautiously since any error in the predicted values will be propagated through the indicators. If species are encountered for which no crown diameter models are available then models for similar species will have to be substituted or else these species must be deleted from the analysis. An alternative to using the *CCV* composite indicator calculated with predicted *CD*s would be to remove the $(0.5\pi R^2)$ portion of equation (5.1) and create an indicator that is a function of only *CL* and *CDEN*.

A second composite indicator is crown surface area (*CSA*). *CSA* requires the same adjustments for *CL* described above for *CCV*. *CSA* for the parabolic crown form is

$$CSA = \frac{4\pi CL}{3R^2}\left[\left(R^2 + \frac{R^4}{4CL^2}\right)^{1.5} - \left(\frac{R^4}{4CL^2}\right)^{1.5}\right]\frac{CDEN}{100} \tag{5.4}$$

In addition to crown volume and surface area, crown shape ratio (*CSHAPE*) and crown production efficiency (*CEFF*) have also been related to a tree's potential to capture and utilize solar energy (Ford 1985; Larocque and Marshall 1993, 1994a, 1994b; Perry 1985). These are defined as

$$CSHAPE = \frac{CDIA}{CL} \tag{5.5}$$

and

$$CEFF = \frac{CSA}{CCV} \tag{5.6}$$

Finally, note that all discussion of composite crown indicators in this report focuses on a univariate approach to analysis. Composite tree- or stand-level crown indicators may disregard possible interactions among the individual crown indicators from which they are derived, which could be inappropriate for some analyses. One alternative that circumvents this problem is a multivariate approach (Morrison 1976), which formulates a vector of responses from all variables in the analysis.

5.2.2 Indicator Thresholds

Thresholds are important to assessing forest health because they can be used to separate the sampled population into categories of good, average, and poor. However, before pursuing an analysis based on thresholds the analyst should consider that information may be lost by reducing the data to a few discrete groups. Extra caution should be used if the thresholds have not been rigorously derived, or if alternative methods are available to analyze the data in their original scale.

5.2.2.1 Biological Thresholds

Ideally, thresholds should be developed on a biological basis. Unfortunately, with respect to the crown indicators, the point at which a tree begins to decline is difficult to pinpoint. This will require the establishment of correlations between crown indicators and losses resulting from future growth reduction and mortality. The task is further complicated because the thresholds are likely to vary by species, and the effects of normal stand dynamics and attrition must be considered. Although biological thresholds for the crown indicators have yet to be developed, some consideration has been given to how such research might proceed. Logistic regression is one approach with the potential to yield rigorous biological thresholds. Because the logistic model is bounded by zero and one, it is particularly useful for modeling mortality and survival. Stepwise logistic regression where crown indicators would be employed as independent variables could be used to identify the most significant variables, and plots of the survival probability (zero to one) over values of the independent variables could be produced. Additional tree and stand variables designed to quantify the effect of natural stand dynamics might also be included. If risk of mortality were correlated with crown condition in this way, and if survival models were developed over multiple regions or years, various hypotheses about changing survival rates could be developed and tested.

Discriminant analysis is an alternative technique that might be used to objectively divide an indicator into categories. This technique produces a discriminant function useful for predicting to which group an observation from a new dataset is most likely to belong. The discriminant function is formed from data that has one group classification variable and several quantitative variables that are used by the function to maximize the probability of correct group membership. For instance, survival (dead or alive) may be the group classification variable and the quantitative variables may be some combination of crown indicators. Again, other tree and stand variables could be included to account for the effect of stand dynamics. The resulting discriminant function would then be used to group recently measured trees into survival categories based on the dependent variables. Discriminant analysis is typically based on the assumption that the data follow a multivariate normal distribution, but if this is not the case then nonparametric discriminant methods can be used.

5.2.2.2 Subjective and Empirical Thresholds

The most serious impediment to the development of biological thresholds is lack of data. Mortality is relatively rare, and individual trees have not yet been tracked long enough on the FIA phase 3 plot network to yield an adequate dataset. In the meantime, there are alternatives to biological thresholds. The simplest are subjective thresholds. When these are employed, analysts use their own experience and judgment to assign trees to categories. Subjective thresholds may be adequate for descriptive purposes and gross comparisons, but they are insufficient for all but the most elementary analyses. For some purposes, improvement over the subjective approach can be achieved through empirical methods that more objectively achieve such groupings. The field of cluster analysis provides numerous analytical methods to cluster observations into groups that tend to be similar with respect to a specified set of variables. These methods include average linkage, centroid, complete linkage, maximum likelihood, flexible beta, and Ward's minimum-variance method (SAS Institute Inc. 1989). It must be emphasized that these techniques have the disadvantage that the thresholds are relative, i.e., they can change from one set of observations to the next. In addition, the traditional analysis of variance is not valid for testing differences between cluster means because the clusters were formed by methods that are intended to maximize the difference between the clusters in the first place.

5.2.2.3 Statistical Thresholds

Statistical thresholds offer a reasonable alternative to biological thresholds. They are easy to establish, available for immediate use, and in some cases may be preferred even when biological thresholds are available. The main disadvantage with statistical thresholds is that they always result in a set of observations designated as poor, even in the absence of a problem, so they must be used cautiously.

Statistical thresholds can be identified by isolating observations at the tails of statistical distributions, or they may involve more elaborate techniques such as the one discussed in the next paragraph. When employed in combination with observations that have been adjusted for the natural influence of tree and stand characteristics, they can be quite useful for detecting spatial patterns and measuring change over time. The residualization and standardization techniques discussed in the next section can accomplish these types of adjustments, and are ideal for use with statistical thresholds.

A more elaborate technique involving statistical thresholds focuses on the relationship between means and variances. For example, a plot-level mean crown density of 0.5 may indicate that all trees have crown densities of 50 percent or that half the trees are totally defoliated while the other half are 100-percent foliated. An indicator based on both the mean and variance could distinguish between these drastically different situations. For indicators that have bounds of zero and one, the beta distribution could be fitted for individual tree crown indicators on a field plot (Zarnoch and others 1995) and plotted on a two-dimensional axis for a sample of plots. Ninety-five percent-confidence ellipsoids, i.e., thresholds, could then be developed, where plots outside the ellipsoids indicate atypical situations for either the mean or variability of the crown indicator.

5.2.3 Residualization and Standardization

Previous discussions have mentioned the need to adjust values of crown indicators for natural factors known to influence crown dimensions. This can be accomplished through residualization, whereby an indicator is modeled as a function of tree and stand conditions in an attempt to remove the effect of natural stresses and stand dynamics, thus increasing the signal-to-noise ratio. Any model form can be used, so long as the parameters are biologically reasonable and unbiased. The resulting residuals are of primary interest, particularly those in the tails of the statistical distributions. Resulting patterns (involving space, time, or specified groups of trees) associated with residuals may signify a potential problem. At a minimum, such adjustments should be performed by species, since reactions to natural factors differ by species, e.g., shade tolerance.

Residualization proceeds as follows. Specifically, let

Y_{ts} = a specific crown indicator for tree t of species s

$\hat{Y}_{ts}$ = the predicted value of the indicator for tree t of species s based on an appropriate adjustment model

Then

$$R_{ts} = Y_{ts} - \hat{Y}_{ts} \tag{5.7}$$

where

R_{ts} = the residualized indicator for tree t of species s

At this point, the residualized indicator is still scaled differently by species, but an additional adjustment can be performed to standardize residuals across species. To do this, one rescales the residualized indicators (R_{ts}) from equation 5.7 to a standard deviation of one by dividing the model residuals by their standard deviation:

$$R'_{ts} = \frac{R_{ts}}{sd_s} \tag{5.8}$$

where

R'_{ts} = the standardized-residual indicator for tree t of species s

sd_s = the standard deviation of the model residuals for species s

We now have a tree-level indicator (R'_{ts}) that has been adjusted for the parameters in the model and standardized (by species) to a mean of zero, i.e., the mean of the model residuals is zero, and a standard deviation of one. Standardization in this manner allows indicator values for trees to be combined across species for analysis. Values for trees can then be averaged or otherwise grouped for direct comparison by tree-level attributes, e.g. overstory vs. understory trees, condition-level attributes, e.g., public vs. private ownership, or plot-level attributes (Piedmont vs. Coastal Plain). More details on residualization and standardization techniques are provided by Zarnoch and others (2004).

Note that standardization is not absolutely contingent on modeling. Had residualization via modeling not been desired or possible, a standardized indicator could still have been produced by replacing the predicted $(\hat{Y}_{ts})$ in equation 5.7 with the mean $(\bar{Y}_{ts})$ from the data. Although adjustment by species is usually desirable, this too is not required. The residualization and standardization described above could have been performed across all trees of interest, rather than by species.

5.2.4 Stratification Variables

Most analyses can be improved by stratification or adjustment of the crown indicators with auxiliary variables known to influence crown condition. Descriptive analyses are more informative when an indicator is stratified into meaningful groups of class variables. Hypothesis testing with analysis of variance requires the grouping of data into discrete classes. For hypothesis testing, the biological aspects of the data must be taken into account so that the groups have a meaningful level of within-group homogeneity and assumptions of the applied statistical test are not violated. It is also important to consider the degree of balance required by the statistical procedure as well as the number of observations available. Overstratification can dilute the analysis; if there are too few observations in some strata, an important signal can be weakened. On the other hand, the signal-to-noise ratio may be too low if the data are reduced to too few groups. Achieving the proper balance for a given analysis may require several iterations.

At the tree level, species, stem size (d.b.h. or d.r.c.), crown light exposure (*CEXP*), and canopy position (*CPOS*), are all candidates for meaningful stratification of tree crown dimensions. Note that the latter three are listed as absolute crown indicators in table 5.1, but their primary value is that they can be used to stratify or adjust indicators that provide measures of crown dimension. At the plot and condition class, i.e., stand, levels, it may be useful to partition the crown indicators by a variety of additional variables recorded by FIA such as latitude, elevation, slope, aspect, stand density (e.g., basal area per acre), forest type, physiographic class, stand origin (planted vs. natural), ownership, and disturbance history. Analysts should also consider correlating the crown indicators with overlays from other datasets such as weather or pollution records.

5.2.5 Data Compilation

There are a number of issues to consider when compiling crown data for analysis. Analyses of crown indicators usually proceed at the tree, plot, or population levels. Most descriptive and inferential analyses will involve population values such as the mean indicator value for a population or domain of interest, or the proportions of trees classified into categories of good or poor via thresholds. Less commonly, tree-level or mean plot-level crown indicators may be the focus of an analysis. Bechtold and Coulston (2005) utilized tree-level and plot-level *CCV*s to check for spatial clustering of trees with small crown volumes. When computing population means and totals from the crown indicators observed on sampled trees, calculations based on simple random sampling are recommended. Another alternative that might yield improved variance estimates would be to use the FIA data processing system, which is based on double sampling for stratification (Bechtold and Patterson 2005).

The level to which the crown data are compiled should also be considered in the interpretation of results. For example, population ecologists often emphasize the importance of population-level data, rather than individual-level data, in predicting the future success of a community. However, from an epidemiological perspective, the distribution of a disease throughout a population is driven by individuals. At the initiation of an epidemic, a population or plot-level subset of individuals may actually exhibit improved crown condition as survivor trees benefit from reduced competition. Plot-level or species-level means may also increase simply due to increased mortality of weaker trees with smaller crowns. In such situations, population-level diagnostics may not detect a disease until much later, when many more trees have been affected.

5.3 Structuring Analyses to Accommodate the Data and Objectives

Whether the objective of analysis involves descriptive statistics, inferential statistics, or modeling, the nature of the variables under study must be understood before analysis can proceed. There are three commonly recognized measurement scales associated with the crown indicators, each of which may require different statistical treatment. In order of increasing scale from discrete to continuous these are the nominal, ordinal, and ratio scales (table 5.1). The ratio scale is required for typical parametric statistical methods that assume the normal or some other well known distribution. Nonparametric statistical methods are appropriate to the nominal and ordinal scales, and to ratio scales where the underlying distribution is nonnormal. Nonparametric procedures can also be applied to the ratio scale with little loss of statistical power in many cases. Tests of normality (or other distributions) may be performed with standard goodness-of-fit tests such as the Chi-square and Kolmogorov-Smirnov tests (Conover 1980).

5.3.1 Descriptive Statistics

The most fundamental descriptors of any ratio variable are measures of central tendency, and the statistic most commonly used for this purpose is the mean. For a mean to be valid, the sample must be randomly drawn from the population of interest. The FIA sampling framework is partially systematic, but this is a reasonably good approximation of a random sample for most practical situations (Milne 1959). The median may be more appropriate than the mean for highly skewed nonnormal data distributions, particularly those with large outliers that substantially influence the sample mean. The median represents the midpoint or 50th percentile; half of the observations in the sample fall below it and the other half above it.

Measures of central tendency are usually accompanied by measures of dispersion, such as the sample variance. The utility and interpretation of the variance is often disregarded, but it is as important as the mean. This is particularly true in forest health problems that focus on epidemiology. For example, if the mean plot-level incidence of diseased trees is 50 percent in each of two populations, then the sample means are equal. However, if population 1 has low variance while population 2 has high variance, it may be inferred that most plots in population 1 are infected while only a portion are infected in population 2. This may indicate that population 2 is exhibiting some kind of biological resistance to the pathogen or may be in an earlier stage of spread of the disease.

There are additional statistics directly related to the variance that have slightly different interpretations and usages. The standard deviation, which is the square root of the variance, expresses the variance in the same units as the mean. It is commonly assumed that the mean plus or minus two standard deviations contains approximately 95 percent of the population, but this assumption is contingent on a normal distribution. Care must be exercised when applying this rule to the crown variables because many of them may have nonnormal distributions. Another measure of dispersion is the standard error of the mean. Unlike the mean, variance, and standard deviation, the standard error is not actually an estimate of any population characteristic since it is a decreasing function of the sample size. However, it is extremely useful for measuring the variability of the mean, establishing confidence intervals, and testing hypotheses.

Beyond the presentation of central tendency and dispersion statistics, it is often useful to characterize the entire frequency distribution associated with an indicator. The upper and lower percentiles (tails) of statistical distribution may be more sensitive than measures of central tendency in connection with forest health issues, so they should definitely not be overlooked. Statistical distributions are commonly displayed with histograms, which plot the distribution of observations over discrete points, intervals, or arbitrary groupings of the variable of interest. Histograms are appropriate for both discrete and continuous variables. When used with continuous data, histograms often include the locations of the mean, median, and various percentiles.

An equivalent (but less common) method to display frequency distributions is the cumulative distribution function (CDF). This is a sigmoid (s-shaped) step function defined as F(x), where F(x) is the proportion of observations less than or equal to x, and x ranges over all values of the crown indicator. The advantage of the CDF is the simplicity with which population percentiles may be calculated and compared. For instance, the lower 10th percentile may be obtained as x such that $F(x) = 0.10$. Another example is ease of computing the proportion of observations between some range of values x_1 and x_2; this is simply $F(x_2) - F(x_1)$.

5.3.2 Inferential Statistics

The hypothesis testing required for detection and evaluation monitoring leads to the field of inferential statistics. There are three types of change detection of primary interest to the crown indicator:

1. Detection of change over space at a point in time
2. Detection of differences among groups of observations at a point in time, e.g., forest types
3. Detection of change over time at a specified geographical location

Statistical tests designed for hypothesis testing must be properly matched to the experimental design. The two simplest experimental designs that might be used in conjunction with FIA crown classification data are the completely random design and the randomized block design. To detect differences among geographic locations or among condition classes at a point in time, a completely random design is generally appropriate if the observations are selected at random. When analyzing change over time for a given geographic location, two situations may be encountered. If the observations made during one period are independent of those made during the other period, a completely random design can be used. However, if the observations are dependent (which may be the case when the same plot is measured at both times), a randomized block design is appropriate. For more complex situations, a repeated-measures analysis may be a better choice. More information about experimental designs and inferential statistics can be found in Kempthorne (1952), Cochran and Cox (1957), or John (1971). Also, when one uses tree-level observations to test hypotheses, one should be aware that the number of trees usually varies from plot to plot, resulting in an unbalanced design. An approximate analysis is possible if one simply uses plot-level means but this does not take into account the unbalanced nature of the design. Therefore, it is recommended that trees be nested within plots and that a two-stage nested design be employed.

Given a random sample from two sets of observations under a completely randomized design, a two-sample t-test can be performed to test whether the means are equivalent:

$$H_0 : u_1 = u_2$$
$$H_1 : u_1 \neq u_2$$

where

H = hypothesis

u = population mean

If three or more locations are tested, this will generalize to the well-known analysis of variance.

5.3.3 Modeling

Modeling has many potential applications to the crown indicators. For example, if the observations of interest in the hypothesis tests described in the previous section occur on a gradient across the landscape, regression methods could be utilized to test for significant gradient effects. Modeling is particularly useful for residualization and other techniques designed to adjust the crown indicators for stand dynamics and other natural factors. Insights into forest health might also be gained by using models to quantify the relationships between two or more crown variables. Those relationships can also be evaluated for change. Here we briefly discuss some of the various model forms that might be considered.

Simple linear regression is the method most commonly used to obtain relationships between a dependent variable y and an independent variable x. The regression equation is

$$\hat{y} = \hat{a} + \hat{b}x$$

where

the parameters $\hat{a}$ and $\hat{b}$ are estimated from the data

Since numerous assumptions and modifications are required or possible when using regression methods, a good statistical regression text such as Draper and Smith (1981) should be consulted for more detail. Multiple linear regression is an extension of simple linear regression; in multiple linear regression several independent variables are used to model the dependent variable. Computation of the parameters becomes more involved with each additional independent variable, so it is almost mandatory to use a statistical software package to do this work. A further extension is the use of nonlinear regression methods for fitting complex models that may be more biologically realistic.

The logistic model is quite useful for modeling a dichotomous (0, 1) variable as a function of continuous or discrete independent variables. It can be especially useful in the development of risk assessment or mortality models. The logistic model is defined as

$$\hat{P} = \left(1 + e^{\hat{b}_0 + \hat{b}_1 x_1 + \hat{b}_2 x_2 + \ldots + \hat{b}_p x_p}\right)^{-1}$$

where

$\hat{P}$ = the predicted probability of a defined event (mortality, survival, etc.)

x_i = the i^{th} independent variable

$\hat{b}_0, \hat{b}_1, \hat{b}_2, \ldots, \hat{b}_p$ are estimated from the data

Categorical data modeling may be quite useful for analyzing relationships when an indicator can have only a limited number of distinct values (as in the case of crown light exposure, for example). This is often the situation in monitoring forest health, where typical data could be represented by r-way contingency tables that are formed by cross tabulation of r different nominal and ordinal variables. In the usual regression modeling approach, the dependent variable is usually continuous and has an approximately normal distribution. In logistic regression the dependent variable is dichotomous. Hence, categorical modeling is a generalization of these methods in which the dependent and independent variables may take on a limited number of values (two or more). It fits linear models to functions of response frequencies and can be used for linear modeling, log-linear modeling, logistic regression, and repeated measures analysis.

In contrast to modeling, where one variable is predicted as a function of one or many variables, correlation analysis measures the strength of the linear relationship between two variables. Generally the Pearson correlation coefficient is calculated; a zero indicates that there is no relationship, and 1 and -1 represent strong positive and negative linear associations, respectively. If the variables under consideration are nonnormal, then nonparametric measures of association such as Kendall's or Spearman's should be employed.

5.3.4 Spatial Analyses

The combination of spatial scan statistics with residualization, standardization, and statistical thresholds is a powerful tool for detection monitoring. Bechtold and Coulston (2005) implemented this approach to check for unusual spatial patterns associated with crown condition in South Carolina, where the spatial scan statistic developed by Kulldorff (1997) was used to search for potential clusters of plots with below average *CCV*s. The Kulldorff statistic was originally developed to test for randomness of disease occurrence in the spatial and spatio-temporal domains and has been applied to other indicators of forest health by Coulston and Riitters (2003). The scanning proceeds by visiting every location, i.e. plot, in the study area. A series of circular windows of increasing size (up to 50 percent of the study area) is then superimposed over each location. The test statistic, ψ_w, is then calculated using the total number of "events" inside and outside each window. ψ_w is the likelihood ratio, based on the Bernoulli distribution, that the occurrence of events is the same everywhere after adjusting for differences in the total number of observations (events and nonevents) inside and outside the window:

$$\psi_w = \left(\frac{E_c}{N_c}\right)^{E_c} \left(1 - \frac{E_c}{N_c}\right)^{(N_c - E_c)} \left(\frac{E_{c'}}{N_{c'}}\right)^{E_{c'}} \left(1 - \frac{E_{c'}}{N_{c'}}\right)^{(N_{c'} - E_{c'})} (I) \qquad (5.9)$$

where

E_c = the number of events within the window
N_c = the number of nonevents within the window
$E_{c'}$ = the number of events outside the window
$N_{c'}$ = the number of nonevents outside the window
$I = 1$ if $E_c / N_c > E_{c'} / N_{c'}$, or 0 otherwise

The indicator function I in equation 5.9 sets up a one-sided test of the null hypothesis $(H_0: E_c / N_c = E_{c'} / N_{c'})$ against the alternative that the rate of events is higher inside the window.

The distribution of ψ across the study area and *p*-values associated with ψ_w are obtained by Monte Carlo simulation based on numerous random replications of the full dataset under the null hypothesis of complete spatial randomness. The significance test for the cluster of observations within the window compares ψ_w for the window to the distribution of ψ from the Monte Carlo simulation. If the value of ψ_w exceeds 95 percent of the values from the Monte Carlo simulation, then the cluster associated with a given window is considered significant at the 5-percent level. An event E is defined as a tree with a residualized indicator value R'_{ts} below some threshold percentile of the frequency distribution of all trees in the study area, and nonevents N as trees with values above the specified threshold:

$$E = E_p = \sum_{1}^{n_p} E_{tp} \tag{5.10}$$

where

E_p = the sum of events on plot p

E_{tp} = 1 if tree t is on plot p and $R'_{ts} \leq T_s$, or 0 otherwise

T_s = the specified percentile of the distribution of the residuals for species s (R'_{ts}) across the study area

When checking for spatial trends, the statistical threshold E might initially be set relatively high, e.g., 25th percentile, and then lowered to verify any spatial trends that result. This technique works with indicators formulated at either the tree level or plot level. The larger sample size attained by using tree-level values increases the power of the test.

6 Literature Cited

Allen, D.C.; Barnett, C.J.; Millers, I.; Lachance, D. 1992. Temporal change (1988-1990) in sugar maple health, and factors associated with crown condition. Canadian Journal of Forest Research. 22: 1776-1784.

Anderson, R.L.; Belanger, R.P. 1987. A crown rating method for assessing tree vigor of loblolly pine and shortleaf pines. In: Phillips, D.R., comp. Proceedings of the fourth biennial southern silvicultural research conference. Gen. Tech. Rep. SE–42. Asheville, NC: U.S. Department of Agriculture Forest Service, Southeastern Forest Experiment Station: 538-543.

Anderson, R.L.; Burkman, W.G.; Millers, I.; Hoffard, W.H. 1992. Visual crown rating model for upper canopy trees in the Eastern United States. Asheville, NC: U.S. Department of Agriculture Forest Service, Southern Region, Forest Pest Management. 15 p.

Bechtold, W.A. 2003a. Crown-diameter prediction models for 87 species of stand-grown trees in the Eastern United States. Southern Journal of Applied Forestry. 27(4): 269-278.

Bechtold, W.A. 2003b. Crown position and light exposure - an alternative to field-assigned crown class. Northern Journal of Applied Forestry. 20(4): 154-160.

Bechtold, W.A. 2004. Largest-crown-width prediction models for 53 species in the Western U.S. Western Journal of Applied Forestry. 19(4): 1-7.

Bechtold, W.A.; Coulston, J.W. 2005. A case study for detection monitoring of crown condition in South Carolina. In: McRoberts, R.E.; Reams, G.A.; Van Deusen, P.C.; McWilliams, W.H., eds. Proceedings of the fifth annual forest inventory and analysis symposium. Gen. Tech. Rep. WO–69. Washington, DC: U.S. Department of Agriculture Forest Service: 167-173.

Bechtold, W.A.; Patterson, P.L., eds. 2005. The enhanced forest inventory and analysis program—national sampling design and estimation procedures. Gen. Tech. Rep. SRS–80. Asheville, NC: U.S. Department of Agriculture Forest Service, Southern Research Station. 85 p.

Belanger, R.P.; Anderson, R.L. 1992. A guide for visually assessing crown densities of loblolly and shortleaf pines. Res. Note SE–352. Asheville, NC: U.S. Department of Agriculture Forest Service, Southeastern Forest Experiment Station. 4 p.

Bonner, G.M. 1964. The influence of stand density on the correlation of stem diameter with crown width and height for lodgepole pine. The Forestry Chronicle. 40: 347-349.

Cochran, W.G.; Cox, G.M. 1957. Experimental designs. 2d ed. New York: John Wiley. 611 p.

Cole, D.M.; Jensen, C.E. 1982. Models for describing vertical crown development of lodgepole pine stands. Res. Pap. INT–292. Ogden, UT: U.S. Department of Agriculture Forest Service, Intermountain Research Station. 10 p.

Conover, W.J. 1980. Practical nonparametric statistics. 2d ed. New York: John Wiley. 493 p.

Coulston, J.W.; Riitters, K.H. 2003. Geographic analysis of forest health indicators using spatial scan statistics. Environmental Management. 31: 764-773.

Dell, T.R.; Feduccia, D.P.; Campbell, T.E. [and others]. 1979. Yields of unthinned slash pine plantations on cutover sites in the west gulf region. Res. Pap. SO–147. New Orleans: U.S. Department of Agriculture Forest Service, Southern Forest Experiment Station. 84 p.

Dolph, K.L. 1988. Predicting height increment of young-growth mixed conifers in the Sierra Nevada. Res. Pap. PSW–191. Berkeley, CA: U.S. Department of Agriculture Forest Service, Pacific Southwest Forest and Range Experiment Station. 7 p.

Dougherty, P.M.; Hennessey, T.C.; Zarnoch, S.J. [and others]. 1995. Effects of stand development and weather on monthly leaf biomass dynamics of a loblolly pine (*Pinus taeda* L.) stand. Forest Ecology and Management. 72: 213-227.

Dougherty, P.M.; Oker-Blom, P.; Hennessey, T.C. [and others]. 1990. An approach to modeling the effects of climate and phenology on the leaf biomass dynamics of a loblolly pine stand. Silva Carelica. 15: 133-143.

Draper, N.R.; Smith, H. 1981. Applied regression analysis. 2d ed. New York: John Wiley. 709 p.

Duff, G.H.; Nolan, N.J. 1953. Growth and morphogenesis in the Canadian forest species. I. The controls of cambial and apical activity in *Pinus resinosa* Ait. Canadian Journal of Botany. 31: 471-513.

Dyer, M.E.; Burkhart, H.E. 1987. Compatible crown ratio and crown height models. Canadian Journal of Forest Research. 17: 572-574.

Feduccia, D.P.; Dell, T.R.; Mann, W.F., Jr. [and others]. 1979. Yields of unthinned loblolly pine plantations on cutover sites in the west gulf region. Res. Pap. SO–148. New Orleans: U.S. Department of Agriculture Forest Service, Southern Forest Experiment Station. 94 p.

Ford, E.D. 1985. Branching, crown structure, and the control of timber production. In: Cannell, M.G.R.; Jackson, J.E. Attributes of trees as crop plants. Abbotts Ripton, Huntingdon, United Kingdom: Institute of Terrestrial Ecology (Natural Environment Research Council), Monks Wood Experimental Station: 228-245.

Francis, J.K. 1986. The relationship of bole diameters and crown widths of seven bottomland hardwood species. Res. Note SO–328. New Orleans: U.S. Department of Agriculture Forest Service, Southern Forest Experiment Station. 3 p.

Grano, C.X. 1957. Growth of loblolly pine seed trees in relation to crown density. Journal of Forestry. 55(11): 852.

Hamilton, G.J. 1969. The dependence of volume increment of individual trees on dominance, crown dimensions, and competition. Forestry. 42: 133-144.

Hennessey, T.C.; Dougherty, P.M.; Cregg, B.M.; Wittwer, R.F. 1992. Annual variation in needle fall of a loblolly pine stand in relation to climate and stand density. Forest Ecology and Management. 51: 329-338.

Holdaway, M.R. 1986. Modeling tree crown ratio. The Forestry Chronicle. 62: 451-455.

Husch, B.; Miller, C.I.; Beers, T.W. 1982. Forest mensuration. 3d ed. New York: John Wiley. 402 p.

Hynynen, J. 1995. Predicting tree crown ratio for unthinned and thinned Scots pine stands. Canadian Journal of Forest Research. 25(1): 57-62.

Jacobi, J.C.; Tainter, F.H.; Oak, S.W. 1988. The effect of drought on growth decline of loblolly pine on littleleaf sites. Plant Disease. 72: 294-297.

Jett, J.B.; McKeand, S.E.; Liu, Y.; Huxster, W.T. 1993. Seed source variation for height and crown traits of Fraser fir Christmas trees. Southern Journal of Applied Forestry. 17: 5-9.

John, P.W.M. 1971. Statistical design and analysis of experiments. New York: Macmillan. 356 p.

Kempthorne, O. 1952. The design and analysis of experiments. New York: John Wiley. 631 p.

Kolb, T.E.; McCormick, L.H.; Simons, E.E.; Jeffrey, D.J. 1992. Impacts of pear thrips damage on root carbohydrate, sap, and crown characteristics of sugar maple in a Pennsylvania sugarbush. Forest Science. 38: 381-392.

Kramer, H. 1966. Crown development in conifer stands in Scotland as influenced by initial spacing and subsequent thinning treatment. Forestry. 39: 40-58.

Kulldorff, M. 1997. A spatial scan statistic. Communications in Statistics: Theory and Methods. 26: 1481-1496.

Kulman, H.M. 1971. Effect of insect defoliation on growth and mortality of trees. Annual Review of Entomology. 16: 289-324.

Kuuluvainen, T. 1988. Crown architecture and stemwood production in Norway spruce (*Picea abies* (L.) Karst). Tree Physiology. 4: 337-346.

Labyak, L.F.; Schumacher, F.X. 1954. The contribution of its branches to the main-stem growth of loblolly pine. Journal of Forestry. 52(5): 333-337.

Lamson, N.F.; Smith, H.C.; Perkey, A.W.; Brooks, S.M. 1990. Crown release increases growth of crop trees. Res. Pap. NE–635. Radnor, PA: U.S. Department of Agriculture Forest Service, Northeastern Forest Experiment Station. 8 p.

Larocque, G.R.; Marshall, P.L. 1993. Evaluating the impact of competition using relative growth rate in red pine (*Pinus resinosa* Ait.) stands. Forest Ecology and Management. 58: 65-81.

Larocque, G.R.; Marshall, P.L. 1994a. Crown development in red pine stands. I. Absolute and relative growth measures. Canadian Journal of Forest Research. 24: 762-774.

Larocque, G.R.; Marshall, P.L. 1994b. Crown development in red pine stands. II. Relationships with stem growth. Canadian Journal of Forest Research. 24: 775-784.

Maguire, D.A.; Hann, D.W. 1990. Constructing models for direct prediction of 5-year crown recession in southwestern Oregon Douglas-fir. Canadian Journal of Forest Research. 20: 1044-1052.

Milne, A. 1959. The centric systematic area sample treated as a random sample. Biometrics. 15: 270-297.

Morrison, D.F. 1976. Multivariate statistical methods. 2d ed. New York: McGraw-Hill Book Co. 498 p.

Nash, B.L.; Saunders, M.C.; Miller, B.J. [and others]. 1992. Forest health, an expert advisory system for assessing foliar and crown health of selected northern hardwoods. Canadian Journal of Forest Research. 22: 1770-1775.

Oak, S.W.; Tainter, F.H. 1988. Risk prediction of loblolly pine decline on littleleaf disease sites in South Carolina. Plant Disease. 72: 289-293.

Perry, D.A. 1985. Competitive processes in forest stands. In: Cannell, M.G.R.; Jackson, J.E., eds. Attributes of trees as crop plants. Cambria, Great Britain: Institute of Terrestrial Ecology, Natural Environment Research Council: 481-506.

Raison, R.J.; Khanna, P.K.; Benson, M.L. [and others]. 1992. Dynamics of *Pinus radiata* foliage in relation to water and nitrogen stress. II. Needle loss and temporal changes in total foliage mass. Forest Ecology and Management. 52: 159-178.

Riitters, K.H.; Tkacz, B. 2004. The United States forest health monitoring program. In: Wierma, G.B. Environmental monitoring. Boca Raton: CRC Press: 669-683.

SAS Institute Inc. 1988. SAS/STAT user's guide. Release 6.03. Cary, NC: SAS Institute Inc. 1,028 p.

SAS Institute Inc. 1989. SAS/STAT user's guide. Version 6. 4th ed. Cary, NC: SAS Institute Inc. 943 p.

Schreuder, H.T.; Swank, W.T. 1974. Coniferous stands characterized with the Weibull distribution. Canadian Journal of Forest Research. 4: 518-523.

Short, E.A., III; Burkhart, H.E. 1992. Predicting crown-height increment for thinned and unthinned loblolly pine plantations. Forest Science. 38: 594-610.

Shreve, F. 1924. The growth record in trees. Publ. 350. Washington, DC: Carnegie Institute: 89-116.

Siemon, G.R.; Wood, G.B.; Forest, W.B. 1976. Effect of thinning on crown structure in *radiata* pine. New Zealand Journal of Forest Science. 6: 57-66.

Smith, W.R.; Farah, R.M., Jr.; Murphy, P.A. [and others]. 1992. Crown and basal area relationships of open-grown southern pines for modeling competition and growth. Canadian Journal of Forest Research. 22: 341-347.

Sprinz, P.T.; Burkhart, H.E. 1987. Relationships between tree crown, stem, and stand characteristics in unthinned loblolly pine plantations. Canadian Journal of Forest Research. 17: 534-538.

Stolte, K.W. 2001. Forest health monitoring and forest inventory analysis programs monitor climate change effect in forest ecosystems. Human and Ecological Risk Assessment. 7(5): 1297-1316.

Stow, T.K.; Allen, H.L.; Kress, L.W. 1992. Ozone impacts on seasonal foliage dynamics of young loblolly pine. Forest Science. 38: 102-119.

Vose, J.M. 1988. Patterns of leaf area distribution within crowns of nitrogen- and phosphorus-fertilized loblolly pine trees. Forest Science. 34: 564-573.

Ward, W.W. 1964. Live crown ratio and stand density in young, even-aged red-oak stands. Forest Science. 10: 56-65.

Young, H.E.; Kramer, P.J. 1952. The effect of pruning on the height and diameter growth of loblolly pine. Journal of Forestry. 50: 474-479.

Zarnoch, S.J.; Anderson, R.L.; Sheffield, R.M. 1995. Using the beta-binomial distribution to characterize forest health. Canadian Journal of Forest Research. 25: 462-469.

Zarnoch, S.J.; Bechtold, W.A.; Stolte, K.W. 2004. Using crown condition variables as indicators of forest health. Canadian Journal of Forest Research. 34: 1057-1070.

Zarnoch, S.J.; Ruehle, R.L.; Belanger, R.P. [and others]. 1994. Growth and crown vigor of 25-year-old shortleaf pine progenies on a littleleaf disease site. Res. Pap. SE–289. Asheville, NC: U.S. Department of Agriculture Forest Service, Southeastern Forest Experiment Station. 12 p.

7 Reference Literature

Adams, C.M.; Hutchinson, T.C. 1992. Fine-root growth and chemical composition in declining Central Ontario sugar maple stands. Canadian Journal of Forest Research. 22: 1489-1503.

Alexander, S.A. 1994. Project summary: Forest Health Monitoring 1992 annual statistical summary. EPA/620/SR-94/010. Research Triangle Park, NC: U.S. Environmental Protection Agency, Environmental Monitoring and Assessment Program. 3 p.

Allen, D.C.; Bauce, E.; Barnett, C.J. 1992. Sugar maple declines - causes, effects, and recommendations. In: Manion, P.D.; Lachance, D., eds. Forest decline concepts. St. Paul, MN: APS Press: 123-136.

Apple, J.D.; Manion, P.D. 1986. Increment core analysis of declining Norway maples. Urban Ecology. 9: 309-321.

Auclair, A.N.D.; Eglinton, P.D.; Minnemeyer, S.L. 1997. Principal forest dieback episodes in northern hardwoods: development of numeric indices of areal extent and severity. Water, Air, & Soil Pollution. 93: 175-198.

Auclair, A.N.D.; Lill, J.T.; Revenga, C. 1996. The role of climate variability and global warming in the dieback of northern hardwoods. Water, Air, & Soil Pollution. 91: 163-186.

Avery, E.T. 1967. Forest measurements. New York: McGraw-Hill Book Co.: 77-82.

Baldwin, V.C., Jr.; Peterson, K.D. 1997. Predicting the crown shape of loblolly pine trees. Canadian Journal of Forest Research. 27: 102-107.

Bauce, E.; Allen, D.C. 1991. Etiology of a sugar maple decline. Canadian Journal of Forest Research. 21: 686-693.

Bechtold, W.A.; Hoffard, W.H.; Anderson, R.L. 1992. Summary report: forest health monitoring in the South, 1991. Gen. Tech. Rep. SE–81. Asheville, NC: U.S. Department of Agriculture Forest Service, Southeastern Forest Experiment Station. 40 p.

Bechtold, W.A.; Mielke, M.E.; Zarnoch, S.J. 2002. Comparison of field methods and models to estimate mean crown diameter. Northern Journal of Applied Forestry. 19(4): 177-182.

Belanger, R.P.; Zarnoch, S.J.; Anderson, R.L.; Cost, N.D. 1991. Relation between visual crown characteristics and periodic radial growth of loblolly pine trees [Abstract]. In: Southwide disease workshop. Durham, NC: 1 p. http://www.sfws.auburn.edu/enebak/swfdw/programs/1991_Jun_03-06.pdf. [Date accessed: March 2007].

Bernier, B.; Brazeau, M. 1988. Foliar nutrient status in relation to sugar maple dieback and decline in the Quebec Appalachians. Canadian Journal of Forest Research. 18: 754-761.

Bernier, B.; Brazeau, M. 1988. Magnesium deficiency symptoms associated with sugar maple dieback in a lower Laurentian site in southeastern Quebec. Canadian Journal of Forest Research. 18: 1265-1269.

Bernier, B.; Brazeau, M. 1988. Nutrient deficiency symptoms associated with sugar maple dieback and decline in the Quebec Appalachians. Canadian Journal of Forest Research. 18: 762-767.

Biging, G.S.; Wensel, L.C. 1990. Estimation of crown form for six conifer species of northern California. Canadian Journal of Forest Research. 20: 1137-1142.

Blank, L.W.; Robert, T.M.; Skeffington, R.A. 1988. New perspectives on forest decline. Nature. 336: 27-30.

Brooks, R.T.; Miller-Weeks, M.; Burkman, W. 1991. Summary report: forest health monitoring, New England Mid-Atlantic, 1990. NE–INF–94–91. Durham, NH: U.S. Department of Agriculture Forest Service, Northeastern Forest Experiment Station. 9 p.

Burkhart, H.E.; Walton, S.B. 1985. Incorporating crown ratio into taper equations for loblolly pine trees. Forest Science. 31: 478-484.

Burkman, W.G. 1990. Quality assurance aspects of the joint USA-Canada sugar maple decline project. In: Hart, D.R., coord. Proceedings of the third annual ecological quality assurance workshop. Burlington, ON: Canada Center for Inland Waters: 83-97.

Cadahia, D.; Cobos, J.M.; Soria, S. [and others]. 1991. Observation of damages to Mediterranean forest species. Commission of the European Communities, Ministry of Agriculture, Fisheries, and Food. 96 p.

Chan, S.S.; McCreight, R.W.; Walstad, J.D.; Spies, T.A. 1986. Evaluating forest vegetative cover with computerized analysis of fisheye photographs. Forest Science. 32: 1085-1091.

Chevonne, B.I.; Linzon, S.N. 1988. Tree decline in North America. Environmental Pollution. 50: 87-89.

Chojnacky, D.C., comp. 1991. Eastern forest health monitoring field measurements guide. 5th ed. Ogden, UT: U.S. Department of Agriculture Forest Service, Intermountain Research Station; Asheville, NC: U.S. Department of Agriculture Forest Service, Southeastern Forest Experiment Station. 84 p.

Ciesla, W.M.; Hildebrandt, G. 1986. Forest decline inventory methods in West Germany: opportunities for application in North American forests. Methods Appl. Rep. 86–3. Ft. Collins, CO: U.S. Department of Agriculture Forest Service, Rocky Mountain Forest and Range Experiment Station. 31 p.

Cline, S.P.; Burkman, W.G.; Geron, C.D. 1989. Use of quality control procedures to assess errors in measuring forest canopy conditions. In: Olson, R.K.; Lefohn, A.S., eds. Transactions: Effects of air pollution on western forests. Pittsburgh: Air and Waste Management Association: 379-394.

Cole, W.G.; Lorimer, C.G. 1994. Predicting tree growth from crown variables in managed northern hardwood stands. Forest Ecology and Management. 67: 159-175.

Collins, S. 1961. Benefits to the understory from canopy defoliation by gypsy moth larvae. Ecology. 42: 836-838.

Cox, R.M.; Malcolm, J.W. 1997. Effects of duration of a simulated winter thaw on dieback and xylem conductivity of *Betula papyrifera*. Tree Physiology. 17: 389-396.

Daniels, R.F. 1976. Simple competition indices and their correlation with annual loblolly pine tree growth. Forest Science. 22: 454-456.

Dean, T.J.; Long, J.N. 1996. Growth in loblolly pine plantations as a function of stand density and canopy properties. Forest Ecology and Management. 82: 49-58.

D'Eon, S.P.; Magasi, L.P.; Lachance, D.; DesRochers, P. 1992. ARNEWS Canada's national forest health monitoring plot network, manual on plot establishment and monitoring. Revised. Info. Rep. PI–X–117. Fredericton, NB: Canadian Forest Service, Petawawa National Forestry Institute. 31 p.

Dubrasich, M.E.; Hann, D.W.; Tappeiner, J.C., II. 1997. Methods for evaluating crown area profiles of forest stands. Canadian Journal of Forest Research. 27: 385-392.

Eagar, C.; Miller-Weeks, M.; Gillespie, A.J.R.; Burkman, W. 1992. Summary report: forest health monitoring in the Northeast, 1991. NE/NA–INF–115–92. Durham, NH: U.S. Department of Agriculture Forest Service, Northeastern Forest Experiment Station; Northeastern Area State & Private Forestry. 13 p.

Farrar, R.M. 1985. Crown ratio used as a surrogate for form in a volume equation for natural longleaf pine stems. In: Shoulders, E., ed. Proceedings of the third biennial southern silvicultural research conference. Gen. Tech. Rep. S0–54. New Orleans: U.S. Department of Agriculture Forest Service, Southern Forest Experiment Station: 429-435.

Freer-Smith, P.H.; Read, D.B. 1995. The relationship between crown condition and soil solution chemistry in oak and Sitka spruce in England and Wales. Forest Ecology and Management. 79: 185-196.

Gagnon, P.A.; Agnard, J.P.; Nolette, C. 1993. Evaluation of a soft-copy photogrammetry system for tree-plot measurements. Canadian Journal of Forest Research. 23: 1781-1785.

Geier-Hayes, K.; Hayes, M.A.; Basford, D.D. 1995. Determining individual tree shade length: a guide for silviculturists. Gen. Tech. Rep. INT–GTR–324. Ogden, UT: U.S. Department of Agriculture Forest Service, Intermountain Research Station. 59 p.

Gering, L.R.; May, D.M. 1991. The relationship of diameter at breast height and crown diameter for four species groups in Hardin County, Tennessee. Southern Journal of Applied Forestry. 19(4): 177-181.

Gering, L.R.; May, D.M. 1997. Point-sampling of tree crowns using aerial photographs for forest inventory. Southern Journal of Applied Forestry. 21(1): 28-36.

Ghosh, S.; Innes, J.L.; Hoffmann, C. 1995. Observer variation as a source of error in assessments of crown condition through time. Forest Science. 41(2): 235-254.

Gillespie, A.J.R.; Allen, H.L.; Vose, J.M. 1994. Amount and vertical distribution of foliage of young loblolly pine trees as affected by canopy position and silvicultural treatment. Canadian Journal of Forest Research. 24: 1337-1344.

Gillespie, A.J.R.; Miller-Weeks, M.; Barnett, C.; Burkman, W. 1993. Summary report: forest health monitoring, New England/Mid-Atlantic, 1992. NE/NA–INF–115–R93. Durham, NH: U.S. Department of Agriculture Forest Service, Northeastern Forest Experiment Station; Northeastern Area State & Private Forestry. 15 p.

Gilmore, D.W.; Seymour, R.S. 1997. Crown architecture of *Abies balsamea* from four canopy positions. Tree Physiology. 17: 71-80.

Gilmore, D.W.; Seymour, R.S.; Maguire, D.A. 1996. Foliage-sapwood area relationships for *Abies balsamea* in central Maine, U.S.A. Canadian Journal of Forest Research. 26: 2071-2079.

Goelz, J.C.G. 1996. Open-grown crown radius of eleven bottomland hardwood species: prediction and use in assessing stocking. Southern Journal of Applied Forestry. 20(3): 156-161.

Gottschalk, K.W.; MacFarlane, W.R. 1992. Photographic guide to crown condition of oaks: use for gypsy moth silvicultural treatments. Gen. Tech. Rep. NE–168. Radnor, PA: U.S. Department of Agriculture Forest Service, Northeastern Forest Experiment Station. 8 p.

Gregoire, T.G.; Valentine, H.T.; Furnival, G.M. 1995. Sampling methods to estimate foliage and other characteristics of individual trees. Ecology. 76(4): 1181-1194.

Gross, H.L. 1972. Crown deterioration and reduced growth associated with excessive seed production by birch. Canadian Journal of Botany. 50: 2431-2438.

Gumpertz, M.L.; Brownie, C. 1993. Repeated measures in randomized block and split-plot experiments. Canadian Journal of Forest Research. 23: 625-639.

Hall, J.P. 1991. ARNEWS annual report 1990. Info. Rep. ST–X–1. Ottawa: Canadian Forest Service. 17 p.

Hann, D.W.; Walters, D.K.; Scrivani, J.A. 1987. Incorporating crown ratio into prediction equations for Douglas-fir stem volume. Canadian Journal of Forest Research. 17: 17-22.

Hasenauer, H.; Monsreud, R.A. 1996. A crown ratio model for Austrian forests. Forest Ecology and Management. 84: 49-60.

Hellgren, M.B.; Stenlid, J. 1995. Long-term reduction in the diameter growth of butt rot affected Norway spruce, *Picea abies*. Forest Ecology and Management. 74: 239-243.

Herrick, O.W.; Gansner, D.A. 1986. Rating forest stands for gypsy moth defoliation. Res. Pap. NE–583. Broomall, PA: U.S. Department of Agriculture Forest Service, Northeastern Forest Experiment Station. 4 p.

Honer, T.G. 1971. Crown shape in open- and forest-grown balsam fir and black spruce. Canadian Journal of Forest Research. 1: 203-207.

Horntvedt, R. 1993. Crown density of spruce trees related to needle biomass. Forest Ecology and Management. 59: 225-235.

Houston, D.R. 1973. Diebacks and declines: diseases initiated by stress, including defoliation. Proceedings of the International Shade Tree Conference. 49: 73-76.

Houston, D.R. 1981. Stress-triggered diseases: the diebacks and declines. Misc. Publ. NE–IN–T–41–81. Broomall, PA: U.S. Department of Agriculture Forest Service, Northeastern Forest Experiment Station. 36 p.

Houston, D.R. 1992. A host-stress-saprogen model for forest dieback-decline diseases. In: Manion, P.D.; Lachance, D., eds. Forest decline concepts. St. Paul, MN: APS Press: 3-25.

Husch, B.; Miller, C.I.; Beers, T.W. 1972. Forest mensuration. 2d ed. New York: The Ronald Press Co. 410 p.

Innes, J.L. 1988. Forest health surveys - a critique. Environmental Pollution. 54: 1-15.

Innes, J.L. 1988. Forest health surveys: problems in assessing observer objectivity. Canadian Journal of Forest Research. 18: 560-565.

Innes, J.L. 1990. Assessment of tree condition. Field Book 12. London, United Kingdom: United Kingdom Forestry Commission. 96 p.

Innes, J.L. 1990. The role of quality assurance in the assessment of forest condition in Europe. In: Hart, D.R., coord. Proceedings of the third annual ecological quality assurance workshop. Burlington, ON: Canada Center for Inland Waters: 99-112.

Innes, J.L. 1992. Observations on the condition of beech (*Fagus sylvatica* L.) In Britain in 1990. Forestry. 65: 35-60.

Innes, J.L. 1993. Methods to estimate forest health. Silva Fennica. 27(2): 145-157.

Innes, J.L. 1993. Some factors affecting crown density of trees in Great Britain based on recent annual surveys of forest condition. In: Huettl, R.F.; Mueller-Dombois, D., eds. Forest decline in the Atlantic and Pacific regions. Berlin, Germany: Springer-Verlag: 40-53.

Innes, J.L. 1994. The occurrence of flowering and fruiting on individual trees over 3 years and their effects on subsequent crown condition. Trees. 8: 139-150.

Innes, J.L.; Boswell, R.C. 1988. Monitoring of forest condition in the United Kingdom. U.K. For. Comm. Bull. 88. 72 p.

Innes, J.L.; Boswell, R.C. 1990. Reliability, presentation, and relationships among data from inventories of forest condition. Canadian Journal of Forest Research. 20: 790-799.

Innes, J.L.; Boswell, R.C. 1991. Monitoring of forest condition in Great Britain - 1990. U.K. For. Comm. Bull. 98. 54 p.

Innes, J.L.; Ghosh, S.; Schwyzer, A. 1996. A method for the identification of trees with unusually colored foliage. Canadian Journal of Forest Research. 26: 1548-1555.

Innes, J.L.; Landmann, G.; Mettendorf, B. 1993. Consistency of observations on forest tree defoliation in three European countries. Environmental Monitoring & Assessment. 25: 29-40.

Innes, J.L.; Schwyzer, A. 1994. Stem damage in Swiss forests: incidence, causes and relations to crown transparency. European Journal of Forest Pathology. 24: 20-31.

Innes, J.L.; Whittaker, R.J. 1993. Relationships between the crown condition of Sitka and Norway spruce and the environment in Great Britain: an exploratory analysis. Journal of Applied Ecology. 30: 341-360.

Jack, S.B.; Long, J.N. 1992. Forest production and the organization of foliage within crowns and canopies. Forest Ecology and Management. 49: 233-245.

Johansson, T. 1985. Estimating canopy density by the vertical tube method. Forest Ecology and Management. 11: 139-144.

Kelley, R.S.; Eav, B.B. 1987. Vermont hardwood tree health survey 1986. Waterbury, VT: Vermont Agency of Natural Resources, Department of Forestry, Parks, and Recreation, Division of Forestry. 27 p.

Kelley, R.S.; Smith, E.L.; Cox, S.M. 1992. Vermont hardwood tree health in 1991 compared to 1986. Waterbury, VT: Vermont Agency of Natural Resources, Department of Forestry, Parks, and Recreation. 4 p.

Kessler, K.J. 1969. Top-dying of yellow birch associated with seed production. Plant Disease Reporter. 53: 694-697.

Kinerson, R.S.; Higginbotham, K.O.; Chapman, R.C. 1974. The dynamics of foliage distribution within a forest canopy. Journal of Applied Ecology. 11: 347-353.

Kleinschmidt, S.; Baskerville, G.L.; Soloman, D.S. 1980. Foliage weight distribution in the upper crown of balsam fir. Res. Pap. NE–455. Upper Darby, PA: U.S. Department of Agriculture Forest Service, Northeastern Forest Experiment Station. 9 p.

Knapp, C.M.; Marmorek, D.R.; Baker, J.P. [and others]. 1990. The indicator development strategy for the environmental monitoring and assessment program. Draft report. Corvallis, OR: U.S. Environmental Protection Agency, Environmental Research Laboratory. 78 p.

Krajicek, J.E.; Brinkman, K.A.; Gingrich, S.F. 1961. Crown competition: a measure of density. Forest Science. 7: 35-42.

Kramer, H. 1996. Crown development in conifer stands in Scotland as influenced by initial spacing and subsequent thinning treatment. Forestry. 39: 40-58

Krause, C.; Morin, H. 1995. Changes in radial increment in stems and roots of balsam fir (*Abies balsamea* (L.) Mill) after defoliation by spruce budworm. The Forestry Chronicle. 71: 747-754.

Landmann, G. 1993. Role of climate, stand dynamics and past management in forest declines: a review of ten years of field ecology in France. In: Huettl, R.F.; Mueller-Dombois, eds. Forest decline in the Atlantic and Pacific regions. Berlin, Germany: Springer-Verlag: 18-39.

Landmann, G., ed. 1991. French research into forest decline. DEFORPA Program: forest decline and air pollution. 2d report. Ecole nationale du Genie rural, des Eaux et des Forets. 120 p.

Lewis, T.E.; Conkling, B.L., eds. 1994. Forest health monitoring Southeast loblolly/short-leaf pine demonstration interim report. EPA/620/R–94/006. Washington, DC: U.S. Environmental Protection Agency. 342 p.

Liu, X.; Ellsworth, D.S.; Tyree, M.T. 1997. Leaf nutrition and photosynthetic performance of sugar maple (*Acer sacchurum*) in stands with contrasting health conditions. Tree Physiology. 17: 169-178.

Liu, X.; Tyree, M.T. 1997. Root carbohydrate reserves, mineral nutrient concentrations and biomass in a healthy and a declining sugar maple (*Acer saccharum*) stand. Tree Physiology. 17: 179-185.

Magnussen, S.; Smith, V.G.; Yeatman, C.W. 1986. Foliage and canopy characteristics in relation to above ground dry matter increment of seven jack pine provenances. Canadian Journal of Forest Research. 16: 464-470.

Maguire, D.A.; Hann, D.W. 1989. The relationship between gross crown dimensions and sapwood area at crown base in Douglas-fir. Canadian Journal of Forest Research. 19: 557-565.

Manion, P.D.; Lachance, D. 1992. Forest decline concepts: an overview. In: Manion, P.D.; Lachance, D., eds. Forest decline concepts. St. Paul, MN: APS Press: 181-190.

Marrakkola, A.M. 1996. Effect of artificial defoliation on biomass allocation in ectomycor-rhizal *Pinus sylvestris* seedlings. Canadian Journal of Forest Research. 26: 899-904.

McCrady, R.L.; Jokela, E.J. 1996. Growth phenology and crown structure of selected loblolly pine families planted at two spacings. Forest Science. 42: 46-57.

McIntyre, B.M.; Scholl, M.A.; Sigmon, J.T. 1990. A quantitative description of a deciduous forest canopy using a photographic technique. Forest Science. 36(2): 381-393.

McLaughlin, D.; Gizyn, W.; McIlveen, W.; Kinch, C. 1992. A quantitative tree crown rating system for deciduous forest health surveys: some results from Ontario. In: Manion, P.D.; Lachance, D., eds. Forest decline concepts. St. Paul, MN: APS Press: 137-154.

McPherson, E.G.; Rowntree, R.A. 1988. Geometric solids for simulation of tree crowns. Landscape and Urban Planning. 15: 79-83.

Meredith, M.P.; Stehman, S.V. 1991. Repeated measures experiments in forestry: focus on analysis of response curves. Canadian Journal Forest Research. 21: 957-965.

Mielke, M.E.; Rezabek, C.L.; Cummings-Carlson, J.; Gillespie, A.J.R. 1990. Survey to assess the health of sugar maple and other northern hardwoods across a pH gradient in Wisconsin, 1987 - 1988. Madison, WI: Wisconsin Department of Natural Resources, Bureau of Air Management and Bureau of Forestry. 39 p.

Miller, J.B. 1967. A formula for average foliage density. Australian Journal of Botany. 15: 141-144.

Millers, I.; Allen, D.C.; Lachance, D.; Cymbala, R. 1993. Sugar maple crowns conditions improve between 1988 and 1992. NA–TP–03–93. Radnor, PA: U.S. Department of Agriculture Forest Service, Northeastern Area State & Private Forestry. 57 p.

Millers, I.; Allen, D.C.; Lachance, D.; Cymbala, R. 1994. Sugar maple crowns in good condition in 1993. NA–TP–03–94. Radnor, PA: U.S. Department of Agriculture Forest Service, Northeastern Area State & Private Forestry. 8 p.

Millers, I.; Lachance, D.; Burkman, W.G.; Allen, D.C. 1991. North American sugar maple decline project: organization and field methods. Gen .Tech. Rep. NE–154. Radnor, PA: U.S. Department of Agriculture Forest Service, Northeastern Forest Experiment Station. 26 p.

Millers, I.; Miller-Weeks, M.; Cooke, R.; Cox, S. 1990. New England forest health monitoring: crown rating guides. In: New England forest health monitoring-methods manual for field measurement. Durham, NH: U.S. Department of Agriculture Forest Service, Northeastern Forest Experiment Station. 11 p. Appendix VI. [Compiled for USDA Forest Service and U.S. EPA Environmental Monitoring and Assessment Program by Dwire, K.; Huntley, B.; Miller-Weeks, M.; Brooks, R.].

Millers, I.; Miller-Weeks, M.; Mielke, M. 1986. Cooperative survey of red spruce and balsam fir decline and mortality in the Northeast: symptoms and trends. Durham Field Office Work Plan. Revised. Durham, NH: U.S. Department of Agriculture Forest Service, Northeastern Area State & Private Forestry. 24 p.

Millers, I.; Shriner, D.S.; Rizzo, D. 1989. History of hardwood decline in the Eastern United States. Gen. Tech. Rep. NE–126. Radnor, PA: U.S. Department of Agriculture Forest Service, Northeastern Forest Experiment Station. 75 p.

Minckler, L.S.; Gingrich, S.F. 1970. Relation of crown width to tree diameter in some upland hardwood stands of southern Illinois. Res. Note NC–99. St. Paul, MN: U.S. Department of Agriculture Forest Service, North Central Forest Experiment Station. 4 p.

Minor, C.O. 1951. Stem-crown diameter relations in southern pine. Journal of Forestry. 49: 490-493.

Mitchell, J.E.; Popovich, S.J. 1997. Effectiveness of basal area for estimating canopy cover of ponderosa pine. Forest Ecology and Management. 95: 45-51.

Moeur, M. 1993. Characterizing spatial patterns of trees using stem-mapped data. Forest Science. 39(4): 756-775.

Moser, E.B.; Saxton, A.M.; Pezeshki, S.R. 1990. Repeated measures analysis of variance: applications to tree research. Canadian Journal of Forest Research. 20: 524-535.

Mott, D.G.; Nairn, L.D.; Cook, J.A. 1957. Radial growth in forest trees and effects of insect defoliation. Forest Science. 3: 286-304.

Nance, W.L.; Grissom, J.E.; Smith, W.R. 1988. A new competition index based on weighted and constrained area potentially available. In: Ek, A.R.; Shifley, S.R.; Burk, T.E., eds. Forest growth modeling and prediction. Gen. Tech. Rep. NC–120. St. Paul, MN: U.S. Department of Agriculture Forest Service, North Central Forest Experiment Station: 134-142.

Nicholas, N.S.; Gregoire, T.G.; Zedaker, S.M. 1991. The reliability of tree crown position classification. Canadian Journal of Forest Research. 21: 698-701.

Nowak, D.J. 1996. Estimating leaf area and leaf biomass of open-grown deciduous urban trees. Forest Science. 42(4): 504-507.

O'Brien, S.T.; Hubbell, S.P.; Sprio, P. [and others]. 1995. Diameter, height, crown, and age relationships in eight neotropical tree species. Ecology. 76: 1926-1939.

Ontario Ministry of Environment and Energy. 1993. Ontario hardwood decline survey 1989 and 1990. Energy PIBS 2283. Toronto, Ontario, Canada: Ontario Ministry of the Environment. 102 p.

Oren, R.; Thies, W.G.; Waring, R.H. 1985. Tree vigor and stand growth of Douglas-fir as influenced by laminated root rot. Canadian Journal of Forest Research. 15: 985-988.

Ottorini, J.M.; LeGoff, N.; Cuzeau, C. 1996. Relationship between crown dimensions and stem development in *Fraxinus excelsior*. Canadian Journal of Forest Research. 26: 394-401.

Power, S.A. 1994. Temporal trends in twig growth of *Fagus sylvatica* L. and their relationships with environmental factors. Forestry. 67(1): 13-30.

Raulier, F.; Ung, C.; Ouellet, D. 1996. Influence of social status on crown geometry and volume increment in regular and irregular black spruce stands. Canadian Journal of Forest Research. 26: 1742-1753.

Renaud, J.P.; Mauffette, Y. 1991. The relationship of crown dieback with carbohydrate content and growth of sugar maple (*Acer saccharum*). Canadian Journal of Forest Research. 21: 1111-1118.

Schutt, P.; Cowling, E.B. 1985. Waldsterben, a general decline of forests in Central Europe: symptoms, development, and possible causes. Plant Disease. 69: 548-558.

Shi, K.; Cao, Q.V. 1997. Predicted leaf area growth and foliage efficiency of loblolly pine plantations. Forest Ecology and Management. 95: 109-115.

Skelly, J.M.; Innes, J.L. 1994. Waldsterben in the forests of Central Europe and Eastern North America: fantasy or reality? Plant Disease. 78(11): 1021-1032.

Smith, D.M. 1986. The practice of silviculture. 8th ed. New York: John Wiley. 527 p.

Smith, W.H.; Stanley, R.G. 1969. Cone distribution in crowns of slash pine (*Pinus elliottii* Englem.) in relation to stem, crown, and wood increment. Silvae Genetica. 18: 86-91.

Smith, W.R. 1987. Area potentially available to a tree: a research tool. In: McKinley, C.R.; Lowe, W.J.; VanBuijtenen, J.P. Proceedings of the 19th southern tree improvement conference. Publ. 41. College Station, TX: Texas A&M University Press: 22-29.

Smith, W.R. 1994. An empirical evaluation of a three-dimensional crown model for predicting volume growth. Forest Ecology and Management. 69: 199-209.

Sommer, R.; Guenther, H.; Barker, P.A.; Swenson, J.P. 1993. Comparison of four methods of street tree assessment. Journal of Arboriculture. 19(1): 27-34.

Strand, G.H. 1996. Detection of observer bias in ongoing forest health monitoring programmes. Canadian Journal of Forest Research. 26: 1692-1696.

Tailleux, I.; Cloutier, C. 1993. Defoliation of tamarack by outbreak populations of larch sawfly in subarctic Quebec: measuring the impact on tree growth. Canadian Journal of Forest Research. 23: 1444-1452.

Tallent-Halsell, N.G., ed. 1994. Forest health monitoring 1994 field methods guide. Washington, DC: U.S. Environmental Protection Agency. 205 p.

Tobiessen, P.L.; Buchsbaum, S. 1976. Ash dieback and drought. Canadian Journal of Botany. 54: 543-545.

Toumey, J.W. Korstian. 1947. Foundations of silviculture upon an ecological basis. 2d ed. New York: John Wiley. 468 p.

Tremmel, D.C.; Bazzaz, F.A. 1993. How neighbor canopy architecture affects target plant performance. Ecology. 74(7): 2114-2124.

Trial, H., Jr.; Devine, M.E. 1994. Forest health monitoring evaluation: brown ash (*Fraxinus nigra*) in Maine. A survey of occurrence and health. Tech. Rep. 33. Augusta, ME: Maine Forest Service Insect and Disease Management Division. 37 p.

UN–ECE. 1989. Manual on methodologies and criteria for harmonized sampling, assessment, monitoring and analysis of the effects of air pollution on forests. ICP Forests, Hamburg, Germany. United Nations Environment Program and United Nations Economic Commission for Europe, Geneva, Switzerland. [Eleven chapters updated annually.]

UN–ECE. 1991. Forest health report 1991, technical report on the 1990 survey. Brussels, Luxembourg: United Nations Economic Commission for Europe. 146 p.

UN–ECE. 1993. Forest condition in Europe, results of the 1992 survey. Brussels, Luxembourg: United Nations Economic Commission for Europe. 90 p.

U.S. Department of Agriculture, Forest Service, 1999. Section 2. Crown condition classification. In: Forest Health Monitoring: field methods guide (National 1999). Research Triangle Park, NC: U.S. Department of Agriculture, Forest Service, National Forest Health Monitoring Program: 2.1–2.7.

U.S. Environmental Protection Agency. 1995. Project summary: Forest Health Monitoring 1991 statistical summary. EPA/620/SR-94/028. Research Triangle Park, NC: U.S. Environmental Protection Agency, Atmospheric Research and Exposure Assessment Laboratory. 3 p.

Urquhart, N.S.; Overton, W.S.; Birkes, D.S. 1992. Comparing sampling designs for monitoring ecological status and trends: impact of temporal patterns. In: Barnett, V., ed. Statistics in the environment. Sussex, England: John Wiley: 71-85.

Valinger, E. 1993. Crown development of Scots pine trees following thinning and nitrogen fertilization. Studia Forestalia Suecica. 188: 1-12.

Van Laar, A. 1969. Influence of tree parameters and stand density on diameter growth of *Pinus radiata*. South African Forestry Journal. 70: 5-14.

Vissage, J.S.; Hoffard, W.H. 1997. Summary report: forest health monitoring in the South, 1992. Resour. Bull. SO–195. New Orleans: U.S. Department of Agriculture Forest Service, Southern Forest Experiment Station. 27 p.

Wang, Y.S.; Miller, D.R.; Welles, J.M.; Heisler, G.M. 1992. Spatial variability of canopy foliage in an oak forest estimated with fisheye sensors. Forest Science. 38(4): 854-865.

Ward, J.S.; Stephens, G.R. 1993. Influence of crown class and shade tolerance on individual tree development during deciduous forest succession in Connecticut, USA. Forest Ecology and Management. 60: 207-236.

Waring, R.H. 1987. Characteristics of trees disposed to die. BioScience. 37: 569-574.

Webster, R.; Rigling, A.; Walthert, L. 1996. An analysis of crown condition of *Picea*, *Fagus*, and *Abies* in relation to environment in Switzerland. Forestry. 69: 347-356.

Weiss, M.J.; McCreery, L.R.; Millers, I. [and others]. 1985. Cooperative survey of red spruce and balsam fir decline and mortality in New York, Vermont, and New Hampshire, 1984. NA–TP–11. Broomall, PA: U.S. Department of Agriculture Forest Service, Northeastern Area. 53 p.

Wilmot, T.R.; Ellsworth, D.S.; Tyree, M.T. 1995. Relationships among crown conditions, growth and plant and soil nutrition in seven northern Vermont sugarbushes. Canadian Journal of Forest Research. 25: 386-397.

Zedacker, S.; Nicholas, N. 1990. Quality assurance methods manual for forest site classification and field measurements. EPA/600/3–90/082. Corvallis, OR: U.S. Environmental Protection Agency: Environmental Research Laboratory. 46 p.

Zeide, B.; Pfeifer, P. 1991. A method for the estimation of fractal dimension of tree crowns. Forest Science. 37: 1253-1265.

8 Appendices

8.1 Appendix A: Field Data Codes

Portable data recorder (PDR) prompt codes for crown indicator variables

Crown vigor[1]	CVIG
Crown light exposure	CEXP
Crown position	CPOS
Crown diameter	CDIA
Uncompacted live crown ratio	ULCR
Crown density	CDEN
Crown dieback	CDBK
Foliage transparency	FTRAN

[1] Crown vigor is recorded for trees < 5.0 inches d.b.h. (or d.r.c. [diameter at root collar]). All other variables are recorded for trees 5.0 inches d.b.h. (or d.r.c.) and larger.

Crown vigor codes

1	Live crown ratio at least 35 percent, at least 80 percent normal foliage (50 percent of each leaf undamaged), and < 6 percent dieback
2	Does not meet class 1 or 3 and has at least 21 percent normal foliage
3	Any live crown ratio, 1 to 20 percent normal foliage, and any amount of dieback

Crown light exposure codes

0	The tree receives no direct light because it is heavily shaded by trees, vines, or other vegetation
1	The tree receives direct light from the top or one side
2	The tree receives direct light from the top and one side (or two sides without the top)
3	The tree receives direct light from the top and two sides
4	The tree receives direct light from the top and three sides
5	The tree receives direct light from the top and four sides

Crown position codes

1	Superstory[1]—the live crown top is at least twice the height of the top of the overstory canopy zone
2	Overstory—the live crown top is above the middle of the overstory canopy zone
3	Understory—the live crown top is at or below the middle of the overstory canopy zone
4	Open canopy—an overstory canopy zone is not evident because the tree crowns in this condition are not fully closed (< 50 percent crown cover)

[1] Code 1 is valid only for trees at least 5.0 inches d.b.h. (or d.r.c. [diameter at root collar]).

Crown diameter codes

00	Epicormic branches only	000	Epicormic branches only
01	< 1.5 feet	001	< 0.15 m
02	1.6 to 2.5 feet	002	0.16 to 0.25 m
03	2.6 to 3.5 feet	003	0.26 to 0.35 m
⋮		⋮	
99	98.6 to 100 feet	995	98.6 to 100 m

Uncompacted live crown ratio, crown density, crown dieback, and foliage transparency codes[1]

	percent		*percent*		*percent*
00	0	35	31 – 35	70	66 – 70
05	1 – 5	40	36 – 40	75	71 – 75
10	6 – 10	45	41 – 45	80	76 – 80
15	11 – 15	50	46 – 50	85	81 – 85
20	16 – 20	55	51 – 55	90	86 – 90
25	21 – 25	60	56 – 60	95	91 – 95
30	26 – 30	65	61 – 65	99	96 – 100

[1] For uncompacted live crown ratio and crown density, the code 00 is used for trees with epicormic branches only.

8.2 Appendix B: Glossary of Terms

crown: the crown stem, branches, twigs, buds, foliage, and seeds or cones of a tree located above the obvious live crown base. Dead lower branches and straggler live branches below the obvious live crown base are normally excluded.

crown cover: the percentage of the ground surface covered by a vertical projection of crowns from above.

crown outline: the two-dimensional side view of a tree crown. Crown outlines applied to sample trees are based on the expected values for a vigorous tree of the same species and stem size.

crown stem: the main axis of a tree stem between the live crown base and the crown top.

crown top: the top of a tree. For uncompacted live crown ratio, the highest live foliage is considered the crown top. The crown outline used for crown density estimates includes dead tops.

diameter at breast height (d.b.h.): the diameter of a tree stem, located at 4.5 feet above the ground (breast height) on the uphill side of a tree. The point of diameter measurement may vary on abnormally formed trees.

diameter at root collar (d.r.c.): the diameter of a woodland tree species, measured outside bark at the groundline or stem root collar.

dripline: the vertical projection of the perimeter of a tree crown.

epicormic branches: recent branches or shoots arising from dormant buds on the main stem of a tree. Epicormic branching often follows stress or damage to the tree. Epicormic branches remain classified as such until they reach the size of regular branches. For trees that had 1.0 inch or larger branches when the epicormic branches formed, epicormic branches are considered regular branches once they reach 1.0 inch in diameter.

five-foot rule: the rule that establishes the position of a live crown base when scattered branches are present in the lower portion of a tree crown. If the point of attachment (to the bole) of any live branch is < 5 feet below the obvious live crown baseline, a new base is established at the lowest foliage of this branch. This process is repeated until no qualifying branches occur within 5 feet of the live crown base.

forest: land that is or was formerly at least 10-percent stocked with forest trees of any size and is not currently developed for a nonforest use. The minimum area for classification as forest land is 1 acre. Roadside, streamside, and shelterbelt strips of timber must have a crown cover width of at least 120 feet to qualify as forest land. Unimproved roads and trails, streams and other bodies of water, or natural clearings in forested areas shall be classified as forest if < 120 feet in width or 1 acre in area. Grazed woodlands, reverting fields, and pastures that are not actively maintained are included if the above qualifications are satisfied.

forest type: a classification of forest land based upon and named for the tree species that forms the majority of live-tree stocking. A forest type classification for a field location indicates the predominant live-tree species cover for the field location; hardwoods and softwoods are first grouped to determine predominant group, and forest type is selected from the predominant group.

indicator: a characteristic of the environment that can be correlated with exposure to an environmental stressor. Indicators may be biotic or abiotic.

live crown base: the point where an imaginary line perpendicular to the main stem intersects the lowest live foliage of the obvious live crown. For trees mature enough to have a live branch at least 1.0 inch in diameter, the obvious live crown base is defined by branches above the 1.0-inch minimum. For trees and saplings that have no branches larger than the 1.0-inch minimum, smaller branches and twigs are included. In cases where no obvious live crown is apparent, the 5-foot rule is used to establish the base.

Epicormic branches are not considered as part of the live crown base until they reach the size of regular branches. For trees that had 1.0-inch branches when the epicormic branches formed, epicormic branches are considered to be regular branches once they reach 1.0 inch in diameter.

live crown length: the distance from the live crown base to the live crown top.

live crown top: the point where an imaginary line perpendicular to the main stem intersects the highest live foliage of a tree.

macroholes: large spaces between branches. These are usually the result of branch mortality but may also be due to species characteristics. Macroholes are included in the crown outline and reduce crown density estimates. Macroholes are usually ignored when estimating dieback and transparency, but are included in dieback and transparency estimations if they are recent.

microholes: small spaces within the crown of a tree where light passes between layers of leaves or closely spaced branches. These areas are considered for all crown measurements.

obvious live crown: the portion of the tree crown where most live branches or twigs are typically concentrated for a given tree species and tree size at a particular site. Epicormic twigs and straggler branches are excluded.

overstory canopy zone: the height zone bounded by the average height to the live crown bases and the average height to the live crown tops of overstory trees in a forest stand.

sapling: a live tree 1.0 to 4.9 inches in diameter at d.b.h. (or d.r.c.).

snag branch: a dead branch above the live crown base without twigs or sprigs.

sprig: a woody or nonwoody lateral shoot, without secondary branching, < 1.0 inch in diameter at the base above the swelling at the point of attachment to a branch or crown stem.

stocking: the degree of occupancy of land by trees, measured by basal area and/or the number of trees in a stand by size or age and spacing, compared to the basal area and/or number of trees required to fully utilize the growth potential of the land; that is, the stocking standard.

straggler branch: a live branch that occurs more than 5 feet below the base of the obvious live crown.

tree: a woody perennial plant, typically large, with a single well-defined stem carrying a more or less definite crown, defined as attaining a minimum diameter of 5.0 inches and a minimum height of 15 feet at maturity.

twig: any woody lateral growth, with secondary branching, < 1.0 inch in diameter at the base above the swelling at the point of attachment to a branch or crown stem.

woodland: forest land with 10 percent or more crown cover in woodland species, or timber and woodland species combined, but < 5-percent crown cover in timber species; or forest land with a minimum of 40 seedlings, or saplings, or both per acre of woodland species.

woodland species: a shrublike tree species. The Forest Inventory and Analysis Program measures the stem diameters of woodland species at the root collar.

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

The Forest Inventory and Analysis (FIA) Program of the Forest Service, U.S. Department of Agriculture, conducts a national inventory of forests across the United States. A systematic subset of permanent inventory plots in 38 States is currently sampled every year for numerous forest health indicators. One of these indicators, crown-condition classification, is designed to estimate tree crown dimensions and assess the impact of crown stressors. The indicator features eight tree-level field measurements in addition to variables traditionally measured in conjunction with FIA inventories: vigor class, uncompacted live crown ratio, crown light exposure, crown position, crown density, crown dieback, foliage transparency, and crown diameter. Indicators of crown health derived from the crown data are intended for analyses at the State, regional, and national levels, and contribute to the core tabular output in standard FIA reports. Crown-condition measurements were originally implemented as part of the Forest Health Monitoring (FHM) Program in 1990. Except for crown diameter, these measurements were continued when the FIA Program assumed responsibility for FHM plot-based detection monitoring in 2000. This report describes in detail the data collection and analytical techniques recommended for crown-condition classification.

Keywords: Forest health indicators, tree crown condition, tree crown health, tree health indicators, tree crown measurement.