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Inter- and Intra-species Variation in Three Crown Condition Indicators for Seven Tree Species in the Southeastern United States

KaDonna Cheryl Randolph
University of Tennessee - Knoxville

To the Graduate Council:

I am submitting herewith a dissertation written by KaDonna Cheryl Randolph entitled "Inter- and Intra-species Variation in Three Crown Condition Indicators for Seven Tree Species in the Southeastern United States." I have examined the final electronic copy of this dissertation for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Doctor of Philosophy, with a major in Natural Resources.

Wayne K. Clatterbuck, Major Professor

We have read this dissertation and recommend its acceptance:

Gregory A. Reams, William L. Seaver, Donald G. Hodges

Accepted for the Council:
Dixie L. Thompson

Vice Provost and Dean of the Graduate School

(Original signatures are on file with official student records.)

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Anne Mayhew___________
Vice Chancellor and Dean of
Graduate Studies

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INTER- AND INTRA-SPECIES VARIATION IN THREE CROWN CONDITION INDICATORS FOR SEVEN TREE SPECIES IN THE SOUTHEASTERN UNITED STATES

A Dissertation
Presented for the
Doctor of Philosophy Degree
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KaDonna Cheryl Randolph
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ABSTRACT

The USDA Forest Service utilizes assessments of tree crowns, specifically crown density, crown dieback, and foliage transparency, to accomplish in part its mission of reporting the long-term status, changes, and trends in forest ecosystem health in the United States. To aid interpretation and provide general guidelines of health across all species the crown condition assessments are classed into categories ranging from "good" to "poor." The purpose of this research was to evaluate and describe the variation in crown density, crown dieback, and foliage transparency between and within species, and to critique the appropriateness of the current threshold levels. In addition, inter-observer deviation between two assessment crews was evaluated for crown density; however, the attempts to effectively predict between-crew variation were unsuccessful. The seven species included in the analyses were slash pine (*Pinus elliottii*), loblolly pine (*Pinus taeda*), Virginia pine (*Pinus virginiana*), red maple (*Acer rubrum*), sweetgum (*Liquidambar styraciflua*), yellow-poplar (*Liriodendron tulipifera*), and white oak (*Quercus alba*).

Between- and within-species differences were determined via pair-wise comparisons at the 10th, 25th, 50th, 75th, and 90th percentiles of the empirical distribution function of each crown condition indicator. Random "error" drawn from uniform distributions on the intervals (-2.5, +2.5) and (-7.5, +7.5) was added to the percentile estimates in order to capture the possible within-crew variation in the crown assessments. Bootstrapping was used to compute two-sided 90 percent confidence intervals (CIs) for each percentile with the percentile CI method.

A clear gradient of expected crown conditions was found among the species, but uncertainty in the data made it difficult to confidently pinpoint species-specific differences for the three crown condition indicators. Assuming limited measurement error in the data, the greatest disparity among species was found in crown density. Dissimilarity was apparent between hardwood and softwood crown densities in general, but only scattered differences were found among the species in each group. In terms of foliage transparency, Virginia pine was the most dissimilar overall. No major differences

were found among the species in terms of crown dieback. In addition, relatively little variation was found within the two species (loblolly pine and sweetgum) examined for intraspecies variation.

Modifications to the current threshold levels were recommended for all three crown condition indicators. The suggested changes resulted in only small adjustments to the percentage of observations in each category and better reflect the distribution of observations across the range of the crown conditions. The proposed thresholds are:

- crown density: exceptional, 51-100 percent; good, 41-50 percent; moderate, 31-40 percent; and poor, 0-30 percent;
- crown dieback: none, 0-5 percent; light, 6-19 percent; moderate, 20-35 percent; and severe, 36-100 percent; and
- foliage transparency: normal, 0-20 percent; moderate, 21-40 percent; and severe, 41-100 percent.

TABLE OF CONTENTS

Chapter Page

LIST OF TABLES

Table Page

Table Page

LIST OF FIGURES

Figure Page

Figure Page

INTRODUCTION

Research Objectives and Justification

Visual assessment of tree crowns has been used worldwide to measure forest health because it is generally felt that tree health and vigor are reflected in the crown condition (Anderson and Belanger 1987, Innes 1993). The size and shape of tree crowns affects the amount of carbohydrates produced by a tree, and therefore can have a major effect on the amount and quality of wood produced (Biging and Gill 1997). Healthy crowns are usually distributed symmetrically in a predictable manner along the stem and careful examinations for deviations from this pattern may indicate a tree undergoing stress (Waring 1987). The USDA Forest Service Forest Inventory and Analysis (FIA) Program utilizes assessments of tree crowns, specifically crown density, crown dieback, and foliage transparency, to accomplish in part the forest health monitoring (FHM) mission of reporting the long-term status, changes, and trends in forest ecosystem health in the United States (USDA Forest Service 1994). To aid interpretation and provide general guidelines of health across all species the crown condition assessments are classed into categories ranging from "good" to "poor." It was expected that these good to poor thresholds would change as further studies noted differences among species (Bechtold et al. 1992); however, no adjustments have been made to date.

The general literature suggests that differences in crown form may be attributed to physiological factors such as epinastic control (Oliver and Larson 1996), flowering and seed production (Gross 1972, Remphrey et al. 1987), and shade tolerance (Sterck et al. 2001, Oliver and Larson 1996); as well as environmental factors like light availability and intensity (King and Maindonald 1999, Oliver and Larson 1996), elevation (Kuuluvainen and Sprugel 1996), and moisture availability (Oliver and Larson 1996). The FHM literature also acknowledges the existence of differences among species (Bechtold et al. 2002, USDA Forest Service 2002a, Millers et al. 1992), but there is no description of how or to what extent crown dieback, crown density, and foliage transparency actually vary among and within species. Therefore, it is not known for purposes of analysis and interpretation of the crown condition data whether species should be considered individually or collectively. Thus, this research has two primary objectives:

1. To evaluate and describe interspecies variation in crown dieback, crown density, and foliage transparency for seven tree species in the Southeastern United States; and
2. To evaluate and describe the intraspecies variation in crown dieback, crown density, and foliage transparency for two tree species found in varying environmental conditions in the Southeastern United States.

In addition to these primary objectives, the quality of the crown density indicator was addressed, and an attempt to estimate the inter-observer deviation between two assessment crews was made.

This research makes use of four years of FIA Phase 3 (formerly FHM detection monitoring) data from Alabama, Georgia, North Carolina, South Carolina, Tennessee, and Virginia. The seven species included in the analyses for Objective 1 were slash pine (*Pinus elliottii*), loblolly pine (*Pinus taeda*), Virginia pine (*Pinus virginiana*), red maple (*Acer rubrum*), sweetgum (*Liquidambar styraciflua*), yellow-poplar (*Liriodendron tulipifera*), and white oak (*Quercus alba*). The two species included in the analyses for Objective 2 were loblolly pine and sweetgum.

As no work has been done to evaluate the appropriateness of the current crown threshold levels, results from the analyses herein are used to critique the thresholds currently set for all species, and recommendations are made regarding the need for species- and/or growing condition specific thresholds.

Literature Review

FHM History

The Forest Health Monitoring Program (FHM) was formally created in 1990 through the combining of the USDA Forest Service's National Vegetation Survey and the Environmental Protection Agency's Environmental and Assessment Program. FHM is presently directed by the USDA Forest Service and state forestry agencies with management from a five-member national Steering Committee, a fifteen-member FHM Management Team, and *ad hoc* groups of interdisciplinary specialists (Riitters and Tkacz 2004).

From the outset, the mission of FHM has been to "monitor, assess, and report on the long-term status, changes, and trends in forest ecosystem health in the United States" (USDA Forest Service 1994). To accomplish its mission, FHM implements five types of activities (Reams et al. *in press*, McRoberts et al. 2004, USDA Forest Service 1994):

1. detection monitoring – determines baseline conditions of forest ecosystems and detects changes and trends over time;
2. evaluation monitoring – examines the extent, severity, and probable causes of undesirable changes in forest health identified in detection monitoring;
3. intensive site ecosystem monitoring – assesses the cause-effect relationships of functions that shape forest ecosystems;
4. research on monitoring techniques – studies biological, statistical, and analytical methods for monitoring forest ecosystems, including urban and riparian forests; and
5. analysis and reporting – produces peer-reviewed publications regarding the status of forest health at national and regional levels.

The detection monitoring component of FHM began in six New England states in 1990. This was followed by the addition of three mid-Atlantic and three Southern states in 1991, and two Western states in 1992 (Vissage and Hoffard 1997). At present, detection monitoring is ongoing in 36 states nationwide, including 11 of the 13 states in the USDA Forest Service Southern Region: AL, AR, FL, GA, KY, LA, NC, SC, TN, TX, and VA (USDA Forest Service 2002b).

In the beginning, detection monitoring field plots were assessed solely by FHM, but this role was assumed by the USDA Forest Service Forest Inventory and Analysis (FIA) program in 1999. Until 1999, the FIA program accomplished its objectives through two phases (McRoberts et al. 2004): 1. identifying and stratifying forest populations of interest through remote sensing, and 2. timber inventorying the accessible forest plots identified through the first phase. FHM detection monitoring became the third phase of FIA and the on-the-ground detection monitoring plots thereby assumed the name Phase 3 plots. Hereafter, FHM detection monitoring plots are referred to as (FIA) Phase 3 plots regardless of the year in which they were assessed.

The Phase 3 plots are a 1:16 subset of the Phase 2 plots, both of which are located via a nationwide hexagonal grid with centers spaced 16.2 miles (27 km) apart. There are approximately 8,000 Phase 3 plots nationwide, corresponding to about one plot for every 96,000 acres (38,450 ha) (Riitters and Tkacz 2004). Each Phase 3 plot is cluster of four 1/24-acre (1/60-hectare) circular subplots with subplot centers located 120 feet (36.6 m) apart. On each plot a set of indicators is assessed to characterize forest health. These indicators range from overall site assessments to measurements taken on individual trees. Included are lichen communities, soils, tree crown condition, vegetation structure, indicator plants for ozone presence, and coarse woody debris (Reams et al. *in press*). Of primary interest for the research herein is the tree crown condition indicator. On each subplot, crown attributes are visually assessed on all live trees at least 5.0 inches (12.7 cm) in diameter. The three pertinent attributes and their definitions are (USDA Forest Service 1999):

1. Crown density – The amount of crown branches, foliage, and reproductive structures that blocks light visibility through the crown; measured as the percent of total light that is blocked by tree material.
2. Crown dieback – Recent mortality of branches with fine twigs, which begins at the terminal portion of a branch and proceeds toward the trunk; measured as the percent of branch tips that are dead.
3. Foliage transparency – the amount of skylight visible through the live, normally foliated portion of the crown; measured as the percent of total light that would be visible if the light were unblocked.

Crown density, crown dieback, and foliage transparency are recorded in 21 five-percent classes from 0 to 100 percent. Low values are desirable for crown dieback and foliage transparency. High values are desirable for crown density.

Crown density and foliage transparency are similar measures of the amount of light penetrating the crown, but they are not exact inverses. Crown density measures the amount of sunlight *blocked* by all plant material (both live and dead) in the crown, whereas foliage transparency measures the amount of sunlight *penetrating* the *live* portion of the crown. Deductions are made from the maximum possible crown density for spaces between branches and other large openings in the crown (Figure 1). Foliage transparency, however, is not penalized for large gaps in the crown. Increases in the foliage transparency rating are made only for small openings in areas where foliage is expected to occur (Figure 2).

Tree crowns as an indicator of forest health

Visual assessment of tree crowns has been used worldwide to measure forest health because it is generally felt that tree health and vigor are reflected in the crown condition (Anderson and Belanger 1987, Innes 1993). The size and shape of tree crowns affects the amount of carbohydrates produced by a tree, and therefore can have a major effect on the amount and quality of wood produced (Biging and Gill 1997). Healthy crowns are usually distributed symmetrically in a predictable manner along the stem and careful examinations for deviations from this pattern may indicate a tree undergoing stress (Waring 1987). The cause of stress may be one or a combination of many factors such as insects, droughty conditions, frost damage, senescence, competition and other stand conditions, and management practices (Kenk 1993).

When a tree is subjected to stress it reacts by slowing growth and shedding parts of its crown thereby changing the crown's appearance (Millers et al. 1989). The shedding of parts, termed dieback for the loss of fine twigs and defoliation for the loss of leaves, is a survival mechanism the tree uses to adjust and conserve its energy reserves. Dieback and defoliation are important because they can be early symptoms of serious decline in trees (Houston 1981).

By causing the tree to shift energy reserves and use patterns, dieback and defoliation can interfere with growth. Subsequently a number of studies have examined crown condition and growth relationships. Studies of loblolly pine have found relationships between crown conditions and radial growth. Grano (1957) reported that seed trees with dense crowns had faster growth than trees with less foliage.

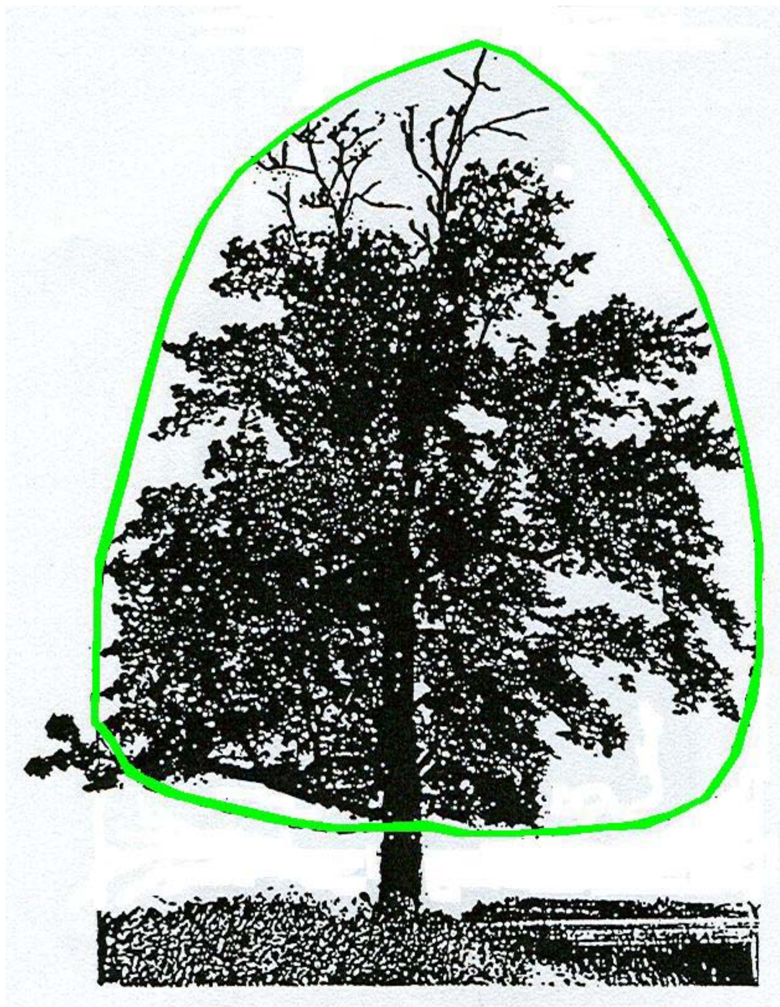


Figure 1. The solid line shows the crown outline for crown density determination. Large openings within the crown outline and gaps between the branches reduce the crown density rating. Crown density for this tree is 60 percent (Millers et al. 1992).

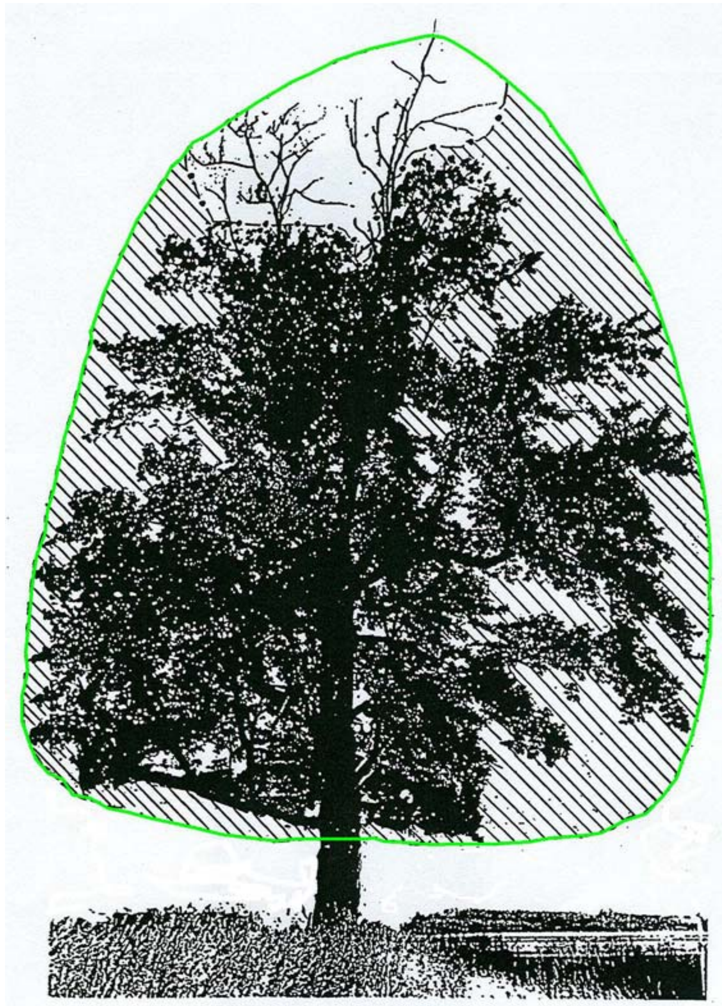


Figure 2. Striped areas are open areas of the crown where foliage is not expected to occur. Foliage transparency in the live portion of the crown is 15 percent (Millers et al. 1992).

Guttenberg (1953) discovered that faster growing trees had longer and wider crowns than the slower growing trees, and Deetlefs (1954) saw that a twofold increase in live crown ratio resulted in an almost doubling of the basal area growth of individual trees.

Anderson and Belanger (1987) reported a general decline in radial growth of loblolly and shortleaf pines as the percentage of defoliation increased. Baker (1941) discovered a direct correlation between decline in radial growth and percentage of gypsy moth defoliation in eastern white pine and four species of oak. Steinman (2000) found that crown condition could be used to distinguish hardwood and softwood trees that died over a four-year period from those that lived.

Not all studies however, have found direct correlations between crown conditions and growth or vigor. In their study of lodgepole pine Kauffmann and Watkins (1990) found no substantial differences in incremental growth for trees in different crown vigor classes. They concluded that the visual separation of trees into crown vigor classes was not an adequate way to assess tree vigor. Though Juknys and Augustaitis (1998) found significant correlations between basal area increment and two crown condition indicators (crown density and foliage transparency) in their work with Scots pine forests in Lithuania, they concluded that the USDA Forest Service FHM crown assessments were not sufficient for "biological interpretation of collected data and estimation of potential tree growth."

In addition to these inconsistent results, an important concern with relating crown condition to overall tree or forest health is that a crown's current condition is a combination of past and present conditions expressed by the tree. Millers et al. (1992) suggest that the size and density of the crown may be the result of past growth processes; defoliation and damage the reflection of current stresses. Insect infestations, frost damage, temperatures, and pollution in previous growing seasons may have effects that are visible for several years in the future; however, the effects of some stresses may not immediately manifest themselves in the crown's appearance (Innes 1988a). A crown's current condition is then the result of a combination of factors including site conditions, stand density, and external stresses from the past and present. These factors should, therefore, be included or considered when making statements about the crown condition or when trying to draw conclusions about why the crown looks like it does. This concern notwithstanding, Anderson and Belanger (1987) concluded from their study that general health of individual trees and forest stands can be assessed by looking at crown characteristics. Kenk (1993) and Innes (1993) would disagree. They both inferred from their studies in Europe that the assessment of crown condition does not provide a clear interpretation of forest health conditions. Oliver and Larson's (1996) general outline of photosynthate allocation supports the arguments that crown condition may not be the best standard for forest and/or tree health. According to their outline, the production of new leaves follows maintaining respiration in priority for photosynthate allocation. The addition of xylem is the last priority for photosynthate which suggests that declining tree health is first likely to be detectable in declining diameter growth rates rather than declining crown conditions.

Despite the incongruities, crown condition is widely used to reflect tree health, and the assessment of crown transparency is still recommended by the United Nations Economic Commission for Europe as a way to gauge tree vitality (Gertner and Köhl 1995). No unambiguous relationship between crown condition and tree vigor has yet been found (Ferretti 1997), but Solberg and Strand (1999) concluded that crown assessments "have the ability to provide crude, but reliable estimates of spatial and temporal trends [of tree health], when these trends are not too weak."

<u>FHM health thresholds for crown condition indicators</u>

A single assessment of forest health results in the categorization of trees as either healthy or unhealthy. The thresholds that demarcate these groups ideally should be based on the level at which trees are stressed to the point of biological decline. These thresholds are difficult to pinpoint, however, so the tails of statistical distributions have been used instead. Although the use of statistical distributions always results in some observations designated as poor, they are useful for identifying spatial and temporal changes in forest condition (Bechtold et al. 2002).

The FHM thresholds established for crown density, crown dieback, and foliage transparency are (Bechtold et al. 1992):

- crown density: good, 51-100 percent; moderate, 21-50 percent; and poor, 0-20 percent;
- crown dieback: none, 0-5 percent; light, 6-20 percent; moderate, 21-60 percent; and severe, 61-100 percent; and
- foliage transparency: normal, 0-30 percent; moderate, 31-50 percent; and severe, 51-100 percent.

The set of current thresholds are the same for all species and were likely defined through one or more of the following means: review of scientific literature and existing data, research studies, retrospective analyses, or expert opinion (Lewis et al. 1994). Steinman (2000) suggested alternative thresholds for crown density and crown dieback based on a one-year survival probability. His results showed that hardwood trees with crown dieback greater than 30 percent and softwood trees with dieback greater than 20 percent were most likely to die within one year of assessment. For both hardwood and softwood trees, those with crown densities less than 30 percent were most likely to die.

Inter- and intra-species variation in crown shape

Crown shapes are controlled by internal physiological factors and external environmental elements. The primary internal factor influencing crown shape is the extent to which terminal buds control the length and orientation of lateral branches (Fisher 1986). This control is known as epinastic control and it varies by species, tree vigor, and position of the lateral branch (Oliver and Larson 1996). Species with strong epinastic control have excurrent growth forms, i.e. they maintain a distinct central stem or trunk. Species with strong epinastic control include Douglas-fir, true firs, spruces, hemlocks, yellow-poplar, and sweetgum. Species with weaker epinastic control tend to have more rounded crowns in which one central stem is not distinguishable, i.e. decurrent growth forms. Oaks are prime examples of species with weak epinastic control.

Branching patterns within species display varying degrees of phenotypic plasticity, and the patterns may be more related to a tree's ability to take advantage of environmental conditions than its inherited or deterministic form (Fisher 1986). Environmental factors may act directly on the crown form, e.g. wind and ice damage or physical abrasion with other trees, or they may influence the tree's ability to maintain epinastic control. External factors influencing epinastic control include drought, flowering and seed production, and light availability and intensity (Oliver and Larson 1996).

Still other factors influencing crown appearance include a species' shade tolerance and the moisture conditions in which the tree is growing. Species that can photosynthesize at lower light intensities generally maintain denser crowns, while species that cannot survive under much shade tend to have less dense crowns. Less dense crowns are also typical of trees growing on dry sites (Oliver and Larson 1996).

Explicit research on inter- and/or intra-specific differences in tree crown architecture has been conducted mostly in tropical forests (e.g. Hallé et al. 1978 and other citations in Sterck et al. 2001). Two recent examples of this research are Sterck et al. (2001) and King and Maindonald (1999). Sterck et al. (2001) found that within understory species of Bornean lowland rainforests, trees with slower growth rates in the ten years prior to measurement had less leaf area and fewer leaf layers than the faster growing trees. Tree height also had an effect on the tree architecture within species in that taller trees had larger total leaf areas and more leaf layers than shorter trees. Their results for interspecific differences generally split along diptocarp and euphorb lines, with the diptocarps having smaller total leaf areas and fewer leaf layers.

King and Maindonald (1999) examined the relationship between tree architecture and leaf dimensions and tree stature for evergreen broad-leaved species of lowland equatorial and temperate Australian rainforests. They found that for understory trees, leaf display (plagiotropic or orthotropic) was more strongly related to leaf dimensions than to abundance or adult stature and shade tolerance; however, this relationship was not as strong for large canopy trees. They concluded that tree architecture changes as trees grow, and that the shift is from a planar arrangement of leaves and branches in saplings to a more three-dimensional arrangement in intermediate-sized trees. Their results suggest that as trees grow into the overstory, light availability and inherent physiological attributes overtake leaf dimension as the strongest factors determining leaf arrangement.

Studies of differences in tree crown architecture of temperate forest species are less pervasive. Two examples of intraspecies differences are summarized here. Kuuluvainen and Sprugel (1996) made an examination of age- and altitude-related variation in tree architecture and needle efficiency for a sample of dominant Norway spruce trees in Switzerland. Their analysis indicated that several characteristics of tree architecture, e.g. the ratio of crown length to total tree height, were associated with tree age and the altitude of the growing site. Given their results, they caution against misinterpreting natural variation in needle and crown characteristics as pollution-induced stress symptoms. They warn that such natural variation may be especially great in environments with steep elevation gradients where other factors such as wind and temperature combine to affect tree growth and foliage density within the crown.

Remphrey et al. (1987) found from their investigation of boulevard (open-grown) green ash trees in Manitoba, Canada, that green ash have a range of crown shapes: from broad and rounded forms to tall and conical forms. They found that tree sex was helpful in differentiating the crown forms but that age and stage of development, as measured by tree height, were not useful. Male trees tended to have broader crowns than female trees, leading the authors to suggest that reproductive demands may reduce crown growth.

Indeed, there are many factors that influence the shape of tree crowns. Some factors such as epinastic control and photosynthetic rates are physiological, while other factors act externally upon the tree. It is likely that the physiological and external factors interact with one another and, as suggested by King and Maindonald (1999), their influence in shaping crown form shifts as a tree matures. Clearly, there is a need to carefully understand expected crown conditions so that forest health data is not misinterpreted.

Advantages and disadvantages of visual assessments

The FHM program uses visual observations to assess crown density, crown dieback, and foliage transparency. Training sessions are held at the beginning of every field season so that field crew members calibrate their eyes to the same standards. Field crews then are tested at the end of the training session and only those who are able to assess crown characteristics within acceptable limits of the trainers are allowed to collect data during the summer. Visual assessments of tree crowns are quick, easy to perform, and cost-effective, but there are concerns regarding the reliability of such data.

Several factors influence an observer's ability to make reliable visual assessments. The most oft noted factor affecting reliable visual assessments is the amount of training and experience of the observer (Caro et al. 1979, Innes 1988b, Valentine and Ismail 1983, Mitchell 1979), but biases still exist even with extensive training (Ghosh et al. 1995). Of secondary importance is the clarity of the definition of the characteristic to be measured (Caro et al. 1979), and a third factor is the frequency of occurrence of a level of the characteristic (Caro et al. 1979). That is, rare levels are more likely to have less inter-observer agreement simply because observers do not see or assess these conditions frequently. Light conditions under which assessments are made also influence the reliability of the data. Observations made in darker conditions such as that of an overcast sky may lead to underestimates of needle/leaf loss (Innes 1988b). In addition to all of these factors, Metzger and Oren (2001) present an interesting argument that the dimensions of the tree crown itself may introduce observer bias. They note that because of the path-length of the line of sight through the crown, trees of certain sizes are likely never to be assessed as having poor crowns.

These problems with observer bias reduce data quality and may lead to incorrect conclusions about the health of the forest. Furthermore, patterns across time and space that exist in the data may not be due to actual differences in tree health but rather due to biases of regional field crews (Strand 1996, Innes 1988b) or the result of changes in survey teams (Strand 1996). Observer bias is not only a problem in forestry applications. Inter-observer disagreements of visual assessments have been found in the agricultural and horticultural disciplines (Valentine and Ismail 1983, Sherwood et al. 1983), as well as in the behavioral sciences (Mitchell 1979, Caro et al. 1979).

To minimize observer bias some forest health monitoring programs utilize reference photographs for crown assessments (Innes 1988a), but even with reference diagrams there can be problems. In their study of Stagonospora leaf spot on orchardgrass Sherwood et al. (1983) found that two kinds of illusion influence visual judgments even with the use of reference diagrams. The first illusion they discovered was that observers tended to overestimate the area of diseased spots on the plant material, especially at low levels of spotting. The second illusion involved the perception of total diseased area. They found that if two leaves had similar total diseased areas, the leaf with the greater number of (smaller) spots was often perceived as having greater total area of spots. Together these results suggest that the eye focuses on the diseased areas and discriminates among frequencies more readily than it does among sizes. Transferring these conclusions to assessments of crown condition suggest that two trees having the same levels of defoliation could receive very different assessments if one tree has a concentrated amount of defoliation while the other has dispersed defoliation.

Data Quality Assurance

Burkman et al. (1991) define quality assurance (QA) as "a planned group of activities that define the way tasks are performed to ensure that the final product will meet a desired level of quality." QA programs are essential for large-scale and/or long-term ecological monitoring programs and they should be developed in the very early stages of monitoring programs. Development of a QA program should involve representatives from all levels of the monitoring program including program managers, data analysts, decision makers (i.e., people who will use conclusions drawn from the data to make decisions), and field personnel. Incorporating all levels of involvement ensures correct statements about the monitoring program's objectives, spatial and temporal boundaries, data performance requirements, data interpretation and analytical techniques, and data collection methodologies (Lawrence and Palmer 1996, Ferretti 1997). QA activities should include training of field personnel prior to data collection and the use of consistent methods and reference materials (Cline et al. 1989). Data quality information should be reviewed annually by program managers and included with all monitoring reports so that the readers can interpret the conclusions in light of the data quality (Burkman et al. 1991, Cline et al. 1989, Ferretti 1997).

A properly designed QA program has several benefits. Most importantly it ensures that the data being collected meets predefined standards so that the needs of users are met with stated levels of confidence (Lawrence and Palmer 1996). Additionally, QA programs improve the consistency, reliability, and cost-effectiveness of monitoring programs over time (Ferretti 1997), and confirm that standard operating procedures are clearly defined, documented, and implemented (Burkman et al. 1991).

FHM QA Program

The overall mission of the FHM QA program is to support the FHM program mission and "to assure that FHM data and statistical products are of documented and sufficient quality to satisfy the needs of data users, policy makers, and the public" (USDA Forest Service 1998). There are three main activities in the QA program: planning, measurements, and assessments. Planning activities focus on identifying data quality requirements, evaluating project planning, and evaluating data collection methods. QA activities regarding measurements involve quality control of the field crew training sessions and field data collection. Assessment QA activities provide documentation of data quality by comparing field crew assessments with experts and other field crews.

QA data are collected primarily from field measurements, although some laboratory measurements are made for the soils and lichen indicators. At the beginning of each field season, regional indicator trainers meet for pre-training in which they calibrate themselves to assure national comparability of training. Following the pre-training session, trainers lead regional sessions for the field crews. Field crew performance is evaluated throughout the training session and culminates with a test on all indicators. Certified field crews then are audited within the first three weeks of the field season through an interactive session with an auditor known as "hot checks" (Pollard and Smith 1999). Retraining and retesting, if necessary, is done at this time. Later in the field season "cold checks" are performed. That is when the field crew's work is checked without its knowledge by an independent evaluation performed by national or regional "expert" auditing crews. After the field season, QA data are compiled and summarized into QA reports that detail the achievement of QA objectives for the year (e.g., Pollard and Smith 2001, 1999).

Measurement quality objectives (MQOs) are set for each forest health indicator (USDA Forest Service 1999). The MQOs for crown density, crown dieback, and foliage transparency are set at 90 percent within the data quality limit (DQL) which is $\pm$ 10 percent. That is, field crew assessments must be within 10 percent of the audit crew assessments for at least 90 percent of all trees.

Methodology

Goodness-of-fit tests

The true distribution of a random variable is rarely known so it is often estimated by the distribution of a sample from the population of interest. This sample distribution is known as an empirical distribution and its function (*edf*) is defined as follows (Stephens 1986): Let $X_1, X_2, \ldots, X_n$ be a random sample, and $X_{(1)}, X_{(2)}, \ldots, X_{(n)}$ the random sample in rank order. Then,

$$\begin{aligned} F_n(x) &= 0 && x < X_{(1)} \\ F_n(x) &= i/n && X_{(i)} \le x \le X_{(i+1)}, i = 1, \ldots, n-1 \\ F_n(x) &= 1 && X_{(n)} \le x. \end{aligned}$$

$F_n(x)$ is a non-decreasing, random function that goes from zero to one in height. It is a step function with steps of height 1/n occurring at the sample values (Conover 1999). Thus for any x, $F_n(x)$ is the proportion of observations less than or equal to x. $F_n(x)$ is a consistent estimator of F(x), the probability that an observation is less than or equal to x. As *n* goes to infinity, $|F_n(x)-F(x)|$ decreases to zero with probability one (Stephens 1986).

Edf plots are easy to generate and are especially helpful because no assumptions about the underlying parametric distribution is required (D'Agostino and Stephens 1986). By examining an *edf* plot, one can readily infer information about the distribution's shape (dispersion, skewness, bimodality) and location, as well as the occurrence of any outlying observations. In addition, *edf* plots do not have the grouping difficulties associated with histograms, and with regard to the quantiles, they are invariant under monotone transformations. One downside of *edf* plots, however, is that they can be sensitive to random occurrences in the data (D'Agostino and Stephens 1986).

Empirical distribution functions can be used to determine if two samples are from the same unknown population. If the samples are from the same population then their *edfs* should be similar. Goodness-of-fit tests designed to test the hypothesis that a sample is from a specified distribution may also be used to test whether or not two samples are from the same (unknown) distribution. The goodness-of-fit tests that utilize the *edf* fall into two classes, the supremum class and the quadratic class (Stephens 1986). The most well known *edf* goodness-of-fit test is based on the Kolmogorov-Smirnov (KS) supremum statistic. Other goodness-of-fit statistics, in the quadratic class, are the Anderson-Darling (AD) and Cramér-von Mises (CM) statistics. The KS statistic is defined as

$$KS = \sup_x \left| F_n(x) - F(x) \right| = \max\left(KS^+, KS^-\right),$$

and the AD and CM statistics are defined as

$$Q = n\int_{-\infty}^{\infty} \{F_n(x) - F(x)\}^2 \psi(x) dF(x),$$

where $\psi(x)$ is a function which gives weights to the squared difference $\{F_n(x)-F(x)\}^2$. For the AD statistic $\psi(x)$ equals $[\{F_n(x)\}\cdot\{F(x)\}]^{-1}$, and for the CM statistic $\psi(x)$ equals one (Stephens 1986). These statistics are used to test the hypothesis

$$H_0: F(x) = F_0(x),$$

where $F_0(x)$ is a completely or partially specified cumulative distribution function. The alternative hypothesis is usually of the general form $F(x) \neq F_0(x)$ (Reynolds et al. 1988). The KS, AD, and CM statistics are defined for continuous distributions, but they may also be used with discrete data if the discreteness is an artifact of imprecise measurement and if the subsequent occurrence of ties is not excessive (Bradley 1968).

When dealing with discrete data or continuous data that can be naturally grouped, the classical goodness-of-fit test is the Pearson chi-square test. Let $X_1, X_2, \ldots, X_n$ be a random sample and let $I_1, I_2, \ldots, I_k$ be the partitioned classes for the set of possible values for X. Then the chi-square statistic is

$$\chi^2 = \sum_{i=1}^{k} \frac{(f_i - e_i)^2}{e_i},$$

where f_i is the observed number of observations falling in I_i and $e_i = np_i$ with p_i being the probability of I_i under the null hypothesis given above (Reynolds et al. 1988). If $F_0(x)$ is completely specified, the asymptotic distribution of χ^2 is chi-square with $k-1$ degrees of freedom. If F_0 is unspecified and q distribution parameters are estimated, then the asymptotic distribution of χ^2 is somewhere between $\chi^2(k-1-q)$ and $\chi^2(k-1)$ (Reynolds et al. 1988).

Bootstrapping

Other measures that can be used to compare distributions include the traditional measures of scale and location, i.e. mean, variance, skewness, and kurtosis, as well as the median and other percentiles. A difficulty with some of these measures, particularly the percentiles, is the calculation of their standard errors which inhibits the calculation of confidence intervals. A solution to this problem is the bootstrap. The bootstrap was first introduced by Efron (1979) and provides for the estimation of the standard errors of the descriptive statistics listed above. To explain, let $X = \{x_1, x_2, \ldots, x_n\}$ be a sample of n independent observations from a population with unknown distribution function F and parameter $\theta = \theta(F)$. The population parameter θ is generally estimated by $\hat{\theta}$ calculated from the sample X. To calculate a confidence interval for θ, the sampling distribution of $\hat{\theta}$, $H_n(\hat{\theta}, F)$, must be known. Bootstrapping provides this sampling distribution with the following general algorithm (Carpenter and Bithell 2000):

1. Sample n observations randomly and with replacement from X to obtain a bootstrap data set, denoted X^*.
2. Calculate the bootstrap version of the statistic of interest, $\hat{\theta}^* = \hat{\theta}(X^*)$.
3. Repeat steps 1 and 2 several times, generally 1000 to 2000, to obtain an estimate of the bootstrap distribution for $\hat{\theta}^*$, designated as $\hat{H}_n(\hat{\theta}^*, \hat{F})$.

Note that since X is sampled with replacement, the bootstrap data sets typically omit several observations and contain multiple copies of others.

With the sampling distribution of $\hat{\theta}^*$ established, several different options exist for calculating a confidence interval (CI) for θ. The percentile-type CI is the simplest and most general bootstrap CI (Dixon 1993). Assume that $\hat{H}_n\left(\hat{\theta}*, \hat{F}\right)$ consists of 1000 estimates of θ and let $\hat{\theta}_1^*,...,\hat{\theta}_{1000}^*$ represent the ordered set so that $\hat{\theta}_i^* < \hat{\theta}_j^*$, for $1 \leq i < j \leq 1000$. Then the lower bound of a two-sided 90 percent percentile CI is the 5th percentile of $\hat{H}_n\left(\hat{\theta}*, \hat{F}\right)$, i.e. $\hat{\theta}_{50}^*$. The upper bound is equal to the 95th percentile, or $\hat{\theta}_{950}^*$. The percentile-type CI works best when $\hat{\theta}$ is the median of the bootstrap distribution (Efron 1982). Two methods exist for correcting the percentile-type CI when the bootstrap distribution is biased and/or skewed. The bias-corrected (BC) bootstrap CI makes a single correction for bias in the distribution, while the accelerated (BCa) bootstrap CI makes a second correction for skewness. When the skewness parameter equals zero, the BCa method reduces to BC. See Lunneborg (2000) for computational details on these methods.

There are advantages and disadvantages for the percentile-type bootstrap CIs. The primary advantage for the basic (uncorrected) percentile method is its simplicity. No estimate of σ is required and the CIs can be calculated for any statistic (Dixon 1993, Carpenter and Bithell 2000). The BC method has the same advantages as the basic method with the additional advantage that it adjusts for the presence of bias in the bootstrap distribution (Stine 1989). Likewise, BCa improves upon the basic and BC methods by taking into account skewness of the bootstrap distribution. A drawback of the BCa method is that it requires more complex calculations than the basic and BC methods (Carpenter and Bithell 2000, DiCiccio and Efron 1996). All of the percentile-type methods are transform invariant (Carpenter and Bithell 2000, DiCiccio and Efron 1996).

A second type of bootstrap CI, known as the bootstrap-*t* interval, uses estimates of θ and the standard deviation of θ (σ) to calculate the bootstrap CI. As described by DiCiccio and Efron (1996) estimates of both θ and σ are calculated from each bootstrap resample and designated $\hat{\theta}*$ and $\hat{\sigma}*$, respectively. Then in the manner of Student's *t*-statistic,

$$T* = \frac{\hat{\theta}* - \hat{\theta}}{\hat{\sigma}*}$$

is calculated for each resample. If B is the number of bootstrap resamples, then $\hat{T}^{(\alpha)} = B \cdot \alpha^{th}$ ordered value of {$T^*(b)$, b = 1, 2, …, B}. The upper bound for a one-sided 100α$^{\text{th}}$ bootstrap-*t* CI is defined to be

$$\hat{\theta}_T[\alpha] = \hat{\theta} - \hat{\sigma}\hat{T}^{(1-\alpha)}.$$

The bootstrap-*t* interval is a reliable method of calculating bootstrap CIs given that $\hat{\sigma}$ is easily available (Carpenter and Bithell 2000); however, erratic behavior may be observed if no obvious, good variance estimator exists (Hall and Martin 1996). Furthermore, the bootstrap-*t* method is not transform invariant, and may produce very long CIs with unstable endpoints, especially if the original sample size is small (DiCiccio and Efron 1996, Polansky 2000).

When comparing bootstrap CI methods it seems logical to select the method that produces the shortest interval; however, interval lengths cannot be compared if the coverage errors of the methods are not the same (Polansky 2000). Coverage accuracy is defined by Polansky (1999):

> Let I be a confidence interval for θ with specified coverage probability equal to α. The true coverage probability of I, denoted as $\pi(I)$ is defined as $\pi(I) = P(\theta \in I)$. The accuracy of I is defined as $|\pi(I) - \alpha|$. I is said to be asymptotically k^{th} order accurate if $|\pi(I) - \alpha| = O(n^{-k/2})$, as $n \to \infty$ for some positive integer k.

The bootstrap-*t* method performs well in terms of coverage error, even for small samples (Polansky 2000), but the coverage errors can be substantial for the basic and BC percentile-type methods, especially if the basic method is applied to asymmetric bootstrap distributions (Carpenter and Bithell 2000). Coverage error is not monotonic for the BCa method as the coverage error tends to be erratic for small α, typically $\alpha < 0.025$ (Hall and Martin 1996, Carpenter and Bithell 2000). Polansky (1999) provides upper bounds on the true coverage for the percentile-type bootstrap CIs. In general, the basic and BC methods are first order accurate; the BCa and bootstrap-*t* methods are second order accurate (Carpenter and Bithell 2000).

CHAPTER I
DATA

Data collection methodology

Each FIA Phase 3 plot is a cluster of four 1/24-acre circular subplots (Figure 1.1). A set of forest health indicators is assessed on each plot by a two-person crew. These indicators range from overall site assessments to measurements taken on individual trees; included are lichen communities, soils, tree crown condition, vegetation structure, indicator plants for ozone presence, and coarse woody debris (Reams et al. *in press*). Plots are assessed during the summer when trees maintain full crown foliage, typically between June and mid-August for plots in the South. Details about the complete collection methods and techniques may be found in the FHM Field Methods Guide (USDA Forest Service 1999, 2002a).

In addition to the collection of the regular forest health data, the Phase 3 plots are assessed for quality assurance (QA) to insure that the data are of sufficient quality to meet stakeholder needs. The performance of the field crews is evaluated through a remeasurement system known as "cold checks" in which a subset of the regional field plots are randomly selected for remeasurement by a reference, or audit, crew. These cold check plots are "double-blind," that is, field crews are not aware of which plots are reevaluated and neither do they know the target values for the plots. An audit crew visits the field plot within two weeks of the field crew (Pollard and Smith 1999), and afterward the differences between the audit crew measurements and field crew measurements are calculated. These differences are compared to the measurement quality objectives (MQOs) outlined in national QA Program plans (USDA Forest Service 1998, Cline 1995). The MQOs for crown density, crown dieback, and foliage transparency are set at 90 percent within the data quality limit (DQL) which is $\pm$ 10 percent. That is field crew assessments must be within 10 percent of the audit crew assessments for at least 90 percent of all trees.

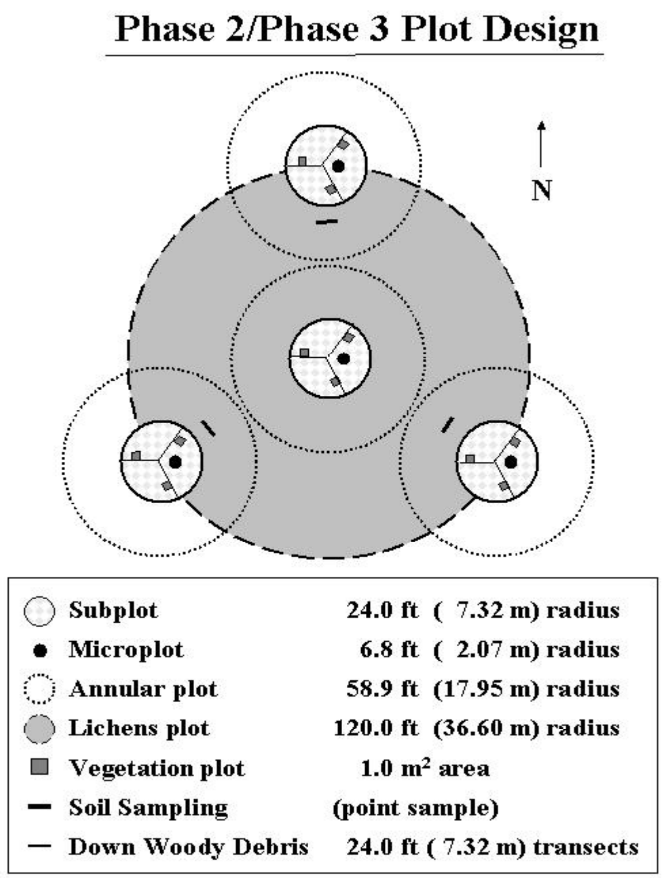


Figure 1.1. Forest Inventory and Analysis Phase 3 (FHM detection monitoring) plot design (USDA Forest Service 2002a).

Forest health indicators

Of primary interest for the research herein are the overall site descriptions for each plot and the crown condition descriptors crown density, crown dieback, and foliage transparency. As part of the overall site assessment each 1/24-acre subplot is assigned a condition classification described by five variables: land use, forest type, stand origin, stand size, and past disturbance. Land use consists of three major categories: forest land, inaccessible forest land, and nonforest land. Forest type follows the major Forest-Type Groups recognized by the Society of American Foresters (Eyre 1980) and is assigned based on the stocking of all live trees in the sampled location. Stand origin has three categories: natural, planted softwoods, and planted hardwoods. Stand size is categorized by the average diameter of all live trees in the stand that are not overtopped. From largest to smallest sized trees these categories are sawtimber, poletimber, sapling/seedling, and nonstocked. Past disturbances are described by 18 different categories including no disturbance and varying descriptors of silvicultural activities, weather events, and disease occurrences. Up to three past disturbances can be recorded for a condition classification; however, each disturbance must be at least one acre (0.4 hectare) in size. Multiple condition classifications are assigned to an individual plot when the plot or one of its subplots straddles different land uses or forest conditions. One other site assessment variable utilized in this research was terrain position. Terrain position is the position of the subplot in relation to the surrounding topography and is recorded as one of seven categories (Figure 1.2).

The crown condition indicators are visually assessed on all subplot trees greater than or equal to 5.0 inches (12.7 cm) in diameter at breast height (dbh). Crown density is the amount of crown branches, foliage, and reproductive structures that blocks light visibility through the crown. It is estimated as the amount of light being blocked by the crown of the survey tree compared to the amount blocked in a full, dense crown for a tree with the same crown form (Figure 1.3). Crown dieback is recent mortality of branches with fine twigs, which begins at the terminal portion of a branch and proceeds toward the trunk and is measured as the percent of branch tips that are dead. Only mortality in the upper and outer portions of the crown is considered (Figure 1.4). Foliage transparency is

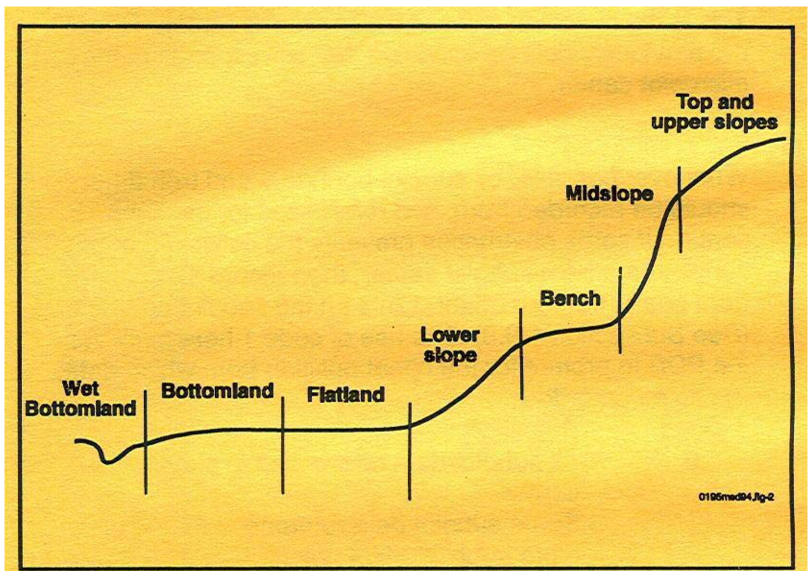


Figure 1.2. The seven possible terrain positions given to each FIA Phase 3 subplot (USDA Forest Service 1999).

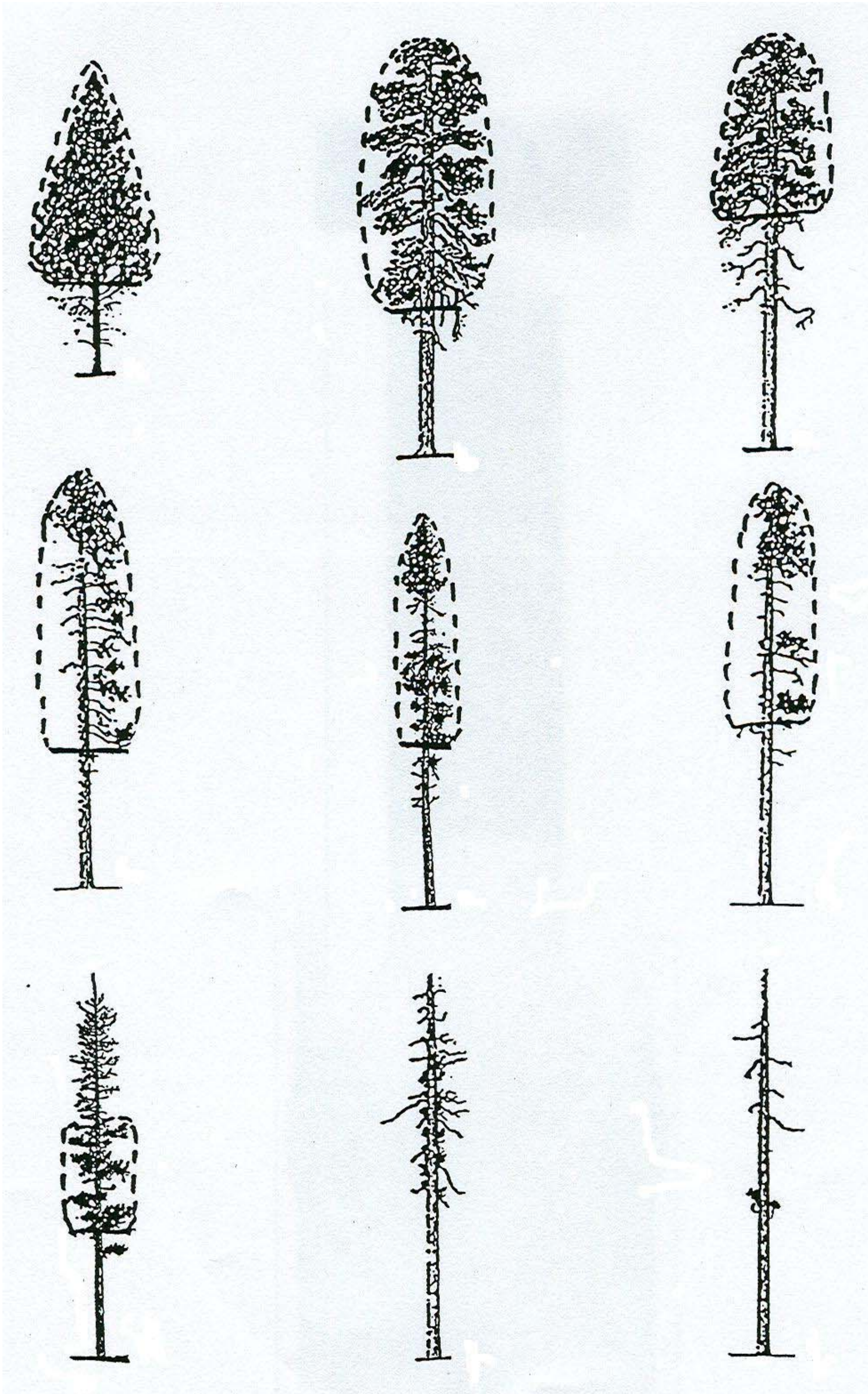


Figure 1.3. The dotted lines show the outline for crown density determination for a variety of tree conditions (Millers et al. 1992). See also Figure 1, page 6.

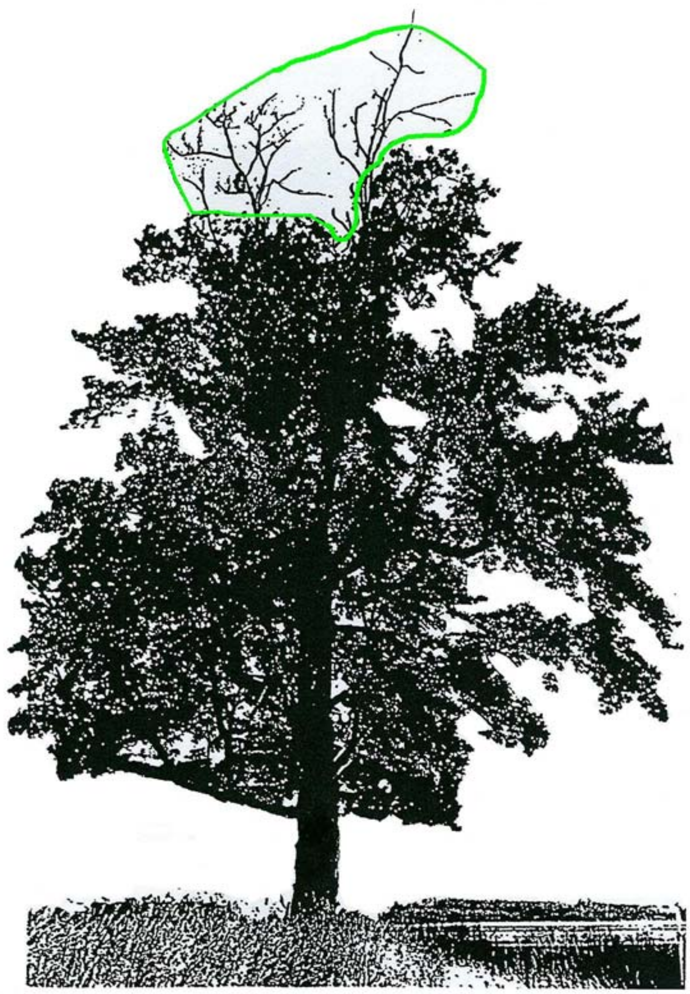


Figure 1.4. The solid line outlines crown dieback, which is 10 percent of the total crown area (Millers et al. 1992).

the amount of skylight visible through the live, normally foliated portion of the crown, and it is estimated by comparing the survey tree crown to the scale provided in the FHM Field Methods Guide (Figure 1.5). All three indicators are recorded in five percent increments from 0 to 100. Low values are desirable for crown dieback and foliage transparency. High values are desirable for crown density. In addition to crown condition, other individual tree variables included in the present research are dbh and species.

Data Summary

General

Quality assurance data set

The QA data included cold check plots measured between 1991 and 1999 in Alabama, Georgia, North Carolina, South Carolina, Tennessee, and Virginia (Table 1.1). The data included 1294 trees; 59.5 percent hardwoods and 40.5 percent softwoods. The most frequent species were loblolly pine (24.4 percent), sweetgum (11.3 percent), slash pine (5.9 percent), and white oak (5.3 percent) (Figure 1.6).

Deviations between the field crew and audit crew assessments were calculated as

deviation = field crew assessment – audit crew assessment.

Trees with missing observations for any of the three crown indicators were omitted. Summaries of the deviations indicated MQOs were met for crown dieback and foliage transparency but not for crown density. Across all years, 98 percent of the trees for crown dieback and 94 percent for foliage transparency were within the $\pm$10 percent DQL (Figures 1.7 and 1.8). Only 75 percent of the trees were within the DQLs for crown density which was well below the MQO goal of 90 percent agreement (Figure 1.9).

Crown condition (Phase 3) data set

The crown condition data came from all forested Phase 3 plots in Alabama, Georgia, North Carolina, South Carolina, Tennessee, and Virginia. Measurements were

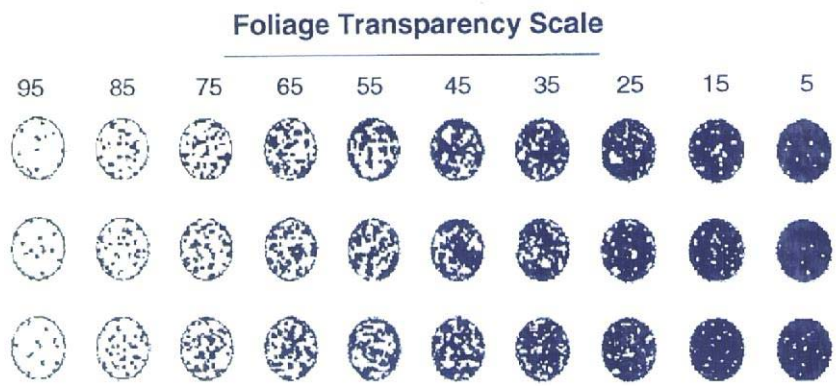


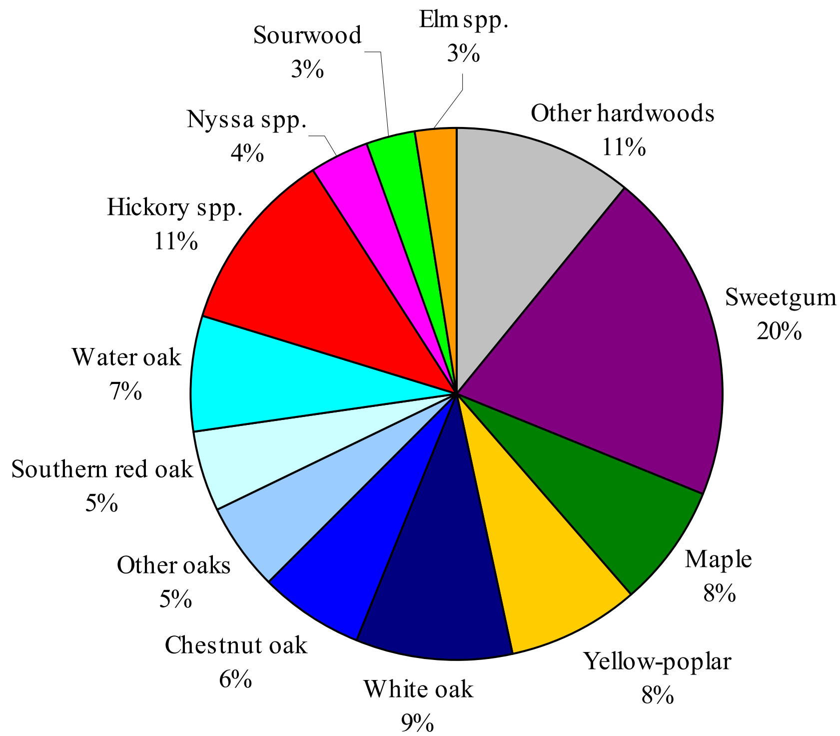
Figure 1.5. Scale used to assess foliage transparency (USDA Forest Service 1999). Dark areas represent foliage and white areas represent skylight visible through the crown. The amount of skylight penetrating the survey tree crown is compared to the scale and foliage transparency is rated according to the numbers above the circles. See also Figure 2, page 7.

Table 1.1. Number of FIA Phase 3 plots assessed for quality assurance by year and state.

State	Year						Total
	1991	1992	1994	1995	1998	1999	
Alabama	12	5	0	0	2	2	21
Georgia	6	6	3	1	2	0	18
North Carolina	---[a]	---	---	---	5	3	8
South Carolina	---	---	---	---	3	0	3
Tennessee	---	---	---	---	---	3	3
Virginia	4	4	0	0	3	2	13
Total	22	15	3	1	15	10	66

[a]No Phase 3 plots established in the state.

A. Hardwoods



B. Softwoods

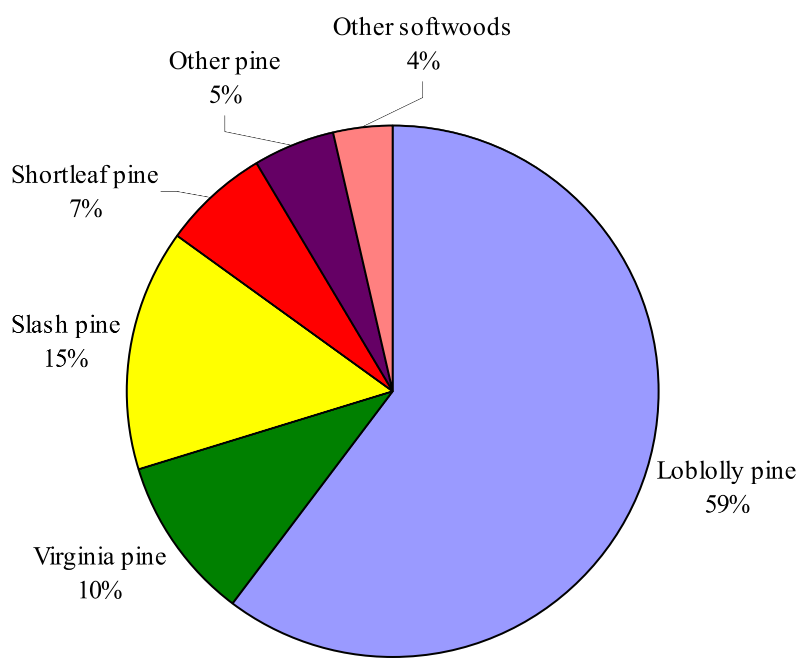


Figure 1.6. Hardwood (A) and softwood (B) species composition of the quality assurance data set.

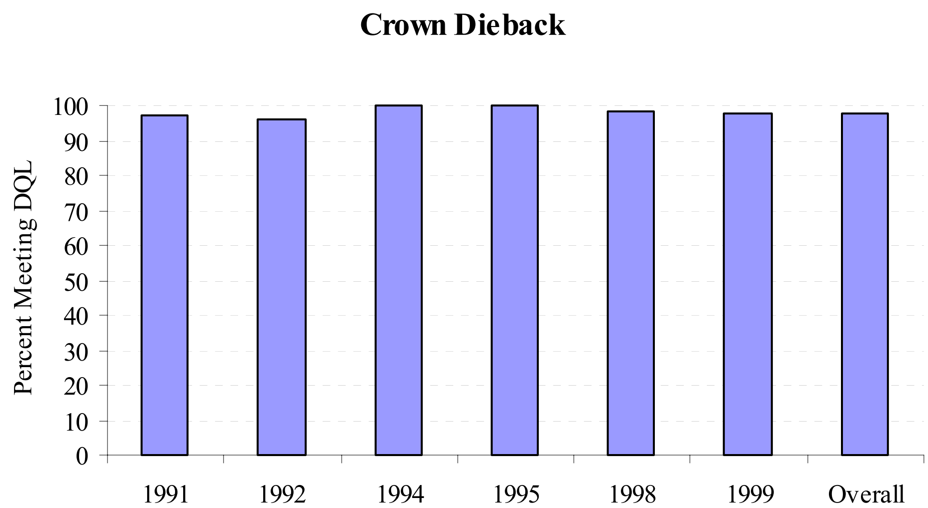


Figure 1.7. Percent of the crown dieback observations within the ±10 percent data quality limit (DQL) by year. The measurement quality objective is 90 percent DQL agreement.

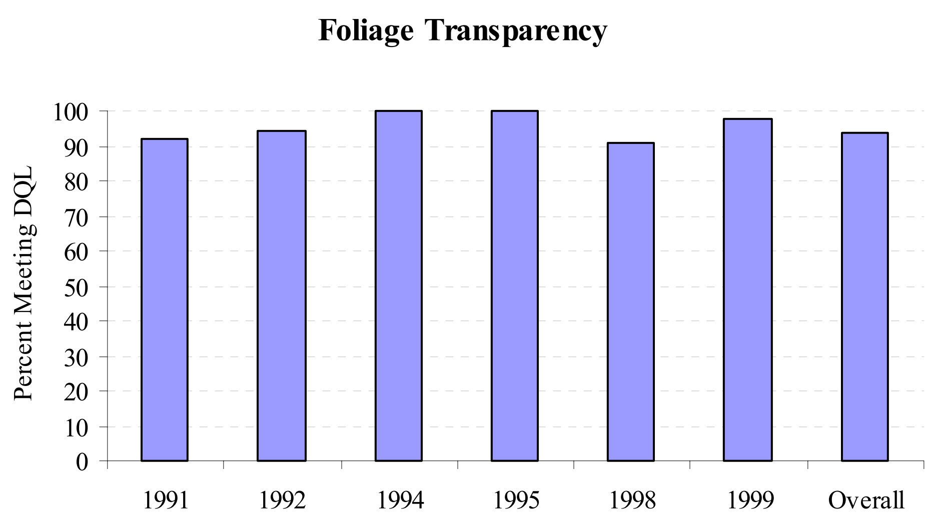


Figure 1.8. Percent of the foliage transparency observations within the ±10 percent data quality limit (DQL) by year. The measurement quality objective is 90 percent DQL agreement.

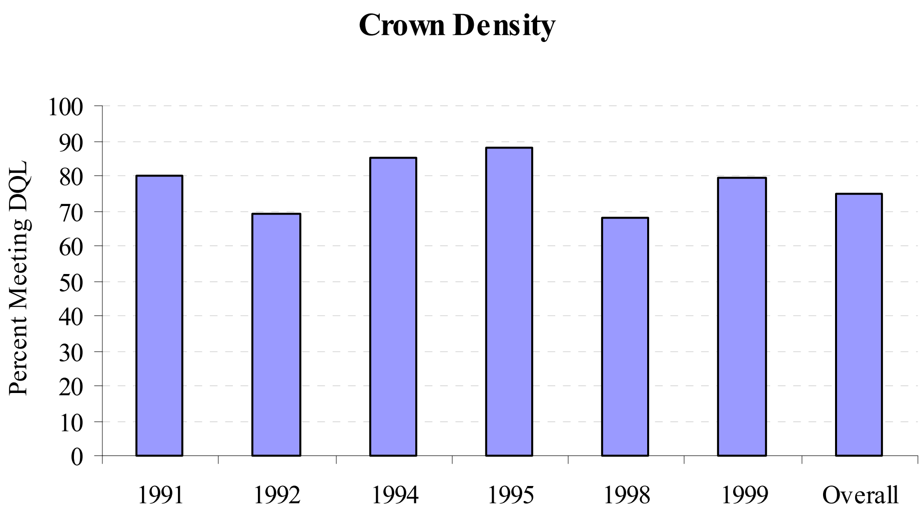


Figure 1.9. Percent of the crown density observations within the ±10 percent data quality limit (DQL) by year. The measurement quality objective is 90 percent DQL agreement.

made in 1995, 1997, 1998, and 1999. Only the most recent measurement for each plot was included; therefore, the range of years differed between the states (Table 1.2). Of the 645 forested plots included in the data set, 207 extended across more than one condition class yielding 852 condition classes overall. Of these 852 condition classifications, 99.8 percent were designated as timberland. The remaining 0.2 percent was reserved timberland, i.e. timberland completely withdrawn by law from commercial timber production.

The most common forest types were loblolly pine (20.9 percent), white oak/red oak/hickory (18.9 percent), loblolly pine/hardwood (9.6 percent), and sweet-gum/yellow-poplar (5.2 percent). The number of different forest types recorded in each state ranged from a low of 22 in South Carolina to a high of 36 in North Carolina. Table 1.3 lists the number of condition classes by forest type group for each state.

The majority of the condition classifications were of natural origin (Table 1.4), and almost half were sawtimber size stands (Table 1.5). Poletimber and seedling/sapling size stands each accounted for approximately one-fourth of the condition classes, while a small portion (2 percent) were non-stocked. At least one past disturbance was recorded on 13.4 percent of the condition classes; 22 condition classes in Alabama, 26 in Georgia, 11 in North Carolina, 19 in South Carolina, 20 in Tennessee, and 16 in Virginia. The most common disturbances were harvest, selective cutting/high grading, and prescribed burning.

There were 49 known genera recorded on the plots. The most prominent were *Quercus* (23 species), *Pinus* (12 species), *Carya* (7 species), and *Acer* (6 species). Fifty-seven percent of the trees were hardwoods and 43 percent were softwoods. The most common species were loblolly pine (*Pinus taeda*), red maple (*Acer rubrum*), sweetgum (*Liquidambar styraciflua*), and yellow-poplar (*Liriodendron tulipifera*) (Figure 1.10).

According to the current thresholds, the majority of the tree crowns were in apparent healthy condition. Overall, less than three percent of the crowns fell into the severe or poor categories (Figure 1.11). The percentages of trees in each category were comparable for hardwoods and softwoods, though a greater disparity was evident in crown density. For hardwood trees, 29.8 percent of the trees fell into the good crown

Table 1.2. Number of forested FIA Phase 3 plots measured in each state by year.

State	Year				Total
	1995	1997	1998	1999	
Alabama	20	34	29	44	127
Georgia	26	40	34	54	154
North Carolina	---[a]	---	67	47	114
South Carolina	---	---	52	24	76
Tennessee	---	---	---	78	78
Virginia	15	24	25	32	96
Total	61	98	207	279	645

[a]No Phase 3 plots established in the state.

Table 1.3. Number of condition classes by forest type group for each state in the Phase 3 data set.

State	Forest Type Group									Total
	White/ Red/Jack Pine	Longleaf/ Slash Pine	Loblolly/ Shortleaf Pine	Oak/ Pine	Oak/ Hickory	Oak/ Gum/ Cypress	Elm/Ash/ Red Maple	Maple/ Beech/ Birch	Indeterminate/ Nonstocked	
Alabama	0	10	55	39	41	19	2	0	3	169
Georgia	1	33	54	37	37	34	1	0	2	199
North Carolina	5	3	36	24	47	15	5	3	10	148
South Carolina	0	4	33	17	29	5	2	1	5	96
Tennessee	2	0	11	11	75	5	1	2	2	109
Virginia	2	0	29	16	73	1	3	2	5	131
Total	10	50	218	144	302	79	14	8	27	852

Table 1.4. Number of condition classes by stand origin and state in the Phase 3 data set.

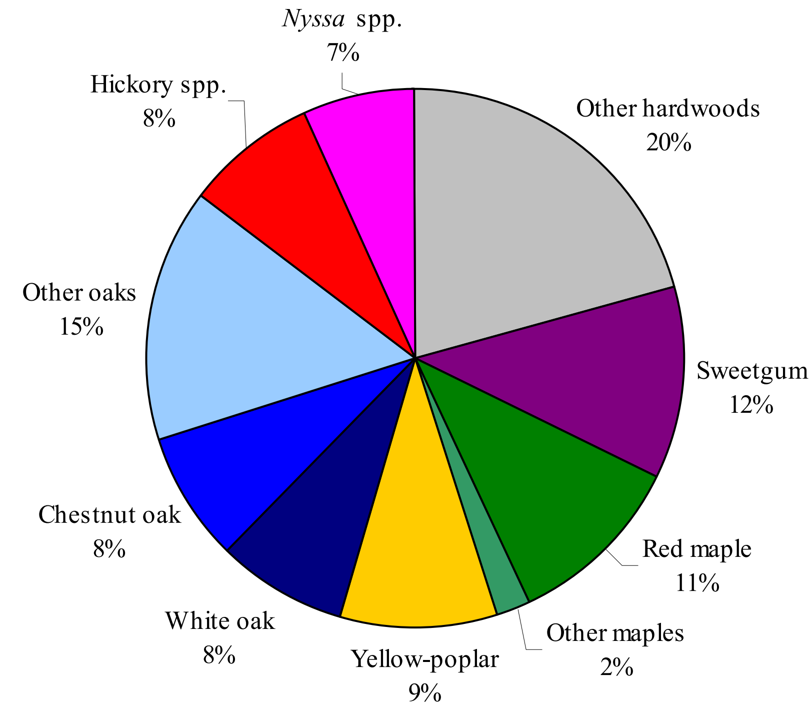
State	Stand Origin[a]		Total
	Natural Stand	Planted Softwoods	
Alabama	128	41	169
Georgia	147	52	199
North Carolina	129	19	148
South Carolina	72	24	96
Tennessee	106	3	109
Virginia	114	17	131
Total	696	156	852

[a]No plots condition classes in 'planted hardwoods.'

Table 1.5. Number of condition classes by stand size and state in the Phase 3 data set.

State	Stand Size				Total
	Sawtimber	Poletimber	Seedlings/ Saplings	Nonstocked	
Alabama	82	34	50	3	169
Georgia	75	51	71	2	199
North Carolina	89	32	23	4	148
South Carolina	41	23	28	4	96
Tennessee	58	33	17	1	109
Virginia	60	44	24	3	131
Total	405	217	213	17	852

A. Hardwoods



B. Softwoods

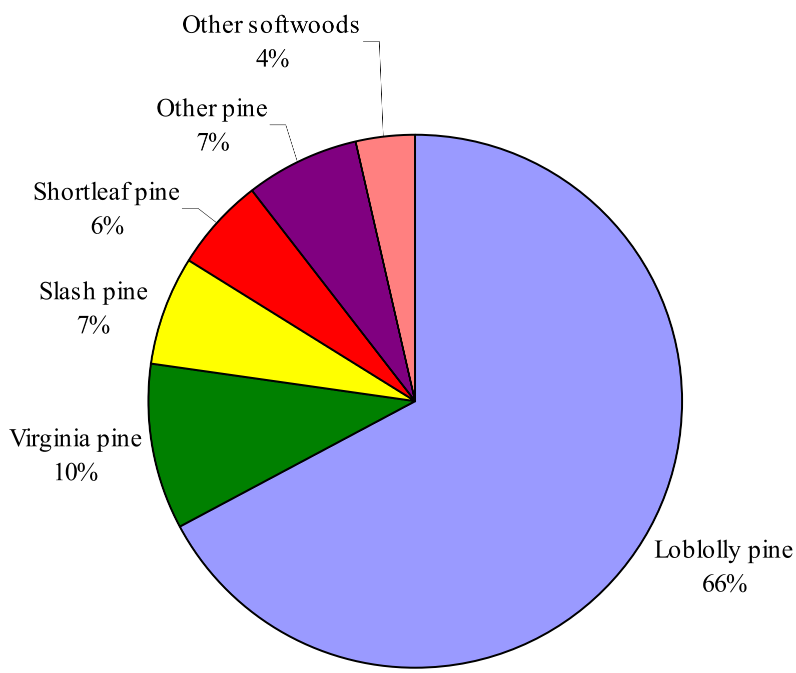


Figure 1.10. Hardwood (A) and softwood (B) species composition of the Phase 3 data set.

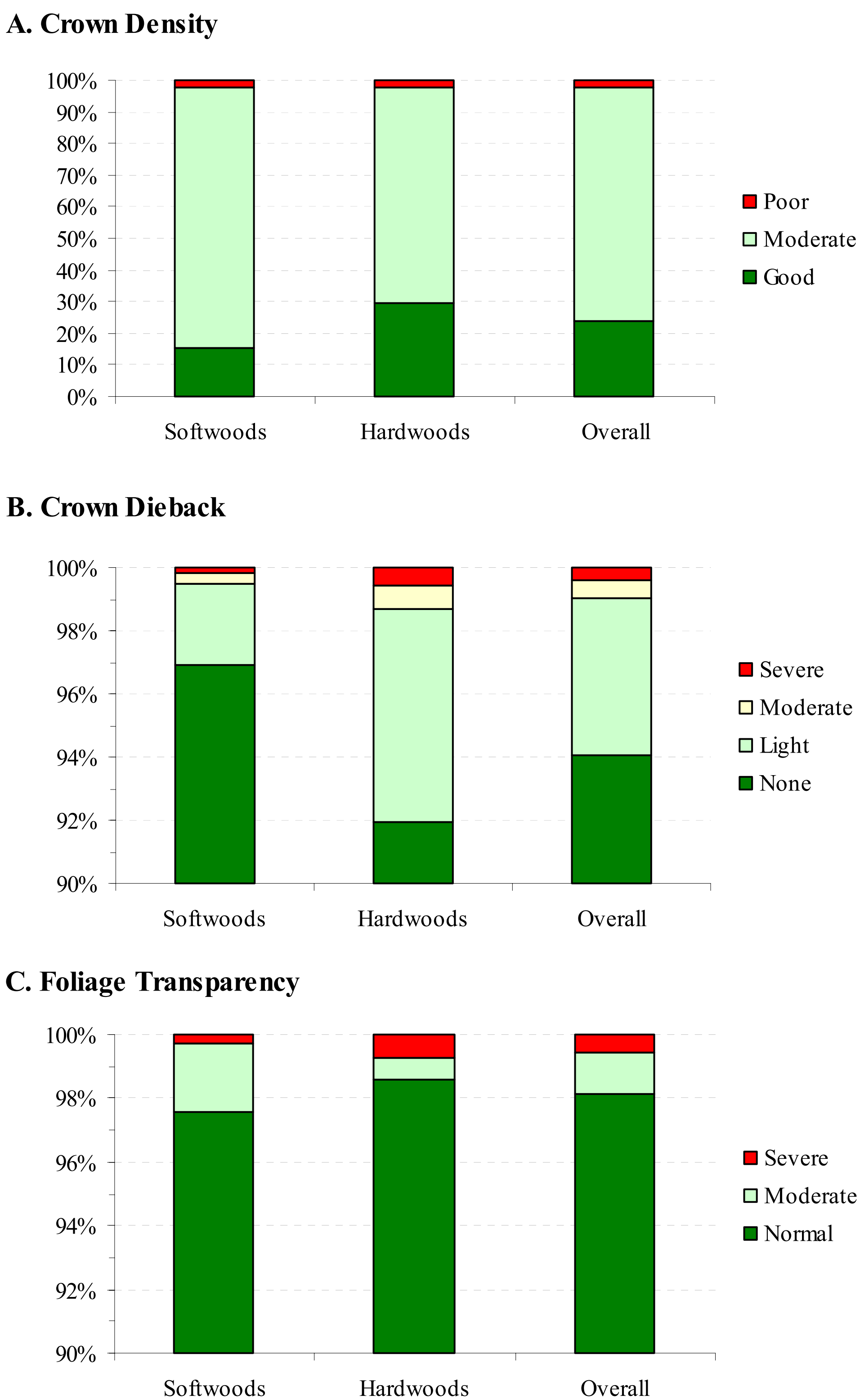


Figure 1.11. Percentage of trees in each crown condition threshold group by species group for (A) crown density, (B) crown dieback, and (C) foliage transparency.

density category; the percentage for softwoods was 15.4. For crown dieback, 99.5 percent of the hardwood trees and 98.7 percent of the softwood trees had no or light crown dieback. Normal foliage transparency was assessed for 98.6 percent of the hardwood trees and 97.6 percent of the softwood trees.

Research specific

Only the most frequent species were included in the analyses of this research. Trees missing assessments for any of the three crown condition indicators were omitted from the data set. In addition, trees occurring on plots with past disturbances and trees on subplots with missing terrain position and percent slope were omitted also. A total of 5276 trees were included in the analysis. The species selected for use were based on the number of observations available in the Quality Assurance data set; a minimum of 50 observations was set. Seven species met this requirement: slash pine (*Pinus elliottii*), loblolly pine, Virginia pine (*Pinus virginiana*), red maple, sweetgum, yellow-poplar, and white oak (*Quercus alba*). Stolte et al. 1994 suggest that a species should occur on at least 50 plots before it is considered for separate analysis. All of the selected species except slash pine and Virginia pine met this guideline.

Table 1.6 lists the forest conditions in which the seven species occurred. Red maple, sweetgum, and loblolly pine were the most ubiquitous species occurring in 33, 25, and 22 different forest types and on 139, 153, and 165 plots, respectively. Slash pine was the most confined species, occurring on only 8 forest types and 26 plots. Approximately two-thirds of the slash and loblolly pines were found in stands of planted origin, while 97 percent or more of the other species were found in natural stands. The hardwood species and Virginia pine were found mostly in sawtimber size stands. Slash pine and loblolly pine occurred mostly in poletimber stands. Terrain positions on which the seven species occurred are listed in Table 1.7. Slash pine, loblolly pine, and sweetgum were found most frequently on flatland, while Virginia pine, red maple, yellow-poplar, and white oak were found mostly on midslopes.

MQOs for the seven species during 1995, 1998, and 1999, were met for crown dieback and foliage transparency, but not for crown density (Table 1.8). Crown density

Table 1.6. Forest conditions in which the seven research specific species occurred.

Species	Number of Trees	Number of States	Number of Plots	Number of Forest Types	Stand Origin		Stand Size		
					Natural (%)	Planted (%)	Sawtimber[a] (%)	Poletimber[b] (%)	Seedling/ Sapling (%)
Slash pine	345	1[c]	26	8	36.5	63.5	20.0	69.3	10.7
Loblolly pine	2936	6	165	22	33.5	66.5	16.3	59.8	23.9
Virginia pine	225	6	41	15	100.0	0.0	59.1	35.6	5.3
Red maple	507	6	139	33	100.0	0.0	80.1	17.5	2.4
Sweet-gum	588	6	153	25	97.6	2.4	81.0	10.4	8.7
Yellow-poplar	362	6	113	23	98.1	1.9	75.7	18.0	6.3
White oak	313	6	103	24	99.7	0.3	80.5	16.3	3.2

[a]Average tree diameter ≥ 9.0 in dbh for softwoods; ≥ 11.0 in dbh for hardwoods
[b]Average tree diameter ≥ 5.0 in – 8.9 in dbh for softwoods; ≥ 5.0 in – 10.9 in dbh for hardwoods
[c]Georgia only

Table 1.7. Number of trees on each terrain position for the seven research specific species. Percentages are given in parentheses.

Species	Terrain Position[a]					
	Top and Upper Slopes	Midslope	Bench	Lower Slope	Flatland	Bottomland
Slash pine	0 (0.00)	0 (0.00)	0 (0.00)	0 (0.00)	344 (99.71)	1 (0.29)
Loblolly pine	25 (0.85)	877 (29.87)	45 (1.53)	27 (0.92)	1934 (65.87)	28 (0.95)
Virginia pine	21 (9.33)	142 (63.11)	9 (4.00)	13 (5.78)	40 (17.78)	0 (0.00)
Red maple	24 (4.73)	237 (46.75)	13 (2.56)	13 (2.56)	143 (28.21)	77 (15.19)
Sweetgum	28 (4.76)	121 (20.58)	62 (10.54)	13 (2.21)	256 (43.54)	108 (18.37)
Yellow-poplar	9 (2.49)	186 (51.38)	16 (4.42)	26 (7.18)	98 (27.07	27 (7.46)
White oak	31 (9.90)	190 (60.70)	9 (2.88)	26 (8.31)	52 (16.61)	5 (1.60)
Total	138 (2.62)	1753 (33.23)	154 (2.92)	118 (2.24)	2867 (54.34)	246 (4.66)

[a]See Figure 1.2 (page 24). No trees occurred on the wet bottomland terrain position.

Table 1.8. Percent of trees in compliance with the ±10 percent data quality limit (DQL) by species for the years 1995, 1998, and 1999. The measurement quality objective is 90 percent DQL compliance.

Species Group	Percent DQL Agreement		
	Crown Density	Crown Dieback	Foliage Transparency
Slash pine	83.3	100	100
Loblolly pine	84.3	98.9	94.9
Virginia pine	80.0	100	93.3
Red maple	68.0	96.0	96.0

DQL agreement ranged from a low of 58.6 percent for white oak to a high of 84.3 percent for loblolly pine. Four species had 100 percent DQL compliance for crown dieback while three species had 100 percent compliance for foliage transparency. For all species, crown dieback and foliage transparency DQL agreement was 93 percent or greater. According to the current thresholds, the majority of the tree crowns for these seven species were apparently healthy (Figure 1.12). The species were most similar for crown dieback where no or light dieback was recorded for at least 98 percent of the trees. Foliage transparencies were normal for 98 percent or more of every species except Virginia pine. Virginia pine had the fewest trees in the normal category at 89.8 percent. The greatest differences among the species occurred in crown density. Slash pine had the fewest trees in the good category with 4.6 percent. Yellow-poplar had the greatest number of trees in the good category with 38.4 percent. Correspondingly, slash pine had the greatest number of trees in the moderate category (93.6 percent) and yellow-poplar had the fewest trees (61.3 percent). Virginia pine had the greatest amount of poor crown densities with 7.6 percent.

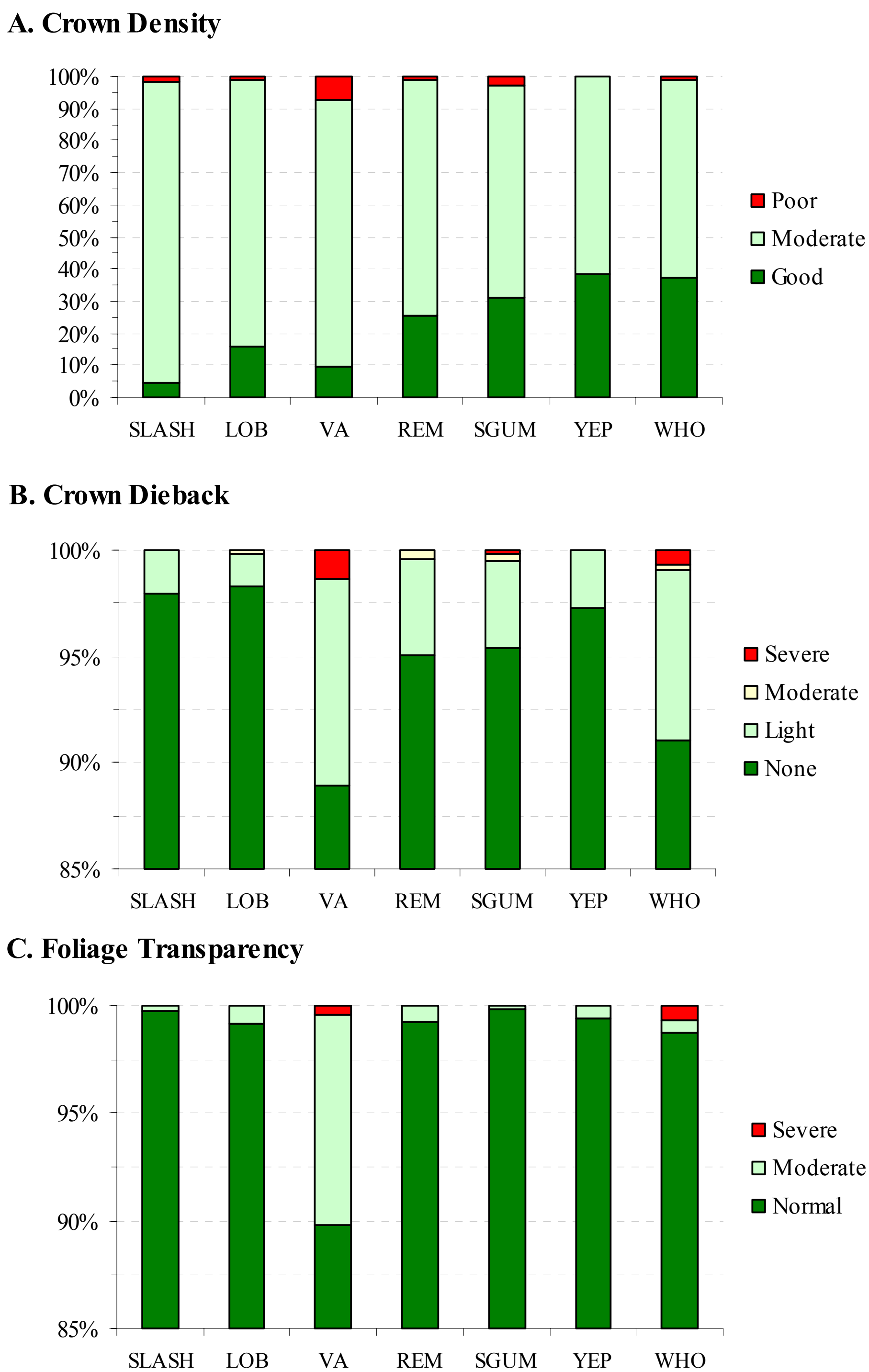


Figure 1.12. Percentage of trees in each crown condition threshold group by species for (A) crown density, (B) crown dieback, and (C) foliage transparency. SLASH=slash pine. LOB=loblolly pine. VA=Virginia pine. REM=red maple. SGUM=sweetgum. YEP=yellow-poplar. WHO=white oak.

CHAPTER II

INTER-OBSERVER VARIATION IN VISUAL ASSESSMENTS OF TREE CROWN DENSITY

Introduction

Tree crowns have been used worldwide as indicators of forest health because it is generally felt that tree health and vigor are reflected in the crown condition (Anderson and Belanger 1987, Innes 1993). The USDA Forest Service Forest Inventory and Analysis (FIA) Program utilizes visual assessments of tree crowns, specifically crown density, crown dieback, and foliage transparency, to accomplish in part the forest health monitoring mission of reporting the long-term status, changes, and trends in forest ecosystem health in the United States (USDA Forest Service 1994).

Visual assessments of tree crowns are quick, easy to perform, and cost-effective, but there are concerns regarding the reliability of such data. Several factors influence an observer's ability to make reliable visual assessments. The most oft noted factor affecting reliability is the amount of training and experience of the observer (Caro et al. 1979, Innes 1988b, Valentine and Ismail 1983, Gertner and Köhl 1995, Mitchell 1979). Other factors influencing observer bias include the clarity of the definition of the characteristic to be assessed (Caro et al. 1979), light conditions under which the assessments are made (Innes 1988b), stage of development of the stand (Gertner and Köhl 1995), and the dimensions of the tree crown itself (Metzger and Oren 2001).

Observer bias reduces data quality and may lead to incorrect conclusions about the health of the forest. For example, patterns across time and space that exist in the data may not be due to actual differences in tree health but rather due to biases of regional field crews (Strand 1996, Innes 1988b) or the result of changes in survey teams (Strand 1996). It is important, therefore, to quantify the bias present in visual assessments and, if possible, take corrective action. To address observer bias and other data quality issues within its program, FIA implements a Quality Assurance (QA) plan to ensure that data is collected with sufficient quality to meet the needs of data users, policy makers, and the public (USDA Forest Service 1998).

Implementation of the forest health monitoring QA plan involves several activities (USDA Forest Service 1998). At the beginning of each field season, regional trainers meet for pre-training in which they calibrate their assessments to assure national comparability of training. Following the pre-training session, trainers lead regional sessions for the field crews. Field crew performance is evaluated throughout the training session and culminates with a test for certification to collect data. Certified field crews then are audited within the first three weeks of the field season through an interactive session with an auditor known as "hot checks" (Pollard and Smith 1999). Retraining and retesting, if necessary, are done at this time. Later in the field season "cold checks" are performed. That is when the field crew's work is checked without its knowledge by a national or regional "expert" auditing crew. After the field season, QA data are compiled and summarized into QA reports that detail the achievement of QA objectives for the year (e.g., Pollard and Smith 2001, 1999).

Recent QA reports indicate that the measurement quality objective (MQO) for crown density is not being met (Pollard and Smith 2001, 1999). FIA defines crown density as the amount of crown branches, foliage, and reproductive structures that blocks light visibility through the crown (USDA Forest Service 1999). Visual assessments of crown density are made on trees at least 5.0 inches in diameter. Crown density is recorded in five percent increments from 0 to 100, with high values indicating the most dense, i.e. most healthy, crowns. Deductions are made from the maximum possible crown density for spaces between branches and other large openings in the crown (Figure 2.1). MQO for crown density is set at 90 percent $\pm$ 10 percent. That is, field crew assessments must be within the $\pm$ 10 percent data quality limit (DQL) for at least 90 percent of all trees. The purpose of this paper is to evaluate the quality of the crown density indicator. The appropriateness of the current MQO is discussed and suggestions for improvement are provided. Additionally, the results of a regression analysis attempting to predict the expected difference between field crew and audit crew assessments are reported.

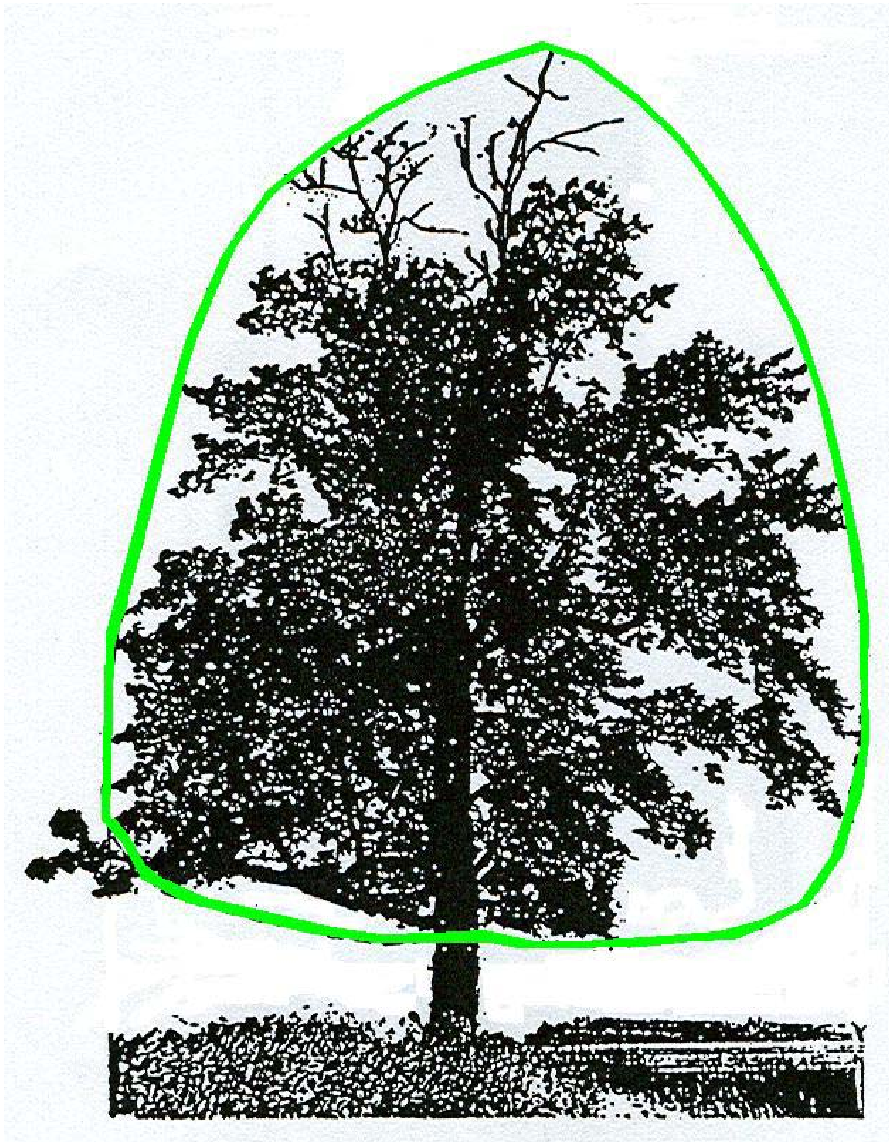


Figure 2.1. The solid line shows the crown outline for determining crown density. Large openings within the crown outline and gaps between the branches reduce the crown density rating. Crown density for this tree is 60 percent (Millers et al. 1992).

Methods

The data utilized in this study came from all QA cold checks implemented on FIA Phase 3 (formerly Forest Health Monitoring detection monitoring) plots between 1991 and 1999 in Alabama, Georgia, North Carolina, South Carolina, Tennessee, and Virginia (Table 2.1). The data included 1294 trees; 59.5 percent hardwoods and 40.5 percent softwoods. The most frequent species were loblolly pine (24.4 percent), sweetgum (11.3 percent), slash pine (5.9 percent), and white oak (5.3 percent) (Figure 2.2).

Deviations between the field crew and audit crew assessments were calculated for each tree as

$$CD_{diff} = \text{Field crew's crown density} - \text{Audit crew's crown density.}$$

Trees with missing observations for either crew were omitted. It should be noted that CD_{diff} is not a true measure of bias because the true crown density is unknown. Rather it is a measure of the uncertainty in the data. Solberg and Strand (1999) refer to CD_{diff} as a measure of precision, i.e. the way in which repeated measurements conform to themselves.

Regression Analysis

Regression analysis was used to develop a model capable of predicting CD_{diff}. Explanatory variables used to model CD_{diff} were the field crew's measurements of crown density (DEN), crown dieback (DBK), foliage transparency (FT), live crown ratio (LCR), and diameter at breast height (DBH); the number of live trees on the corresponding subplot for each observation (LT); the number of years the observation's corresponding state was included in the QA data set (YRS); and indicator variables for species group (softwood or hardwood) and state. Alabama had the smallest average CD_{diff} and was selected as the base state for the indicator variables, which were defined as follows:

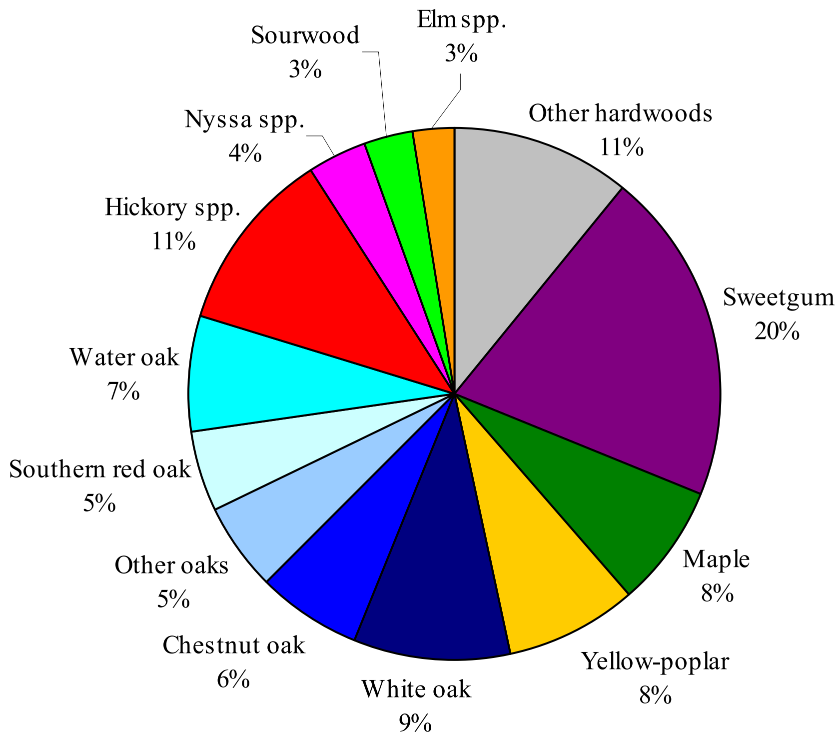
state1 = 1 if Georgia, 0 otherwise;
state2 = 1 if North Carolina, 0 otherwise;
state3 = 1 if South Carolina, 0 otherwise;
state4 = 1 if Tennessee, 0 otherwise; and
state5 = 1 if Virginia, 0 otherwise.

Table 2.1. Number of FIA Phase 3 cold check plots assessed for quality assurance by year and state.

State	Year						Total
	1991	1992	1994	1995	1998	1999	
Alabama	12	5	0	0	2	2	21
Georgia	6	6	3	1	2	0	18
North Carolina	---[a]	---	---	---	5	3	8
South Carolina	---	---	---	---	3	0	3
Tennessee	---	---	---	---	---	3	3
Virginia	4	4	0	0	3	2	13
Total	22	15	3	1	15	10	66

[a]No Phase 3 plots established in the state.

A. Hardwoods



B. Softwoods

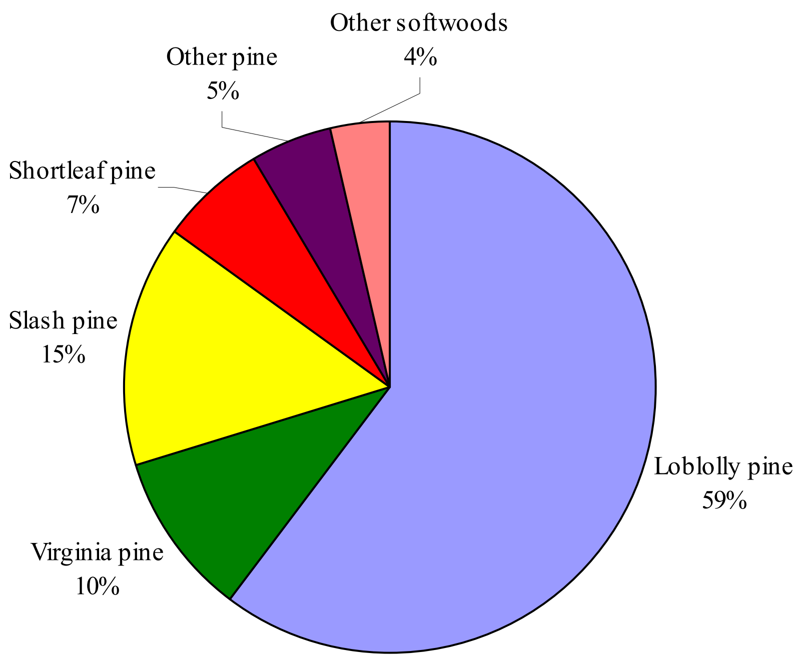


Figure 2.2. Species composition of the quality assurance data set. (A) Hardwoods. (B) Softwoods.

YRS was used as a surrogate for year of assessment because the intent was to use the resulting model to predict CD_{diff} for trees measured in years not included in the QA data set.

Trees with missing observations for one of the crews, a crown density of 0 percent, and/or diameters exceeding the diameter MQO were excluded from the analyses. In addition, 13 outliers were identified and removed leaving a total of 1240 trees to predict CD_{diff}. Audit crew crown densities are plotted against the field crew crown densities in Figure 2.3. Ten percent of these trees were set aside as a validation data set. Regression analysis was performed with the SAS statistical software procedure REG (SAS Institute Inc., Cary, NC). Table 2.2 gives the combinations of independent variables used to predict CD_{diff}. Models 1 and 2 were run as baseline models to establish the amount of variation accounted for by the state and non-state variables alone. Then the all-possible regressions approach was used to select the best subsets of independent variables. Based upon the R-square criterion, Model 3 was the best subset from the non-state variables; Models 4 and 5 the best subsets from all independent variables.
Higher order models including interactions among the independent variables were also considered. These models performed no better than those presented here and subsequently are not included in this discussion.

Results and Discussion

Data Quality

Summaries of CD_{diff} show that the crown density MQO was not met in any year (Figure 2.4). The proportion of trees within the DQLs ranged from a low of 68.2 percent in 1998, to a high of 88.1 percent in 1995. Overall, only 75 percent of the trees met the DQL. On average the audit crews assessed crown density 3.9 percent lower than the field crews. Standard deviation of CD_{diff} was 10.98 percent. The Pearson correlation coefficient for field crew crown density versus audit crew crown density was 0.54, and the Kappa statistic was 0.34. The Kappa statistic is an alternate measure of association or correlation for categorical measurements. In general, a Kappa statistic less than 0.4

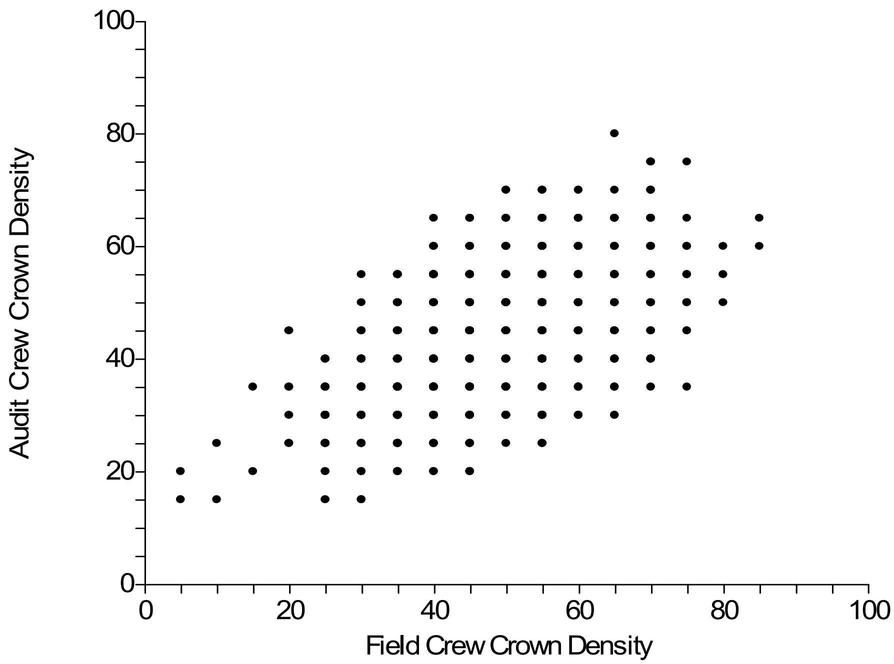


Figure 2.3. Audit crew and field crew crown densities (%) in the regression analysis data set.

Table 2.2. R-square values for the models used to predict CD_{diff}. See text for variable definitions.

Model Number	Regression R^2	Regression Adjusted R^2	Regression Press R^2	Validation R^2	Variables in Model[a]
1	0.0537	0.0494	0.0440	---	state1, state2, state3, state4, state5
2	0.3336	0.3288	0.3229	---	DBH, DBK, DEN, FT, LCR [b], LT [b], SPG [b], YRS [b]
3	0.3319	0.3289	0.3248	0.4265	DBH, DBK, DEN, FT, LT
4	0.3520	0.3461	0.3392	0.4581	DBH, DBK, DEN, FT, LCR, state1, state2, state3[b], state4, state5 [b]
5	0.3493	0.3440	0.3377	0.4675	DBH, DBK, DEN, FT, state1, state2, state3 [b], state4, state5 [b]

[a]all models include an intercept

[b]not significant $\alpha = 0.05$

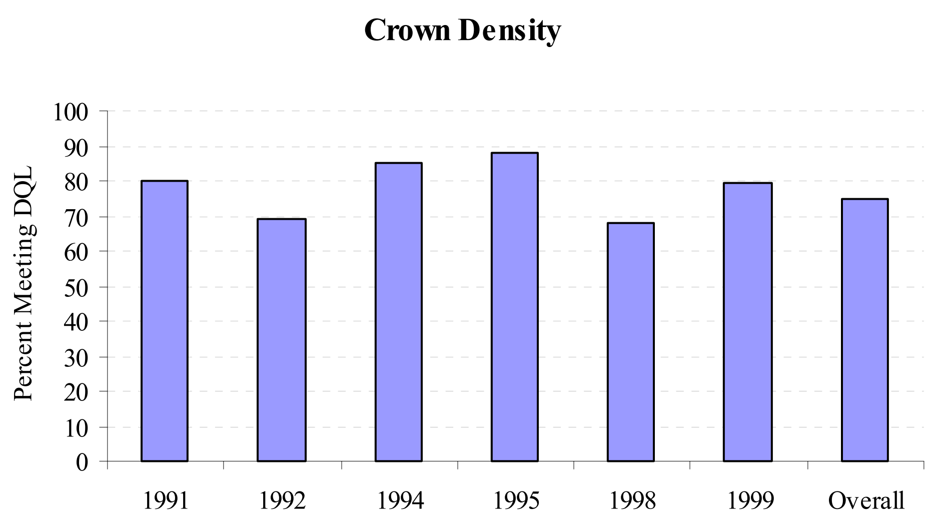


Figure 2.4. Percent of the crown density observations meeting the ±10 percent data quality limit (DQL) by year. The measurement quality objective is 90 percent.

indicates low association between two measurements of the same individual (Stokes et al. 2000). CD_{diff} was five percent or less for 55.3 percent of the trees, and was 15 percent or less for 87.6 percent of the trees. These figures are similar to those reported by Solberg and Strand (1999) for Norway spruce (*Picea abies*) trees. They studied the differences in crown density assessments between regular forest officers and those in charge of the national forest health monitoring training courses in Norway. They reported a correlation coefficient of 0.56 between the two sets of observers, and found that on average the training officers assessed crown density 1.4 percent lower than the regular forest officers; standard deviation of CD_{diff} was 13.5 percent. CD_{diff} was less than five percent for 45 percent of their trees and less than 15 percent for 82 percent.

Variations in DQL agreement were found among states, between species groups, and across the levels of crown density. DQL agreement was lowest in Georgia at 70.6 percent and highest in Alabama at 81.8 percent (Figure 2.5). A chi-square test indicated the differences among the states were significant at the 95% level (p-value=0.0149). DQL agreement was also significantly different between the hardwood and softwood species groups (chi-square test p-value=0.0016); agreement was higher for softwoods (79.6 percent) than for hardwoods (71.8 percent). Across the levels of crown density, DQL agreement was greatest in the middle of the distribution (Figure 2.6). DQL agreement was 70 percent or greater for crown densities between 25 and 55 percent, as well as for a single tree with crown density of 0 percent. DQL achievement was poorest for the extreme crown densities, i.e., less than 25 percent and greater than 60 percent. This coincides with the rarest crown densities. Only 22 percent of the trees assessed had crown densities in this range. The crown densities with the highest DQL attainment, those between 30 and 50 percent, made up 61 percent of the trees assessed. This is consistent with the notion that inter-observer agreement rates vary for rare and common events, in that uncommon events or occurrences are less reliably measured (Caro et al. 1979).

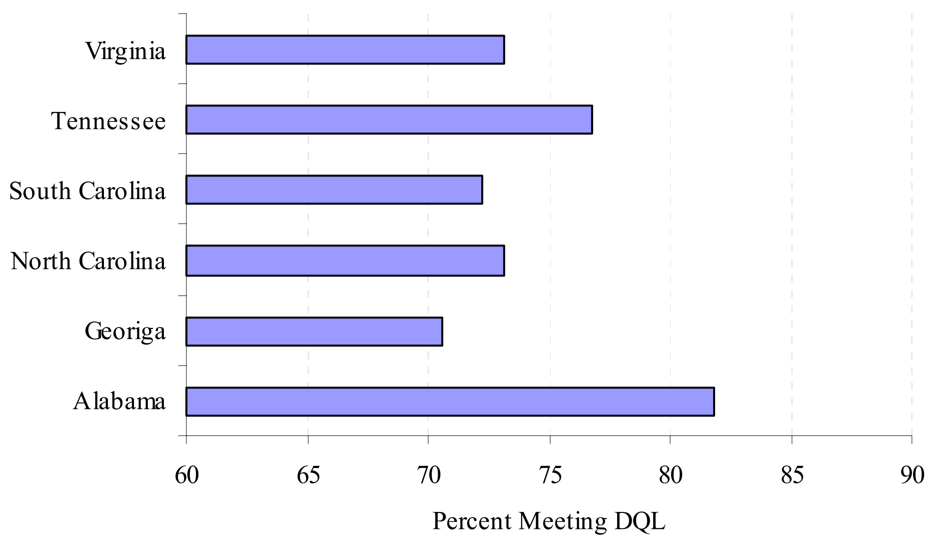


Figure 2.5. Percent of the crown density observations within the ±10 percent data quality limit (DQL) by state. The measurement quality objective is 90 percent.

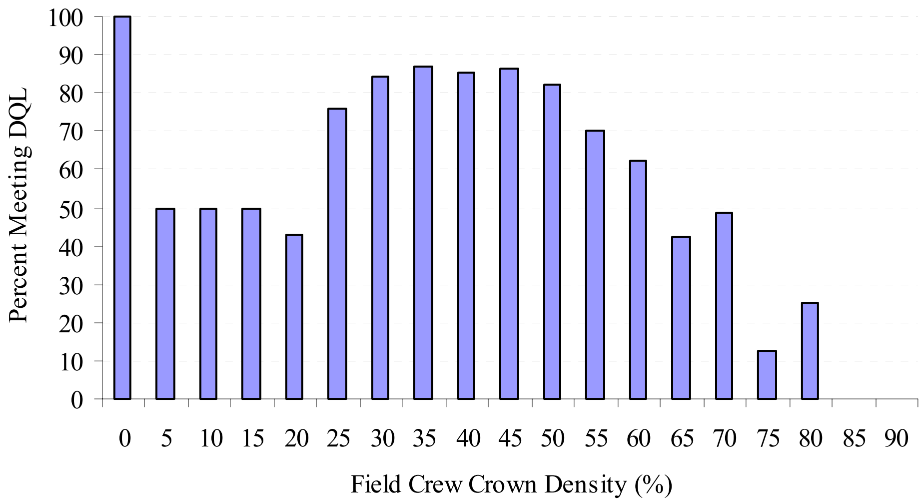


Figure 2.6. Percent of the crown density observations within the ±10 percent data quality limit (DQL) by field crew crown density. The measurement quality objective is 90 percent.

Regression Analysis

Models 3, 4, and 5 were applied to the holdout validation data set, and selection of the preferred model was based on R-square values for the regression and validation samples, with preference given to the highest validation R-square value. R-square values among the models were comparable (Table 2.2, page 53). Model 4 had the highest regression R-square value, 0.3520. Model 5, however, had the highest validation R-square value (0.4675) and was selected as the preferred model. The robust regression procedure in the Number Cruncher Statistical System software (NCSS Statistical Software, Kaysville, UT) improved the fit of Model 5, increasing the regression R-square value to 0.4035 and the validation R-square value to 0.5308 (Table 2.3). The robust regression version of Model 5 was selected to predict CD_{diff}:

$$CD_{diff} = -21.9123 + 0.0815*DBK + 0.5196*DEN - 0.3304*DBH + 0.0936*FT + 3.5644*state1 + 3.4143*state2 + 1.9106*state3 + 4.4761*state4 + 1.5265*state5.$$

Validation R-square values indicated the model performed best for Alabama and Georgia (Table 2.3). Despite its effectiveness in the regression stage, model performance for the Tennessee validation sample was marginal, possibly a consequence of the small sample size.

All explanatory variables except state3 were significant at the $\alpha = 0.05$ level. Lack of significance for state3 indicated that for any given level of DBK, DEN, DBH, and FT, CD_{diff} for South Carolina and Alabama were not significantly different. The coefficients for the other state variables indicated that CD_{diff} were significantly different between Alabama and all other states. For any given levels of DBK, DEN, DBH, and FT Alabama CD_{diff} were approximately 1.5 percent less than Virginia, 3.5 percent less than Georgia and North Carolina, and 4.5 percent less than Tennessee. DBH had the only negative coefficient implying that as trees grow larger CD_{diff} decreases. Unit increases in all other variables result in increases in CD_{diff}.

Graphical residual analyses indicated that the linear function was appropriate for these data and that the error variance was constant (Figure 2.7); however, the magnitude of the mean residuals varied among species. Absolute residual means for the seven most frequent species ranged from a low of 4.6 percent for slash pine to a high of 7.8 percent

Table 2.3. Regular and robust regression R-square values for Model 5.

	Regression R^2		Regression	Validation R^2		Validation
	Regular	Robust	*n*	Regular	Robust	*n*
Alabama	0.2811	0.2809	308	0.5737	0.5733	34
Georgia	0.3456	0.3457	346	0.3503	0.3520	40
North Carolina	0.3862	0.3830	127	0.1658	0.1715	14
South Carolina	0.2832	0.2857	30	----	---	3
Tennessee	0.5581	0.5547	59	0.0955	0.0717	7
Virginia	0.2095	0.2090	246	0.4110	0.4140	26
Overall	0.3493	0.4035	1116	0.4675	0.5308	124

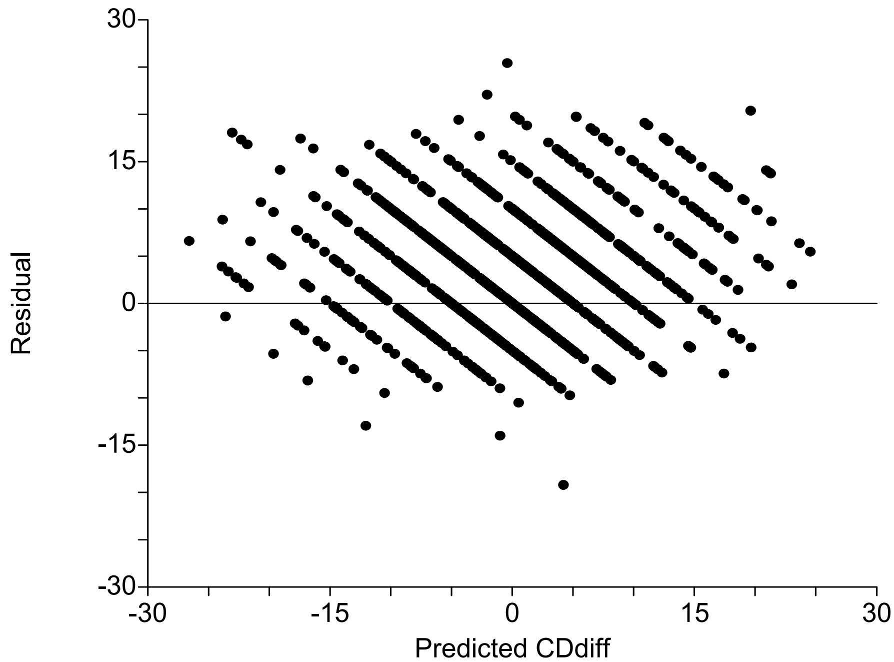


Figure 2.7. Residuals versus predicted crown density differences (CD_{diff}).

for yellow-poplar (Table 2.4). Of these seven species, three occurred in all six states: loblolly pine, sweetgum, and white oak. A plot of the absolute residual means by species and state suggests a species*state interaction (Figure 2.8).

A potential application of this model would be to calculate MQO performance for all trees in a Phase 3 data set. In this instance, some margin of error is acceptable in the CD_{diff} predictions for individual trees. To gauge this model's ability to adequately predict MQO performance, predicted CD_{diff} were rounded to the nearest five percent and the percentage no greater than 10 percent was calculated. The model predicted a 91.2 percent DQL agreement for all observations; 88.5 percent for hardwoods and 96.3 percent for softwoods. These percentages are much greater than those observed, and assert that crown density MQO is achieved. As a further check, Model 5 was applied to three years of FIA Phase 3 data and similar findings resulted i.e., the MQO is purportedly realized (Table 2.5). Figure 2.9 illustrates how the model fails to capture the variability of CD_{diff}, especially for the extreme cases. Considering the range of inter-crew variation for any given level of crown density (Figure 2.3, page 52), it is not surprising that the CD_{diff} are less than desirable. An interesting note, however, is that the model reflects the pattern of DQL agreement across years. That is, the year with poorest observed DQL agreement year is also the year with the poorest predicted DQL agreement.

Given its failure to adequately capture the variability in the QA data as well the potential for species and state interactions, Model 5 is not recommended for future use. The range of inter-crew variation for any given level of crown density is too great for simple modeling. Other methods, such as principle components and cluster regression, were applied but with no success. Further study into the inter-crew variability of crown density would be profitable, however, much larger sample sizes are necessary to address specific issues such as the presence of state*species interactions.

Table 2.4. Absolute residual means and standard errors for the seven most frequent species.

Species	N	Mean	Standard Error
Slash Pine	75	4.6198	0.5015
Loblolly Pine	307	5.8835	0.2624
Virginia Pine	49	5.3993	0.6524
Red Maple	46	6.1047	0.7726
Sweetgum	140	7.1206	0.4749
Yellow-poplar	53	7.8468	0.7619
White Oak	64	7.4803	0.6799

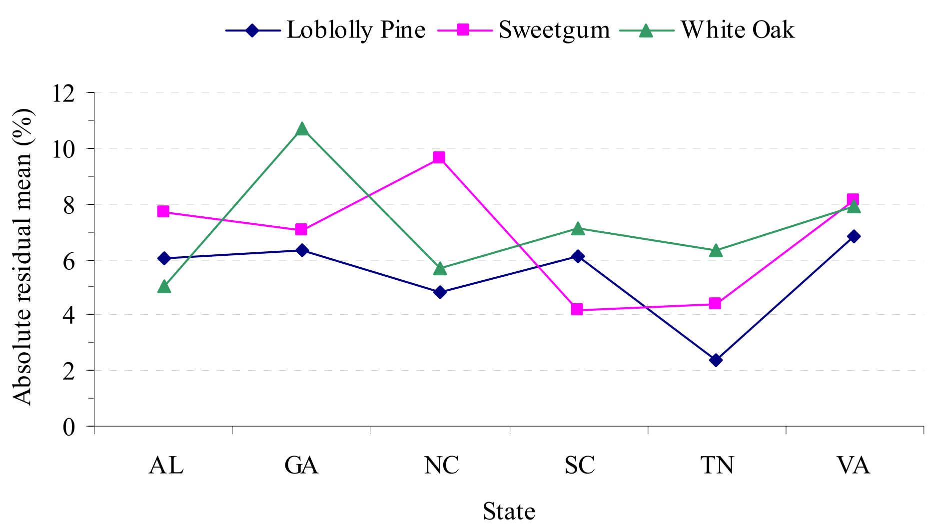


Figure 2.8. Absolute residual means by state for loblolly pine, sweetgum, and white oak.

Table 2.5. Comparison of the observed and predicted proportion of trees within the ± 10 percent data quality limit (DQL). The measurement quality objective is 90 percent within the DQL.

Year	QA Cold Check Plots Observed percent within the DQL	 Predicted percent within the DQL	Phase 3 Plots Predicted percent within the DQL
1995	88.2	100	94.4
1998	68.4	88.0	91.8
1999	79.2	95.7	97.2
Overall	74.4	92.1	94.9

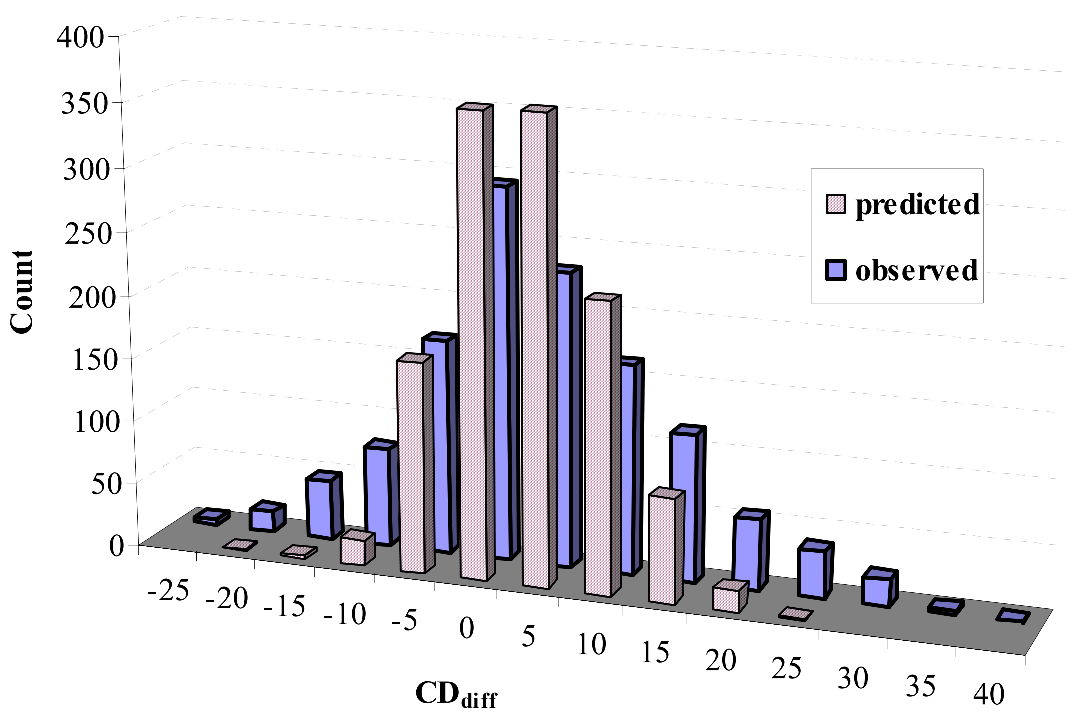


Figure 2.9. Distribution of the observed and (rounded) predicted crown density differences (CD_{diff}).

Conclusion

Between 1991 and 1999, crown density consistently failed to meet the MQO set forth in the FIA QA plan. During this time, percent DQL agreement varied by year, state, and species group, and any conclusions about the status of forest health which were based, either in part or in whole, on crown density are suspect due to the unreliability of the data. An attempt to predict inter-crew differences in the crown density assessments was unsuccessful, and the resulting linear regression model is not recommended.

Despite the apparent problems with repeatability, crown density continues to be measured and utilized as an indicator of forest health. FIA Phase 3 training session schedules are already full and with limited time and personnel it is not feasible to increase the length of training. A shift in how the training is conducted, however, could improve data quality if, for example, emphasis is placed on correctly rating very sparse and very dense crowns.

Ferretti et al. (1999) suggest that the most reproducible assessments are those with fewer rating classes. A second possible remedy to the poor data quality, then, would be to increase the width of the crown density classes. That is, record crown density in ten percent increments instead of in five percent increments as is currently done. Doing so would cut the number of classes in half and likely improve the repeatability of measurement. A third option would be to keep the rating classes as they are and alter the MQO. If the MQO had been 90 percent within $\pm$ 15 percent, then the crown density MQO would have been met in four out of the six years presented here. Likewise the MQO could be changed to 80 percent within $\pm$ 10 percent. In this instance, three out of the six years would have achieved MQO. Relaxing the MQO, however, does not improve the quality of the data *per se*, it simply alters the level of uncertainty considered acceptable. Along these lines Taylor (1988) argues that data quality objectives should not be based on the perceived capability of the measurement system. Instead, they should reflect the level of uncertainty considered tolerable for decision-making. Thus, changes to the MQO must be made in light of how crown density is to be used.

Perhaps the best way to improve crown density assessments is to make use of advancing digital imaging and remote sensing technologies. Current research is exploring the feasibility of digital imagery, light detection and ranging (lidar), and laser imaging in forestry applications: Clark et al. (2004) illustrate the use of digital images to assess crown density and foliage transparency in the Urban Forest component of the Forest Health Monitoring Program. Henning and Radtke (2003) explore the capability of a ground based three-dimensional laser imaging device to measure canopy related parameters. Popescu et al. (2003) and Leckie et al. (2003) demonstrate the ability to isolate and measure individual trees using remotely sensed lidar data. Methods such as these provide more precise estimations of tree crown characteristics and give a more complete representation of the forest as a whole. As emerging technologies, these methods still have practical and theoretical problems to overcome, but their potential usefulness is evident. Their use for measuring tree crown conditions on the FIA Phase 3 plots should be investigated.

In closing, inter-crew variations in the assessment of crown density are only significant if the biological interpretation from the data is affected. Nicholas et al. (1991) suggest that field measurements with repeatability of only 75-80 percent throw considerable doubt onto the validity of conclusions drawn from such data. Overall repeatability of the data presented here was estimated at 75 percent, and a chi-square test on the number of trees in each health category found significant differences among the field and audit crews (Table 2.6). Consequently, it may be argued that the inter-crew variation in these data is influencing conclusions about forest health. Considerable efforts are needed to improve the reliability of the crown density measure because in the words of Nicholas et al. (1991) “collection of nonrepeatable data is wasted effort.”

Table 2.6. Number of trees in each crown density condition category as assessed by the audit and field crews. Chi-square test p-value < 0.0001.

Field Crew	Audit Crew			Total
	Poor	Moderate	Good	
Poor	3	5	1	9
Moderate	7	729	82	818
Good	3	270	194	467
Total	13	1004	277	1294

CHAPTER III

INTERSPECIES VARIATION IN THREE CROWN CONDITION INDICATORS FOR SEVEN TREE SPECIES IN THE SOUTHEASTERN UNITED STATES

Introduction

Visual assessment of tree crowns has been used worldwide to measure forest health because it is generally felt that tree health and vigor are reflected in the crown condition (Anderson and Belanger 1987, Innes 1993). The size and shape of tree crowns affects the amount of carbohydrates produced by a tree, and therefore can have a major effect on the amount and quality of wood produced (Biging and Gill 1997). The USDA Forest Service Forest Inventory and Analysis (FIA) Program utilizes visual assessments of tree crowns, specifically crown density, crown dieback, and foliage transparency, to accomplish in part the forest health monitoring (FHM) mission of reporting the long-term status, changes, and trends in forest ecosystem health in the United States (USDA Forest Service 1994).

The general literature suggests that differences in crown form may be attributed to physiological factors such as epinastic control (Oliver and Larson 1996), flowering and seed production (Gross 1972, Remphrey et al. 1987), and shade tolerance (Sterck et al. 2001, Oliver and Larson 1996); as well as environmental factors like light availability and intensity (King and Maindonald 1999, Oliver and Larson 1996), elevation (Kuuluvainen and Sprugel 1996), and moisture availability (Oliver and Larson 1996). The FHM literature also acknowledges the existence of differences among species (Bechtold et al. 2002, USDA Forest Service 2002a, Millers et al. 1992), but there is no description of how or to what extent crown dieback, crown density, and foliage transparency actually vary among species. Therefore, it is not known for purposes of analysis and interpretation of the crown condition data whether species should be considered individually or collectively. The purpose of this paper is to evaluate and describe the interspecies variation in crown dieback, crown density, and foliage transparency for seven tree species in the southeastern United States.

Methods

Data Description

This study utilized four years of data from all FIA Phase 3 (formerly Forest Health Monitoring detection monitoring) plots in Alabama, Georgia, North Carolina, South Carolina, Tennessee, and Virginia. Data were collected in 1995, 1997, 1998, and 1999, but only the most recent measurement for each plot was utilized. The species included in the analyses are seven of the most frequent species in the South: slash pine (*Pinus elliottii*), loblolly pine (*Pinus taeda*), Virginia pine (*Pinus virginiana*), red maple (*Acer rubrum*), sweetgum, (*Liquidambar styraciflua*), yellow-poplar (*Liriodendron tulipifera*), and white oak (*Quercus alba*).

Each FIA Phase 3 plot is cluster of four 1/24-acre circular subplots with subplot centers located 120 feet apart. On each plot a set of indicators is assessed to characterize forest health. These indicators range from overall site assessments to measurements taken on individual trees. Of primary interest for the research herein are the tree crown condition indicators, specifically (USDA Forest Service 1999):

- Crown density – The amount of crown branches, foliage, and reproductive structures that blocks light visibility through the crown; measured as the percent of total light that is blocked by tree material.
- Crown dieback – Recent mortality of branches with fine twigs, which begins at the terminal portion of a branch and proceeds toward the trunk; measured as the percent of branch tips that are dead.
- Foliage transparency – The amount of skylight visible through the live, normally foliated portion of the crown; measured as the percent of total light that would be visible if the light were unblocked.

Crown density and foliage transparency are similar measures of the amount of light penetrating the crown, but they are not exact inverses. Crown density measures the amount of sunlight *blocked* by all plant material (both live and dead) in the crown, whereas foliage transparency measures the amount of sunlight *penetrating* the *live* portion of the crown. Deductions are made from the maximum possible crown density for spaces between branches and other large openings in the crown (Figure 3.1).

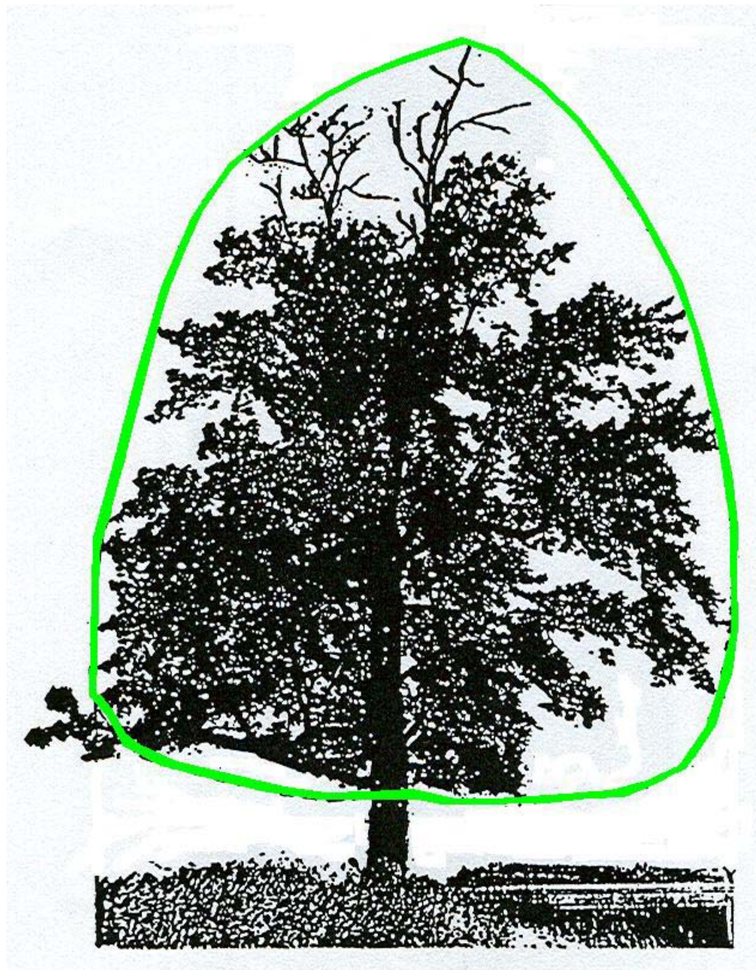


Figure 3.1. The solid line outlines the crown for determining crown density. Large openings within the crown outline and gaps between the branches reduce the crown density rating. Crown density for this tree is 60 percent (Millers et al. 1992).

Foliage transparency, however, is not penalized for large gaps in the crown. Increases in the foliage transparency rating are made only for small openings in areas where foliage is expected to occur (Figure 3.2).

Visual assessments of crown density, crown dieback, and foliage transparency are made on all live trees at least 5.0 inches in diameter. Crown density is estimated as the amount of light being blocked by the crown of the survey tree compared to the amount blocked in a full, dense crown for a tree with the same crown form. Foliage transparency is estimated by comparing the survey tree crown to the scale provided in the FIA field guide (Figure 3.3). Only dieback in the upper and outer portions of the crown is taken into account during assessment of crown dieback. All three indicators are recorded in five percent increments from 0 to 100. Low values are desirable for crown dieback and foliage transparency. High values are desirable for crown density. FIA Phase 3 plots are assessed during the summer when trees maintain full crown foliage, typically between June and mid-August for plots in the South. Current details about the complete collection methods and techniques of Phase 3 data may be found in the FIA national core field guide (USDA Forest Service 2002a).

Trees missing assessments for any of the three crown condition indicators were omitted from the data set. In addition, trees occurring on plots with past disturbances and trees on subplots with missing terrain position and percent slope were omitted also. A total of 5276 trees were included in the analysis. Table 3.1 gives the number of trees by species as well as a summary of the forest conditions in which the seven species occurred. Red maple, sweetgum, and loblolly pine were the most ubiquitous species occurring in 33, 25, and 22 different forest types and on 139, 153, and 165 plots, respectively. Slash pine was the most confined species, occurring on only 8 forest types and 26 plots. Approximately two-thirds of the slash and loblolly pines were found in stands of planted origin, while 97 percent or more of the other species were found in natural stands. The hardwood species and Virginia pine were found mostly in sawtimber size stands. Slash pine and loblolly pine occurred mostly in poletimber stands. Crown form and leafing characteristics for each species are given in Table 3.2.

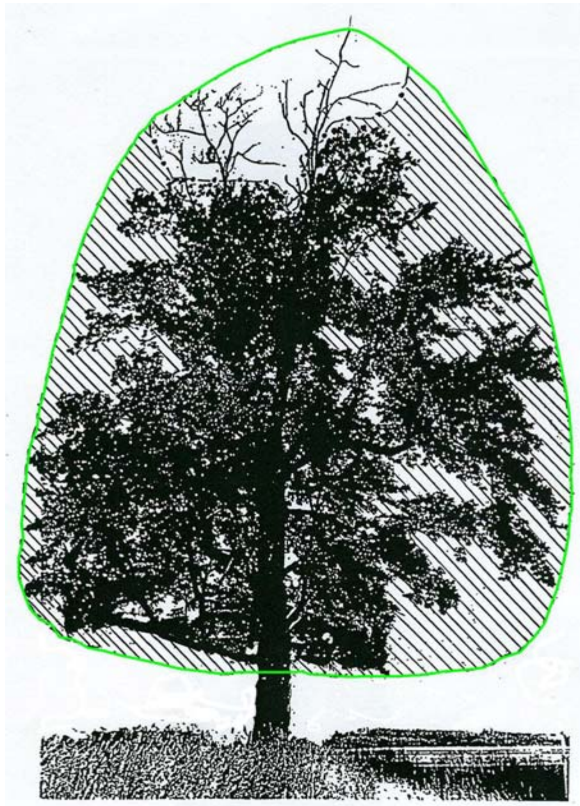


Figure 3.2. Striped areas indicate open areas of the crown where foliage is not expected to occur. Foliage transparency in the live portion of the crown is 15 percent (Millers et al. 1992).

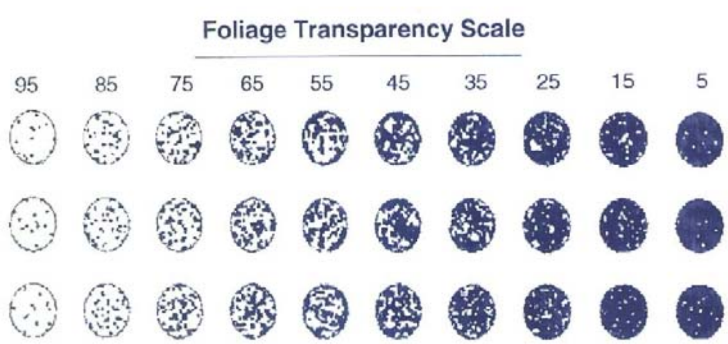


Figure 3.3. Scale used to evaluate foliage transparency (USDA Forest Service 1999). Dark areas represent foliage and white areas represent skylight visible through the crown. The amount of skylight penetrating the survey tree crown is compared to the scale and foliage transparency is rated according to the numbers above the circles.

Table 3.1. Forest conditions in which the seven species occurred.

Species	Number of Trees	Number of States	Number of Plots	Number of Forest Types	Stand Origin		Stand Size		
					Natural (%)	Planted (%)	Sawtimber[a] (%)	Poletimber[b] (%)	Seedling/ Sapling (%)
Slash pine	345	1[c]	26	8	36.5	63.5	20.0	69.3	10.7
Loblolly pine	2936	6	165	22	33.5	66.5	16.3	59.8	23.9
Virginia pine	225	6	41	15	100.0	0.0	59.1	35.6	5.3
Red maple	507	6	139	33	100.0	0.0	80.1	17.5	2.4
Sweetgum	588	6	153	25	97.6	2.4	81.0	10.4	8.7
Yellow-poplar	362	6	113	23	98.1	1.9	75.7	18.0	6.3
White oak	313	6	103	24	99.7	0.3	80.5	16.3	3.2

[a]Average tree diameter ≥ 9.0 in dbh for softwoods; ≥ 11.0 in dbh for hardwoods
[b]Average tree diameter ≥ 5.0 in – 8.9 in dbh for softwoods; ≥ 5.0 in – 10.9 in dbh for hardwoods
[c]Georgia only

Table 3.2. Crown form and leafing characteristics for the seven species.

Species	Crown Form[1]	------------ Leafing Characteristics[1]	-----------	Shade Tolerance[2]
Slash Pine	narrow, ovoid	evergreen	3 needles per fascicle, 7-10 in. long	intolerant
Loblolly Pine	oval	evergreen	3 needles per fascicle, 6-9 in. long	intolerant
Virginia Pine	poor form, flat-topped	evergreen	2 needles per fascicle, 1.5-3 in. long	intolerant
Red Maple	rounded	deciduous	opposite, simple	tolerant
Sweetgum	pyramidal	deciduous	alternate, simple	intolerant
Yellow-poplar	pyramidal when young, becoming oval	deciduous	alternate, simple	intolerant
White Oak	oval	deciduous	alternate, simple	intermediate

[1]Virginia Tech (2004)
[2]USDA Forest Service (1990)

Data Analysis

The true distribution of a random variable is rarely known so it is often estimated by the distribution of a sample from the population of interest. This sample distribution is known as an empirical distribution and its function (*edf*) is defined as follows (Stephens 1986): Let $X_1, X_2, \ldots, X_n$ be a random sample, and $X_{(1)}, X_{(2)}, \ldots, X_{(n)}$ the random sample in rank order. Then,

$$\begin{aligned} F_n(x) &= 0 && x < X_{(1)} \\ F_n(x) &= i/n && X_{(i)} \le x \le X_{(i+1)}, i = 1,\ldots,n-1 \\ F_n(x) &= 1 && X_{(n)} \le x. \end{aligned}$$

$F_n(x)$ is a non-decreasing, random function that goes from zero to one in height. It is a step function with steps of height 1/n occurring at the sample values (Conover 1999). Thus for any x, $F_n(x)$ is the proportion of observations less than or equal to x. $F_n(x)$ is a consistent estimator of F(x), the probability that an observation is less than or equal to x. As *n* goes to infinity, $|F_n(x)-F(x)|$ decreases to zero with probability one (Stephens 1986

Empirical distribution functions can be used to determine if two samples are from the same unknown population. If the samples are from the same population then their *edfs* should be similar. In this application, *edfs* are used to determine if the distributions of the crown condition indicators are the same for the seven species. Goodness-of-fit tests are designed to test the hypothesis that two samples are from the same (unknown) distribution. Classical goodness-of-fit tests are based on the Kolmogorov-Smirnov supremum statistic or the Anderson-Darling and Cramér-von Mises quadratic statistics (Stephens 1986). These statistics are defined for continuous distributions, but they may also be used with discrete data if the discreteness is an artifact of imprecise measurement and if the subsequent occurrence of ties is not excessive (Bradley 1968). The classical goodness-of-fit tests are not used here, however, because the coarseness of the measurement system resulted in an unmanageable number of ties.

Instead of the utilizing the goodness-of-fit tests, the species' distributions were compared by examining the 10^{th}, 25^{th}, 50^{th}, 75^{th}, and 90^{th} percentiles of the empirical distribution functions for each crown condition indicator. The 50^{th} percentile, the median, provides a measure of central tendency while the additional percentiles provide information about the tails of the distribution, important because they describe the poorest and best crown conditions. Significant differences at the 75^{th} and 90^{th} percentiles of crown density, for example, indicate whether the densest crowns of one species are denser than the densest crowns of another species. In order to determine statistically significant differences among the species at the various percentiles, a measure of standard error was needed; however, no natural estimate for the variance of percentiles exists (Hall and Martin 1989). Therefore, bootstrapping was utilized to calculate two-sided 90 percent confidence intervals (CIs) for each percentile with the percentile confidence interval method (Lunneborg 2000).

Bootstrapping permits the formation of confidence intervals by generating a sampling distribution around the parameter estimate of interest, in this case, the 10^{th}, 25^{th}, 50^{th}, 75^{th}, or 90^{th} percentile. The sampling distributions of the percentile estimates were generated by sampling with replacement *n* observations from the original data set (*n* equaled the size of the original data). The five percentiles were calculated from the resample, and the sampling algorithm was repeated 2000 times. After all 2000 resamples were generated, the estimates for each percentile level were ranked in order. As is proper with the percentile confidence interval method, the upper and lower confidence limits for the percentile estimates were, respectively, the 1900^{th} and 100^{th} observations of the ranked estimates. The bootstrapping and CI calculations were performed with SAS macros available from the SAS Technical Support website (http://ftp.sas.com/techsup/download/stat/jackboot.html).

Due to the discrete-like nature of the original data, the initial bootstrap CIs had no width. That is, for many percentiles the upper and lower confidence limits were exactly the same. To correct for this problem, random "error" was added to each percentile estimate from every bootstrap sample. The errors were drawn from uniform distributions on the intervals (-2.5, +2.5) and (-7.5, +7.5) with the SAS function RANUNI (seed=37919). These distributions capture the possible within-crew variation in a single crown condition assessment, which is recorded in five percent increments. In the field, two crew members assess each tree. If the crew members agree on the condition of the crown indicator then the value stands. The first uniform distribution interval represents this case (the “best” case). If the two crew members disagree on the condition of the crown indicator but are within 10 percent of each other then the average of the two assessments is recorded. The second interval represents this scenario (the “averaging” case).

Two species were declared significantly different at a percentile level if their CIs for the given percentile did not overlap. Using overlapping CIs to determine statistical significance is, under normal theory, a “valid but underpowered test of the hypothesis of no difference” (Mulla and Cole 2004). Under normal theory the standard method to test the hypothesis of no difference is to calculate the 100(1-α)% confidence interval for the difference in the two sample means. That is, $H_0 : \mu_b - \mu_a = 0$ and

$$\bar{b} - \bar{a} \pm z_{\alpha/2}\sqrt{\frac{s_a^2}{n} + \frac{s_b^2}{m}} ,$$

where *a*-bar and *b*-bar are sample estimates of the means, s_a^2 and s_b^2 are sample estimates of the variances, and *n* and *m* are the sample sizes for samples A and B, respectively. The null hypothesis is rejected if the 100(1-α)% confidence interval does not include zero.

Alternatively, the overlapping method utilizes confidence intervals calculated for the two sample means individually, each of the form $\bar{a} \pm z_{\alpha/2} SE_a$ where *a*-bar is the sample mean and SE_a is the standard error of the mean. Rejection of the null hypothesis of no difference with the overlapping method implies rejection of the null hypothesis with the standard method, but failure to reject the null hypothesis with the overlapping method does not necessarily imply failure to reject with the standard method (Schenker and Gentleman 2001). Wolfe and Hanley (2002) show that two confidence intervals overlap when

$$\bar{b} - \bar{a} < z_{\alpha/2} SE_a + z_{\alpha/2} SE_b ,$$

and that $\bar{b} - \bar{a}$ does not equal zero when

$$\bar{b} - \bar{a} > z_{\alpha/2}\sqrt{\left(SE_a^2 + SE_b^2\right)} .$$

Together,

$$z_{\alpha/2}\sqrt{\left(SE_a^2 + SE_b^2\right)} < \bar{b} - \bar{a} < z_{\alpha/2}SE_a + z_{\alpha/2}SE_b$$

give a rule of thumb for determining when the difference between two means is significant at the α-level and at the same time the 100(1- α)% confidence intervals overlap.

Despite its deficiencies, the overlapping confidence interval approach was employed in this research to determine differences among the species. Thus, it should be realized that the results from these comparisons are conservative, and that differences among the species may exist even though the overlapping confidence intervals signify otherwise.

Results and Discussion

Smoothed *edf* plots indicate that the shapes of the crown condition indicator distributions are similar for all species (Figure 3.4). [*Edfs* are plotted as step functions for each species individually in Appendix A.] Observed crown densities covered almost the entire scale of possible values, ranging from 5 to 85 percent. Crown dieback ranged from 0 to 95 percent, but 95 percent of the trees had less than 25 percent dieback. Foliage transparency ranged from 0 to 75 percent, and was 25 percent or less for more than 95 percent of the trees in all species except Virginia pine. Median crown density ranged from 40 percent for the pines to 50 percent for yellow-poplar (Table 3.3). The median crown dieback was zero percent for all species (Table 3.4). Median foliage transparency was 20 percent for Virginia pine and 15 percent for all other species (Table 3.5).

Confidence intervals for the best-case scenario

<u>Crown Density</u>

Differences in the locations of the distributions were established through pair-wise comparisons of the CIs. Comparisons of the best-case CIs revealed that differences in crown density were most prevalent between the softwood and hardwood species

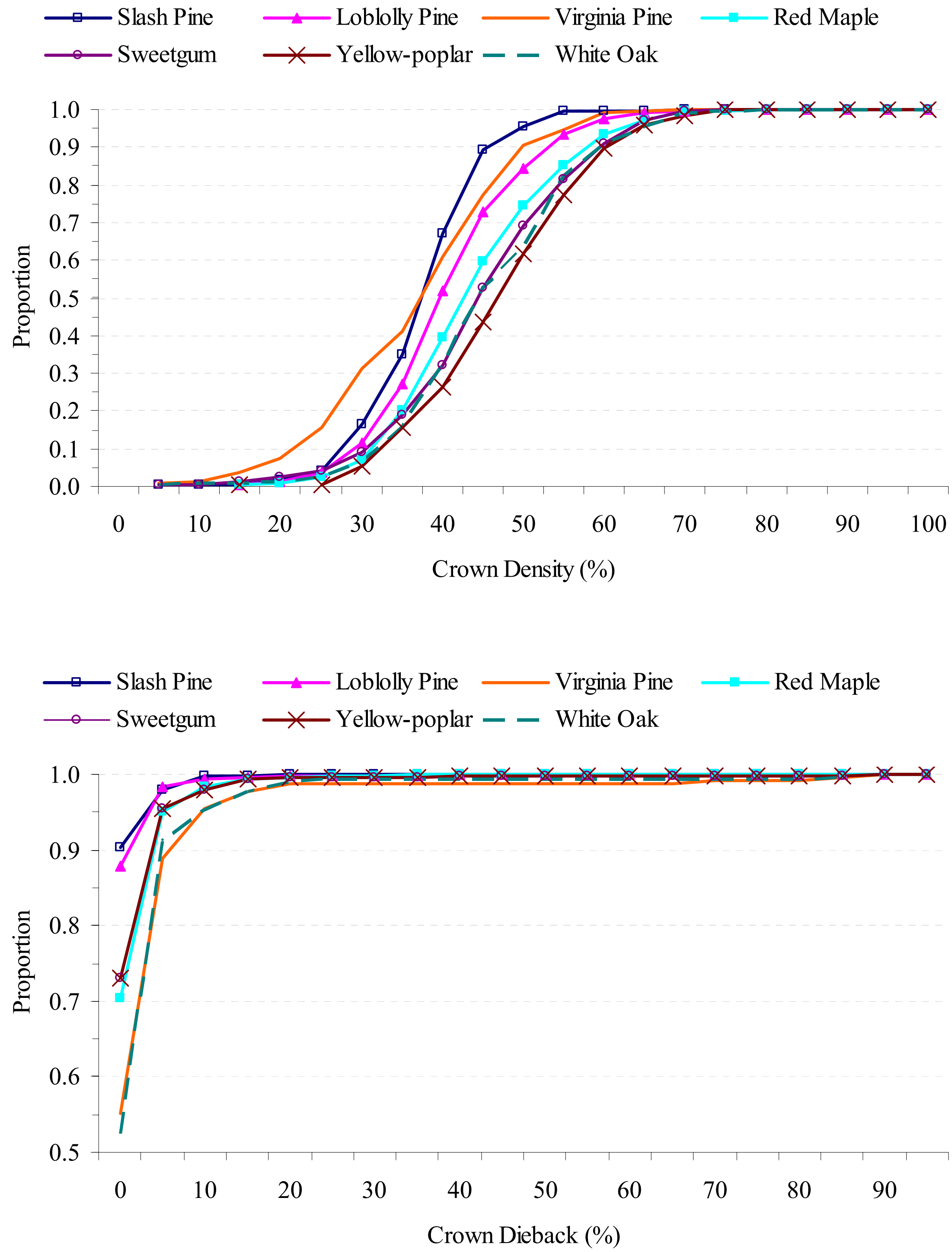


Figure 3.4. Smoothed empirical distribution functions for crown density, crown dieback, and foliage transparency.

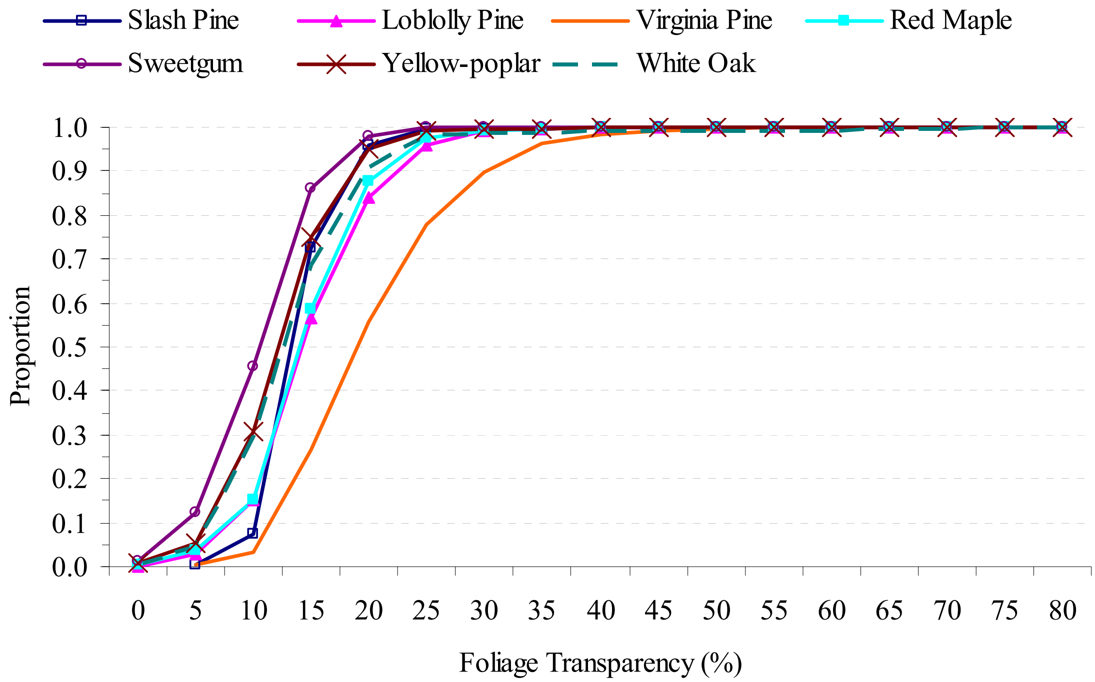


Figure 3.4. Continued.

Table 3.3. Observed crown density percentiles by species.

Species	Crown Density Percentile				
	10^{th}	25^{th}	50^{th}	75^{th}	90^{th}
Slash Pine	30	35	40	45	50
Loblolly Pine	30	35	40	50	55
Virginia Pine	25	30	40	45	50
Red Maple	35	40	45	50	60
Sweetgum	35	40	45	55	60
Yellow-poplar	35	40	50	55	65
White Oak	35	40	45	55	60

Table 3.4. Observed crown dieback percentiles by species.

Species	Crown Dieback Percentile				
	10^{th}	25^{th}	50^{th}	75^{th}	90^{th}
Slash Pine	0	0	0	0	0
Loblolly Pine	0	0	0	0	5
Virginia Pine	0	0	0	5	10
Red Maple	0	0	0	5	5
Sweetgum	0	0	0	5	5
Yellow-poplar	0	0	0	0	5
White Oak	0	0	0	5	5

Table 3.5. Observed foliage transparency percentiles by species.

Species	Foliage Transparency Percentile				
	10th	25th	50th	75th	90th
Slash Pine	15	15	15	20	20
Loblolly Pine	10	15	15	20	25
Virginia Pine	15	15	20	25	35
Red Maple	10	15	15	20	25
Sweetgum	5	10	15	15	20
Yellow-poplar	10	10	15	15	20
White Oak	10	10	15	20	20

(Table 3.6). Virginia pine was different than sweetgum, yellow-poplar, and white oak at all percentiles, and different than red maple at all percentiles except the 75th. In general, Virginia pine crown density was consistently about 10 percent lower than yellow-poplar and 5 to 10 percent lower than the other three hardwoods. Slash pine was different than red maple, yellow-poplar, and white oak at all percentiles, and different than sweetgum at all percentiles except the 10th. Slash pine was about 5 percent lower than these species in the first half of the distribution and about 10 percent lower in the upper half of the distribution. Loblolly pine was different than yellow-poplar and white oak at all percentiles, and different than red maple and sweetgum at all percentiles except the 75th and 10th, respectively. Loblolly pine was generally 5 percent lower than the hardwood species.

Differences in crown density were less pervasive within the hardwood and softwood species groups. There was no difference among the three pine species at the 50th percentile; however, Virginia pine was different than slash pine and loblolly pine at the 10th and 25th percentiles, and loblolly pine was different than slash pine at the 75th and 90th percentiles. These relationships are evident in Figure 3.4 (page 78) where the Virginia pine *edf* converges with slash pine and loblolly pine near the 50th percentile. Beyond the 50th percentile, the slash pine *edf* diverges from loblolly pine and the Virginia pine *edf* splits the middle. Yellow-poplar and red maple had significantly different medians, but otherwise, there were no differences among the crown density distributions of the hardwood species.

The average width of the best-case CIs was 5.94 percent across all percentiles and all species. The CIs were widest for the 90th percentile and narrowest for the 25th percentile. On average across all percentiles, the best-case CIs were widest for Virginia pine (7.30 percent) and narrowest for loblolly pine (4.52 percent). Given the interval width of the Uniform distribution from which the "errors" were drawn, the widths of the best-case CIs were not unexpected.

Oliver and Larson (1996) suggest that species with higher shade tolerances can maintain denser crowns than species with lower shade tolerances. The *edfs* of the species examined here only partially support this idea. Of the species examined, the pines are

Table 3.6. Best-case 90 percent confidence intervals for crown density. LCL=lower confidence limit. UCL=upper confidence limit.

Species	Crown Density (%)									
	10th percentile		25th percentile		50th percentile		75th percentile		90th percentile	
	LCL	UCL	LCL	UCL	LCL	UCL	LCL	UCL	LCL	UCL
Slash Pine	27.79	32.19	32.73	37.24	37.77	42.24	42.71	47.28	43.32	52.15
Loblolly Pine	27.29	32.21	32.74	37.26	37.78	42.4	47.72	52.28	52.75	57.27
Virginia Pine	20.23	27.24	27.74	32.37	37.73	42.24	42.80	50.98	47.87	56.78
Red Maple	32.75	37.19	37.71	42.24	42.77	47.24	48.21	57.08	57.75	62.27
Sweetgum	28.73	37.16	37.73	42.24	42.82	49.96	52.72	57.28	57.84	66.52
Yellow-poplar	32.79	37.20	37.86	46.65	47.72	52.24	52.77	60.81	57.98	67.05
White Oak	32.71	37.21	37.73	42.24	42.82	51.02	52.72	57.29	57.84	66.37

probably the most shade intolerant, and they did tend to have less dense crowns than the hardwood species; however, it is among the hardwood species that Oliver and Larson's assumption seemingly falters. Of the four hardwood species examined, red maple is the most shade tolerant yet only one significant difference was found between red maple and the other hardwoods. Perhaps the spectrum of shade tolerance among the hardwoods is not great enough to validate Oliver and Larson's claim, especially since red maple shade tolerance diminishes as trees grow from seedlings into the overstory (USDA Forest Service 1990).

Excurrent and decurrent growth forms also did not appear to have a distinguishable impact on crown density. Sweetgum and white oak are premier examples of excurrent and decurrent growth forms, respectively, yet their *edfs* were not significantly different at any percentile level.

Crown Dieback

As with crown density, differences in the locations of the crown dieback distributions were established through pair-wise comparisons of the CIs. Comparisons of the best-case CIs revealed differences among the seven species at the 75th percentile only (Table 3.7). The distinguishing characteristic at the 75th percentile was the inclusion of zero or five percent. The CIs for Virginia pine, red maple, and white oak included five percent, whereas the CI for sweetgum included both zero and five percent. The CIs for slash pine, loblolly pine, and yellow-poplar included zero percent but not five percent.

The average width of the best-case CIs was 5.10 percent across all percentiles and all species. The CIs were widest for the 90th percentile and narrowest for the 10th percentile. On average across all percentiles, the best-case CIs were widest for white oak (5.68 percent) and narrowest for red maple (4.49 percent). Given the interval width of the Uniform distribution from which the "errors" were drawn, the widths of the best-case CIs were not unexpected. It should be noted that the CIs in Table 3.7 include negative lower bounds for the 10th, 25th, 50th, and 75th percentiles. These negative numbers are the result of generating two-sided confidence intervals around a point estimate of zero. It

Table 3.7. Best-case 90 percent confidence intervals for crown dieback. LCL=lower confidence limit. UCL=upper confidence limit.

Species	Crown Dieback (%)									
	10th percentile		25th percentile		50th percentile		75th percentile		90th percentile	
	LCL	UCL	LCL	UCL	LCL	UCL	LCL	UCL	LCL	UCL
Slash Pine	-2.21	2.19	-2.27	2.24	-2.23	2.24	-2.28	2.28	-2.08	6.84
Loblolly Pine	-2.21	2.19	-2.27	2.24	-2.23	2.24	-2.28	2.28	2.75	7.27
Virginia Pine	-2.21	2.19	-2.27	2.24	-2.19	3.27	2.72	7.28	3.23	12.15
Red Maple	-2.21	2.19	-2.27	2.24	-2.23	2.24	2.68	7.18	2.75	7.27
Sweetgum	-2.21	2.19	-2.27	2.24	-2.23	2.24	-0.56	7.22	2.75	7.27
Yellow-poplar	-2.21	2.19	-2.27	2.24	-2.23	2.24	-2.28	2.29	2.75	7.27
White Oak	-2.21	2.19	-2.27	2.24	-2.18	6.33	2.72	7.28	2.81	11.52

should be understood that negative crown diebacks are not possible and therefore, the practical lower bounds for these percentiles is zero.

Crown dieback is an unmistakable indicator of tree health and extreme dieback is detrimental to any tree regardless of species. Dieback greater than 15 percent was rare for all species and the differences noted at the 75th percentile were inconsequential as the levels of crown dieback were minimal at this percentile (0-5 percent). Though Stoyenoff et al. (1998) suggest that hardwood species maintain slightly higher levels of dieback due to the energy requirements of flushing new leaves each year, this was not evident in this analysis. Perhaps this is caused by the lack of repeated measurements because Steinman (2001) found that the threshold for imminent death was higher for hardwoods than for softwoods. That is, softwoods with crown dieback greater than 20 percent were found most likely to die within one year of assessment, whereas the threshold was 30 percent for hardwoods. Thus, some species may be able to tolerate (i.e. live longer) greater amounts of dieback than other species, but this was not fully evident in the one-time assessments analyzed here.

<u>Foliage Transparency</u>

As with crown density and crown dieback, differences in the locations of the foliage transparency distributions were established through pair-wise comparisons of the CIs (Table 3.8). Comparisons of the best-case CIs revealed differences between Virginia pine and all of the other species at all or most of the percentiles. Virginia pine was different than sweetgum, yellow-poplar, and white oak at all percentiles, and different from red maple, loblolly pine, and slash pine at all percentiles except the 10th, 10th and 25th, and 10th percentiles, respectively. Sweetgum was different from all species at the 10th percentile, and different from the three pines at the 25th percentile. All species except Virginia pine were alike at the 50th percentile. Two sets of species were alike at all percentiles: yellow-poplar and white oak, and loblolly pine and red maple. From Figure 3.4 (page 78) it can be seen that the *edfs* for sweetgum and Virginia pine form the borders for all other *edfs*. Virginia pine had the highest foliage transparencies and sweetgum had the lowest foliage transparencies.

Table 3.8. Best-case 90 percent confidence intervals for foliage transparency. LCL=lower confidence limit. UCL=upper confidence limit.

Species	Foliage Transparency (%)									
	10th percentile		25th percentile		50th percentile		75th percentile		90th percentile	
	LCL	UCL	LCL	UCL	LCL	UCL	LCL	UCL	LCL	UCL
Slash Pine	12.53	17.23	12.73	17.24	12.77	17.24	14.24	22.23	17.74	22.23
Loblolly Pine	7.73	12.24	12.73	17.24	12.77	17.24	17.72	22.28	22.74	27.23
Virginia Pine	12.73	17.24	12.88	21.74	17.77	22.45	22.78	31.09	28.06	37.00
Red Maple	7.73	12.25	12.73	17.24	12.77	17.24	17.72	22.28	21.55	27.23
Sweetgum	2.74	7.46	7.73	12.24	12.67	17.24	12.72	17.28	17.72	22.23
Yellow-poplar	7.73	12.24	7.74	12.3	12.77	17.24	12.96	22.02	17.74	22.23
White Oak	7.73	12.24	7.75	12.39	12.77	17.24	17.71	22.28	17.90	26.81

The average width of the best-case CIs was 5.28 percent across all percentiles and all species. The CIs were widest for the 75th percentile and narrowest for the 50th percentile. On average across all percentiles, the best-case CIs were widest for Virginia Pine (6.62 percent) and narrowest for loblolly pine (4.51 percent). Given the interval width of the Uniform distribution from which the "errors" were drawn, the widths of these CIs were not unexpected.

Oliver and Larson's (1996) suggestion that species with higher shade tolerances maintain denser crowns than species with lower shade tolerances can be considered in light of foliage transparency as it was for crown density. That is, shade intolerant trees should have higher foliage transparencies than shade tolerant trees. As with crown density, the *edfs* of the species examined herein do not fully support this idea. Virginia pine, most likely the most shade intolerant species, generally had higher foliage transparency than the other species. Yet, red maple and loblolly pine were not significantly different at any of the percentiles despite their disparate shade tolerances.

Confidence intervals for the averaging-case scenario

Pair-wise comparisons of the averaging-case CIs revealed no differences among the species for any of the crown condition indicators (Tables 3.9, 3.10, and 3.11). The average width of the averaging-case CIs across all species and percentiles was 14.21 percent for crown density, 13.80 percent for crown dieback, and 13.99 percent for foliage transparency. It should be noted that the CIs in Tables 3.10 and 3.11 include negative lower bounds for some of the percentiles. As in the best-case scenario, these negative numbers are the result of adding the "error" term to a crown condition of zero percent. Again, it should be understood that negative crown conditions are not possible and therefore, the practical lower bound for these percentiles is zero. The interval width of the Uniform distribution from which the "errors" were drawn was (-7.5, +7.5); therefore, the average widths of the averaging-case CIs were not unexpected.

Table 3.9. Averaging-case 90 percent confidence intervals for crown density. LCL=lower confidence limit. UCL=upper confidence limit.

Species	Crown Density (%)									
	10th percentile		25th percentile		50th percentile		75th percentile		90th percentile	
	LCL	UCL	LCL	UCL	LCL	UCL	LCL	UCL	LCL	UCL
Slash Pine	23.38	36.58	28.20	41.72	33.30	46.73	38.15	51.85	39.96	56.44
Loblolly Pine	23.88	36.58	28.21	41.73	33.34	46.96	43.17	56.85	48.26	61.81
Virginia Pine	18.01	31.58	23.21	36.83	33.27	46.73	38.40	52.93	43.60	60.35
Red Maple	28.32	41.58	33.18	46.72	38.30	51.73	44.62	61.23	53.26	66.81
Sweetgum	26.20	41.48	33.20	46.72	38.45	52.26	48.16	61.85	53.32	69.55
Yellow-poplar	28.38	41.58	33.59	49.95	43.27	56.73	48.31	62.49	53.95	71.15
White Oak	28.27	41.62	33.20	46.72	38.47	53.07	48.17	61.85	53.51	69.11

Table 3.10. Averaging-case 90 percent confidence intervals for crown dieback. LCL=lower confidence limit. UCL=upper confidence limit.

Species	Crown Dieback (%)									
	10th percentile		25th percentile		50th percentile		75th percentile		90th percentile	
	LCL	UCL	LCL	UCL	LCL	UCL	LCL	UCL	LCL	UCL
Slash Pine	-6.62	6.58	-6.80	6.72	-6.70	6.73	-6.83	6.85	-6.25	10.52
Loblolly Pine	-6.62	6.58	-6.80	6.72	-6.70	6.73	-6.83	6.85	-1.74	11.81
Virginia Pine	-6.62	6.58	-6.80	6.72	-6.57	6.99	-1.83	11.85	-0.31	16.44
Red Maple	-6.62	6.58	-6.80	6.72	-6.70	6.73	-1.87	11.85	-1.74	11.81
Sweetgum	-6.62	6.58	-6.80	6.72	-6.70	6.30	-2.46	11.66	-1.74	11.81
Yellow-poplar	-6.62	6.58	-6.80	6.72	-6.70	6.73	-6.83	6.85	-1.74	11.81
White Oak	-6.62	6.58	-6.80	6.72	-6.54	9.00	-1.83	11.85	-1.56	14.57

Table 3.11. Averaging-case 90 percent confidence intervals for foliage transparency. LCL=lower confidence limit. UCL=upper confidence limit.

Species	Foliage Transparency (%)									
	10th percentile		25th percentile		50th percentile		75th percentile		90th percentile	
	LCL	UCL	LCL	UCL	LCL	UCL	LCL	UCL	LCL	UCL
Slash Pine	7.98	21.70	8.20	21.72	8.30	21.73	12.54	26.69	13.23	26.69
Loblolly Pine	3.19	16.73	8.20	21.72	8.30	21.73	13.17	26.85	18.23	31.69
Virginia Pine	8.19	21.73	8.64	25.22	13.31	26.96	18.34	33.27	24.18	41.00
Red Maple	3.19	16.73	8.20	21.72	8.30	21.73	13.17	26.85	17.90	31.63
Sweetgum	-1.79	11.94	3.20	16.72	8.17	21.73	8.17	21.85	13.20	26.69
Yellow-poplar	3.19	16.73	3.21	16.80	8.30	21.73	8.89	26.05	13.23	26.69
White Oak	3.19	16.73	3.25	16.90	8.30	21.73	13.15	26.83	13.69	30.42

Conclusion

Based upon the averaging-case scenario CIs, no significant differences among the species were found for any of the crown condition indicators. This casts a shadow on the validity of the differences observed from the best-case CIs. Nevertheless, some interspecies differences likely exist, particularly for crown density and foliage transparency, because the two sets of CIs are based on *all* observations being either the best-case *or* averaging-case. Since a combination of the two cases unquestionably occurs in the field, the "true" CIs probably lie somewhere between the CI sets reported here.

Further complicating the conclusions herein is that the error incorporated in the bootstrap estimates is only part of the known error in the crown condition assessments. The best-case and averaging-case errors incorporated expected within-crew variation only. Between crew variation also exists—more so for crown density than for crown dieback or foliage transparency (See Chapters I and II)—but no practical way of incorporating between-crew error was found. Consequently, these CI sets are best case CIs and as such the differences noted among species should be considered carefully.

Overall, no one species proved to be completely different than all other species, though Virginia pine was the most conspicuous. The poor crown conditions exhibited by Virginia pine are in concordance with the findings of Burkman and Bechtold (2000). They compared the crown conditions of shortleaf, slash, loblolly, and Virginia pines on FIA Phase 3 plots in Alabama, Delaware, Georgia, Maryland, New Jersey, and Virginia for the years 1991-1995 and 1997. They found that in general, Virginia pine had the poorest crown conditions of the four pines. In addition, their graphs of mean crown conditions by year indicate that slash pine tended to have the best crown conditions overall with loblolly pine falling between slash pine and Virginia pine. The results of this work coincide with their graphs in that slash pine tended to have slightly better crown conditions than loblolly pine.

In closing, there is clearly a gradient of expected crown conditions among species. Most plausibly, Virginia pine can be expected to have relatively poorer crowns and while there may be a difference between hardwood and softwood crown densities in general, uncertainty in the data makes it difficult to confidently pinpoint species-specific differences for any of the crown condition indicators.

CHAPTER IV

INTRASPECIES VARIATION IN THREE CROWN CONDITION INDICATORS FOR LOBLOLLY PINE AND SWEETGUM TREES IN ALABAMA AND GEORGIA

Introduction

Chapter III investigated the potential *inter*species variation in tree crowns for seven species in the southeastern United States. In addition to intrinsic species differences, other external factors influence crown shape. These factors include latitude, elevation, canopy position, stage of tree development, stocking levels, moisture availability, damage, insect infestations, and exposure to harsh weather conditions such as extreme winds and snowfall (USDA Forest Service 1999, Kuuluvainen and Sprugel 1996, Oliver and Larson 1996, Farmer 1976, Helms 1976, and Horn 1971). Hence, *intra*species variation in tree crowns may occur depending upon the environmental conditions in which the trees are growing. The purpose of this paper is to evaluate and describe intraspecies variation in three crown condition indicators for loblolly pine (*Pinus taeda*) and sweetgum (*Liquidambar styraciflua*) trees growing in different environmental conditions in Alabama and Georgia.

Methods

Data Description

The data used in this study are subsets of the data utilized in Chapter III. In order to control as much variation as possible, the data were classified by several environmental variables. The number of observations in each subset limited the different environmental conditions that could be considered (Table 4.1). At least 50 trees per subset were preferred. In order to retain an adequate number of trees per subset, some environmental conditions were not separated as subgroups. These "uncontrolled" conditions were forest type, elevation, aspect, stand size, and tree crown position. The "controlled" environmental variables were state, stand origin, terrain position, and

Table 4.1. Subset definitions and pair-wise comparisons used to evaluate intraspecies differences in the empirical distribution functions of crown density, crown dieback, and foliage transparency. SPB=southern pine beetle.

Subset	State	Species	Stand Origin	Terrain Position	SPB present	Number of trees	Pair-wise Comparisons
1	Alabama	Loblolly Pine	Planted	Flatland	yes	323	Subset 2, Subset 5
2	Alabama	Loblolly Pine	Planted	Midslope	yes	261	Subset 1, Subset 6
3	Georgia	Loblolly Pine	Natural	Flatland	yes	180	Subset 4, Subset 5
4	Georgia	Loblolly Pine	Natural	Midslope	yes	103	Subset 3, Subset 6
5	Georgia	Loblolly Pine	Planted	Flatland	yes	386	Subset 1, Subset 3, Subset 6
6	Georgia	Loblolly Pine	Planted	Midslope	yes	231	Subset 2, Subset 4, Subset 5
7	Alabama	Sweetgum	Natural	Flatland	yes	52	Subset 8, Subset 9
8	Alabama	Sweetgum	Natural	Midslope	yes	40	Subset 7
9	Georgia	Sweetgum	Natural	Flatland	yes	55	Subset 9

historical presence of southern pine beetle infestations (*Dendroctonus frontalis* Zimm., SPB). Descriptions of stand origin and terrain position are given in Chapter I (page 21).

Loblolly pine is a primary host for the SPB and depending upon the severity of the SPB outbreak, most loblolly pines are either killed or suffer severe defoliation. SPB outbreaks have periodically occurred in the southeastern US for many years. Historic SPB presence was included as a subset variable because tree crowns are the result of both present and past influences on the tree. SPB presence was not specifically recorded for each FIA Phase 3 plot, thus external literature was used to assign SPB presence/absence to each observation. An observation was coded for SPB presence if the county in which it occurred had any infestation spots during the years 1990-1996 (Price et al. 1998).

Data Analysis

Crown density, crown dieback, and foliage transparency empirical distribution functions (*edfs*) for the species-specific subsets were compared by examining the 10th, 25th, 50th, 75th, and 90th percentiles as done in Chapter III. Two-sided 90 percent bootstrap confidence intervals (CIs) were calculated in the same manner, resulting in two sets of CIs reflecting the best-case and averaging-case within-crew errors. As in Chapter III, two subsets were declared significantly different at a percentile level if their CIs for the given percentile did not overlap. Table 4.1 lists the pair-wise comparisons used to evaluate intraspecies differences in the *edfs*.

Results and Discussion

Loblolly Pine

Smoothed *edf* plots illustrate that the shapes of the crown condition indicator distributions are similar for the loblolly pine subsets (Figure 4.1). [*Edfs* are plotted as step functions for each subset individually in Appendix B.] Observed crown densities ranged from 15 to 65 percent. Crown dieback ranged from 0 to 50 percent, but 95 percent of the trees had less than 5 percent dieback. Foliage transparency ranged from 0 to 35 percent. Median crown density was 40 percent for all loblolly subsets except

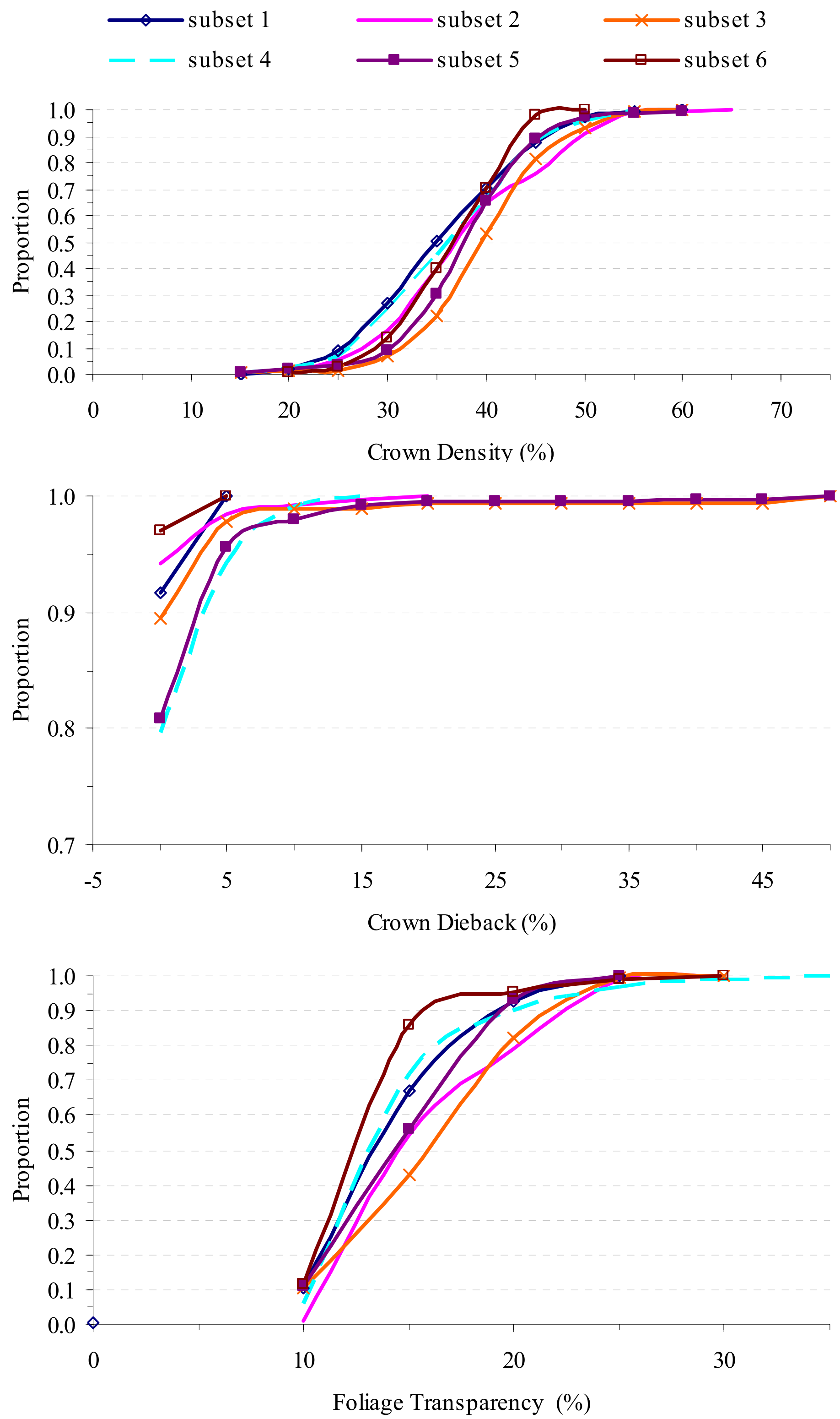


Figure 4.1. Smoothed empirical distribution functions for loblolly pine crown density, crown dieback, and foliage transparency.

Subset 1; median crown density was 35 percent for Subset 1 (Table 4.2). Median crown dieback was zero percent for all subsets (Table 4.3). Median foliage transparency was 20 percent for Subset 3 and 15 percent for all other subsets (Table 4.4).

Confidence intervals for the best-case scenario

Pair-wise comparisons of the subset best-case CIs (Tables 4.5, 4.6, and 4.7) addressed three questions:

1. In Georgia, are there significant differences in crown density, crown dieback, and foliage transparency between stands of planted and natural origins?

2. Within a state, are there significant differences in crown density, crown dieback, and foliage transparency between trees growing on midslopes and flatland?

3. Between Alabama and Georgia, are there significant differences in crown density, crown dieback, and foliage transparency for a given terrain position or stand origin?

To answer question one, pair-wise comparisons were made between Subsets 3 and 5, and Subsets 4 and 6. Results indicated that at the 50th and 90th percentiles, loblolly pine trees in flat, natural stands (Subset 3) had significantly higher (i.e. poorer) foliage transparency than trees in flat, planted stands (Subset 5) (Table 4.7). At the 75th percentile both subsets were centered near 20 percent; however, examination of the subsets indicated that the natural stands included several trees with foliage transparency beyond 20 percent while only a few trees in the planted subset were beyond 20 percent (Figure B.3). This was the reason for the significant difference at the 90th percentile. No other differences in the crown indicators were found between Subsets 3 and 5, and no differences at all were found between trees in natural and planted stands on midslopes (Subsets 4 and 6).

In addressing question two, pair-wise comparisons were made between Subsets 1 and 2, Subsets 3 and 4, and Subsets 5 and 6. In Alabama, the only significant difference was at the 90th percentile for foliage transparency. Trees on planted midslopes (Subset 2) had higher (i.e. poorer) foliage transparency than trees planted on flatland (Subset 1). In Georgia, trees growing in natural, flatland stands (Subset 3) had higher (poorer) foliage transparency at the 50th percentile than trees growing on natural, midslope stands (Subset

Table 4.2. Observed crown density percentiles by loblolly pine subset.

Subset	State	Stand Origin	Terrain Position	Crown Density Percentile				
				10th	25th	50th	75th	90th
1	Alabama	Planted	Flatland	30	30	35	45	50
2	Alabama	Planted	Midslope	30	35	40	45	50
3	Georgia	Natural	Flatland	35	40	40	45	50
4	Georgia	Natural	Midslope	30	35	40	45	50
5	Georgia	Planted	Flatland	35	35	40	45	50
6	Georgia	Planted	Midslope	30	35	40	45	45

Table 4.3. Observed crown dieback percentiles by loblolly pine subset.

Subset	State	Stand Origin	Terrain Position	Crown Dieback Percentile				
				10th	25th	50th	75th	90th
1	Alabama	Planted	Flatland	0	0	0	0	0
2	Alabama	Planted	Midslope	0	0	0	0	0
3	Georgia	Natural	Flatland	0	0	0	0	5
4	Georgia	Natural	Midslope	0	0	0	0	5
5	Georgia	Planted	Flatland	0	0	0	0	5
6	Georgia	Planted	Midslope	0	0	0	0	0

Table 4.4. Observed foliage transparency percentiles by loblolly pine subset.

Subset	State	Stand Origin	Terrain Position	Foliage Transparency Percentile				
				10th	25th	50th	75th	90th
1	Alabama	Planted	Flatland	10	15	15	20	20
2	Alabama	Planted	Midslope	15	15	15	20	25
3	Georgia	Natural	Flatland	10	15	20	20	25
4	Georgia	Natural	Midslope	15	15	15	20	20
5	Georgia	Planted	Flatland	10	15	15	20	20
6	Georgia	Planted	Midslope	10	15	15	15	20

Table 4.5. Best-case 90 percent confidence intervals for loblolly pine crown density. LCL=lower confidence limit. UCL=upper confidence limit.

Subset	Crown Density (%)									
	10th percentile		25th percentile		50th percentile		75th percentile		90th percentile	
	LCL	UCL	LCL	UCL	LCL	UCL	LCL	UCL	LCL	UCL
1	23.85	32.15	27.85	36.41	32.96	41.98	42.64	47.28	46.36	52.26
2	27.78	32.19	32.73	37.24	37.77	42.24	42.85	51.81	47.85	56.57
3	30.82	37.17	34.09	42.15	37.86	46.32	42.73	47.33	47.77	52.44
4	25.4	32.18	28.02	36.98	34.34	42.23	42.62	47.27	43.17	52.18
5	28.83	37.15	32.73	37.29	37.77	42.24	42.72	47.28	43.3	52.18
6	27.80	32.66	32.73	37.24	37.75	42.24	42.51	47.27	42.75	47.27

Table 4.6. Best-case 90 percent confidence intervals for loblolly pine crown dieback. LCL=lower confidence limit. UCL=upper confidence limit.

Subset	Crown Dieback (%)									
	10th percentile		25th percentile		50th percentile		75th percentile		90th percentile	
	LCL	UCL	LCL	UCL	LCL	UCL	LCL	UCL	LCL	UCL
1	-2.21	2.19	-2.27	2.24	-2.23	2.24	-2.28	2.28	-2.20	5.82
2	-2.21	2.19	-2.27	2.24	-2.23	2.24	-2.28	2.28	-2.25	2.28
3	-2.21	2.19	-2.27	2.24	-2.23	2.24	-2.28	2.28	-1.81	7.03
4	-2.21	2.19	-2.27	2.24	-2.23	2.24	-2.22	5.89	2.75	7.42
5	-2.21	2.19	-2.27	2.24	-2.23	2.24	-2.27	2.29	2.75	7.27
6	-2.21	2.19	-2.27	2.24	-2.23	2.24	-2.28	2.28	-2.25	2.27

Table 4.7. Best-case 90 percent confidence intervals for loblolly pine foliage transparency. LCL=lower confidence limit. UCL=upper confidence limit.

Subset	Foliage Transparency (%)									
	10th percentile		25th percentile		50th percentile		75th percentile		90th percentile	
	LCL	UCL	LCL	UCL	LCL	UCL	LCL	UCL	LCL	UCL
1	7.93	16.87	12.73	17.24	12.77	17.24	17.72	22.28	17.76	22.43
2	12.72	17.26	12.73	17.24	12.78	19.63	17.74	22.53	22.75	27.27
3	7.94	16.87	12.73	17.24	17.65	22.23	17.73	22.32	22.73	27.27
4	12.52	17.25	12.73	17.24	12.77	17.24	13.78	22.19	17.93	26.83
5	7.81	16.31	12.73	17.24	12.77	17.29	17.72	22.28	17.76	22.31
6	7.83	16.41	12.73	17.24	12.77	17.24	12.72	17.28	17.58	22.27

4). Even though the smoothed *edf* plot (Figure 4.2) suggests potential differences at the 75th and 90th percentiles as well, wider than average CIs for the midslope stands barred significant differences at these percentiles. Also in Georgia, trees growing on planted, midslopes (Subset 6) had higher transparency at the 75th percentile than trees growing on planted, flatland (Subset 5). In addition to this difference in foliage transparency, Subsets5 and 6 differed at the 90th percentile for crown dieback: Subset 5 had more crown dieback (Table 4.6).

To answer question three, pair-wise comparisons were made between Subsets 1 and 5, and Subsets 2 and 6. No significant differences were found between Alabama and Georgia trees growing in planted, flatland stands (Subsets 1 and 5, respectively); however, differences were found between trees growing in planted, midslope stands. Trees in Georgia (Subset 6) had lower crown density at the 90th percentile but better foliage transparency at the 75th and 90th percentiles than Alabama (Tables 4.5 and 4.7).

The average width of the best-case CIs across all subsets and all percentiles was 6.36 percent for crown density, 4.88 percent for crown dieback, and 5.47 percent for foliage transparency. Across all subsets the crown density CIs were widest for the 10th percentile (6.75 percent) and narrowest for the 90th percentile (4.98 percent). For crown dieback, the CIs were widest for the 50th percentile (4.56 percent) and narrowest for the 10th percentile (4.40 percent). The foliage transparency CIs were widest at the 10th percentile (7.37 percent) and narrowest at the 25th percentile (4.51 percent). Note that the negative lower bounds for crown dieback in Table 4.6 are the result of adding the random "error" to an observed dieback of zero percent. As negative crown conditions are not possible, the practical lower bound for these CIs is zero percent.

<u>Confidence intervals for the averaging-case scenario</u>

Pair-wise comparisons of the averaging-case CIs revealed no differences among the subsets for any of the crown condition indicators (Tables 4.8, 4.9, and 4.10). The average width of the averaging-case CIs across all subsets and all percentiles was 14.49 percent for crown density, 13.62 percent for crown dieback, and 14.10 percent for foliage transparency. It should be noted that the CIs in Table 4.9 include negative lower bounds

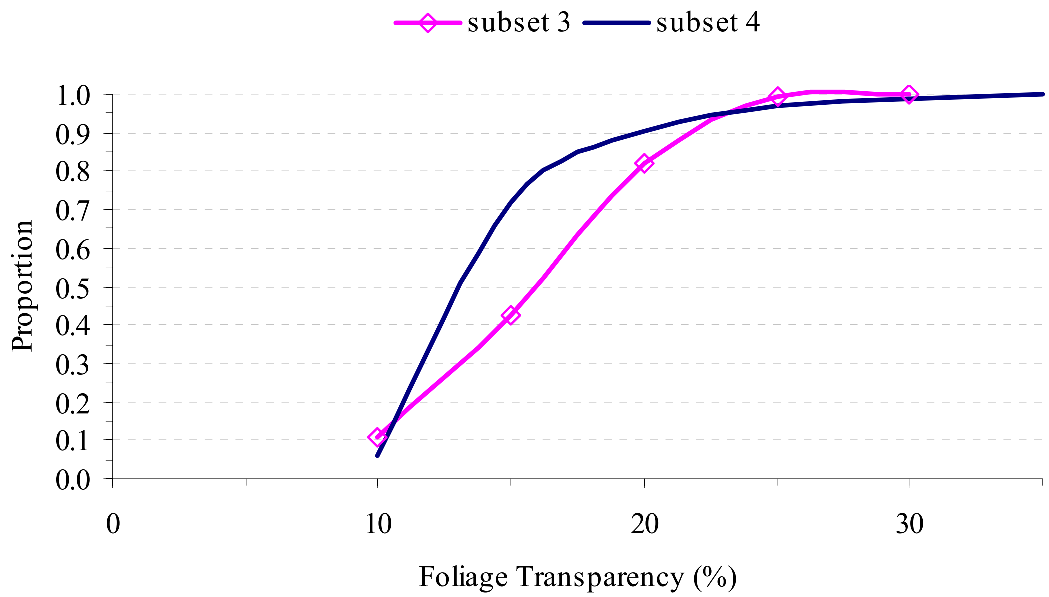


Figure 4.2. Smoothed foliage transparency empirical distribution functions for loblolly pine Subsets 3 and 4.

Table 4.8. Averaging-case 90 percent confidence intervals for loblolly pine crown density. LCL=lower confidence limit. UCL=upper confidence limit.

Subset	Crown Density (%)									
	10th percentile		25th percentile		50th percentile		75th percentile		90th percentile	
	LCL	UCL	LCL	UCL	LCL	UCL	LCL	UCL	LCL	UCL
1	21.56	36.46	23.54	39.23	32.96	41.98	42.64	47.28	46.36	52.26
2	23.37	36.58	28.20	41.72	33.30	46.73	38.54	55.44	43.55	59.72
3	27.95	41.52	31.78	46.45	33.58	49.10	38.18	51.92	43.32	56.94
4	22.97	36.53	24.05	40.94	32.62	46.7	38.1	51.82	39.52	56.51
5	26.49	41.44	28.20	41.78	33.30	46.73	38.17	51.85	39.90	56.53
6	23.41	36.85	28.20	41.72	33.29	46.73	37.99	51.80	38.26	51.81

Table 4.9. Averaging-case 90 percent confidence intervals for loblolly pine crown dieback. LCL=lower confidence limit. UCL=upper confidence limit.

Subset	Crown Dieback (%)									
	10th percentile		25th percentile		50th percentile		75th percentile		90th percentile	
	LCL	UCL	LCL	UCL	LCL	UCL	LCL	UCL	LCL	UCL
1	-6.62	6.58	-6.8	6.72	-6.70	6.73	-6.83	6.85	-6.61	7.49
2	-6.62	6.58	-6.80	6.72	-6.7	6.73	-6.83	6.85	-6.74	6.82
3	-6.62	6.58	-6.80	6.72	-6.70	6.73	-6.83	6.85	-5.44	11.09
4	-6.62	6.58	-6.80	6.72	-6.70	6.73	-6.66	7.66	-1.72	11.93
5	-6.62	6.58	-6.80	6.72	-6.70	6.73	-6.82	6.85	-1.74	11.81
6	-6.62	6.58	-6.80	6.72	-6.70	6.73	-6.83	6.85	-6.74	6.81

Table 4.10. Averaging-case 90 percent confidence intervals for loblolly pine foliage transparency. LCL=lower confidence limit. UCL=upper confidence limit.

Subset	Foliage Transparency (%)									
	10th percentile		25th percentile		50th percentile		75th percentile		90th percentile	
	LCL	UCL	LCL	UCL	LCL	UCL	LCL	UCL	LCL	UCL
1	3.79	20.62	8.2	21.72	8.30	21.73	13.15	26.85	13.29	26.97
2	8.16	21.70	8.20	21.72	8.34	22.09	13.21	27.08	18.26	31.81
3	3.82	20.60	8.20	21.72	13.16	26.70	13.18	26.87	18.26	31.81
4	7.94	21.74	8.20	21.72	8.30	21.73	11.35	26.58	13.78	30.48
5	3.43	18.92	8.20	21.72	8.17	21.84	13.17	26.85	13.27	26.86
6	3.48	19.24	8.20	21.72	8.30	21.73	8.17	21.85	13.11	26.80

for some of the crown dieback percentiles. As in the best-case scenario, these negative numbers are the result of adding the "error" to zero percent dieback. Again, it should be understood that negative crown conditions are not possible and therefore, the practical lower bound for these percentiles is zero.

Sweetgum

Smoothed *edf* plots show that the shapes of the crown condition indicator distributions are similar for the sweetgum subsets (Figure 4.3). [*Edfs* are plotted as step functions for each subset individually in Appendix C.] Observed crown densities ranged from 15 to 65 percent. Crown dieback ranged from 0 to 25 percent, and foliage transparency ranged from 5 to 20 percent. Median crown density was 45 percent for Subsets 8 and 9, and 37.5 percent for Subset 7 (Table 4.11). Median crown dieback was zero percent for all subsets (Table 4.12), and median foliage transparency was 15 percent (Table 4.13).

<u>Confidence intervals for the best-case scenario</u>

Pair-wise comparisons of the subset best-case CIs (Tables 4.14, 4.15, and 4.16) addressed two questions:

1. In Alabama, are there significant differences in crown density, crown dieback, and foliage transparency between sweetgum trees growing on midslopes and flatland?
2. Between Alabama and Georgia, are there significant differences in crown density, crown dieback, and foliage transparency for sweetgum trees growing on flatland?

To address question one, pair-wise comparisons were made between Subsets 7 and 8. No significant differences were found at any of the percentiles for any of the crown indicators. This indicates that in Alabama, sweetgum trees growing on flatlands are expected to have the same crown density, crown dieback, and foliage transparency distributions as trees growing on midslopes. That is, neither midslope nor flatland sweetgum trees had significantly better or poorer crowns.

To answer question two, pair-wise comparisons were made between Subsets 7 and 9. Only one significant difference was found for these subsets, at the 25th percentile

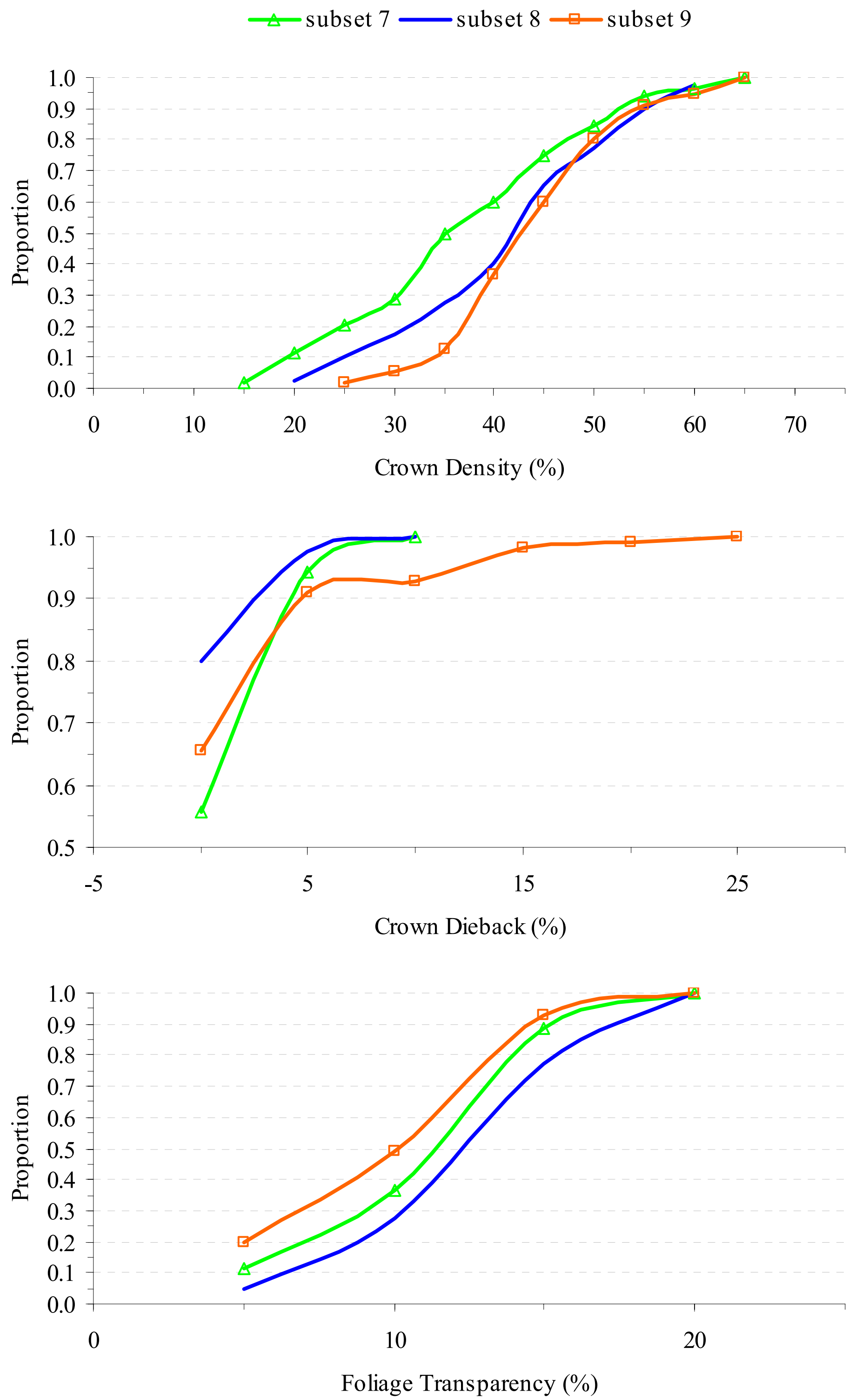


Figure 4.3. Smoothed empirical distribution functions for sweetgum crown density, crown dieback, and foliage transparency.

Table 4.11. Observed crown density percentiles by sweetgum subset.

Subset	State	Stand Origin	Terrain Position	Crown Density Percentile				
				10th	25th	50th	75th	90th
7	Alabama	Natural	Flatland	20	30	37.5	47.5	55
8	Alabama	Natural	Midslope	27.5	35	45	50	57.5
9	Georgia	Natural	Flatland	35	40	45	50	55

Table 4.12. Observed crown dieback percentiles by sweetgum subset.

Subset	State	Stand Origin	Terrain Position	Crown Dieback Percentile				
				10th	25th	50th	75th	90th
7	Alabama	Natural	Flatland	0	0	0	5	5
8	Alabama	Natural	Midslope	0	0	0	5	5
9	Georgia	Natural	Flatland	0	0	0	5	5

Table 4.13. Observed foliage transparency percentiles by sweetgum subset.

Subset	State	Stand Origin	Terrain Position	Foliage Transparency Percentile				
				10th	25th	50th	75th	90th
7	Alabama	Natural	Flatland	5	10	15	15	20
8	Alabama	Natural	Midslope	10	10	15	15	20
9	Georgia	Natural	Flatland	5	10	15	15	15

Table 4.14. Best-case 90 percent confidence intervals for sweetgum crown density. LCL=lower confidence limit. UCL=upper confidence limit.

Subset	Crown Density (%)									
	10th percentile		25th percentile		50th percentile		75th percentile		90th percentile	
	LCL	UCL	LCL	UCL	LCL	UCL	LCL	UCL	LCL	UCL
7	17.94	31.91	27.85	36.40	33.07	44.35	42.97	52.29	48.90	59.93
8	23.08	34.34	30.09	41.95	40.33	47.34	45.61	56.50	52.79	62.03
9	30.53	41.48	37.72	42.41	42.71	48.95	47.74	56.14	52.66	64.22

Table 4.15. Best-case 90 percent confidence intervals for sweetgum crown dieback. LCL=lower confidence limit. UCL=upper confidence limit.

Subset	Crown Dieback (%)									
	10th percentile		25th percentile		50th percentile		75th percentile		90th percentile	
	LCL	UCL	LCL	UCL	LCL	UCL	LCL	UCL	LCL	UCL
7	-2.21	2.19	-2.27	2.24	-2.14	5.95	2.72	7.28	2.77	9.3
8	-2.21	2.19	-2.27	2.24	-2.14	5.95	2.72	7.28	2.77	9.3
9	-2.21	2.19	-2.27	2.24	-2.23	2.29	2.14	7.27	2.88	16.34

Table 4.16. Best-case 90 percent confidence intervals for sweetgum foliage transparency. LCL=lower confidence limit. UCL=upper confidence limit.

Subset	Foliage Transparency (%)									
	10th percentile		25th percentile		50th percentile		75th percentile		90th percentile	
	LCL	UCL	LCL	UCL	LCL	UCL	LCL	UCL	LCL	UCL
7	2.89	11.95	7.76	12.45	12.65	17.24	12.72	17.31	13.07	22.05
8	6.07	12.22	7.97	16.68	12.76	17.24	12.93	21.61	17.62	22.27
9	2.73	7.35	3.85	12.16	8.03	17.01	12.72	17.28	12.82	21.30

for crown density: sweetgum trees in Georgia (Subset 9) had greater (better) crown density than those in Alabama (Subset 7). Even though the observed crown density at the 10th percentile was 15 percent better for Georgia than for Alabama, wider than average CIs for Alabama precluded significant differences at this percentile (Table 4.14). The average width of the best-case CIs across all subsets and all percentiles was 9.75 percent for crown density, 5.88 percent for crown dieback, and 6.64 percent for foliage transparency. Across all subsets the crown density CIs were widest for the 10th percentile (12.06 percent) and narrowest for the 50th percentile (7.87 percent). For crown dieback, the CIs were widest for the 90th percentile (8.21 percent) and narrowest for the 10th percentile (4.40 percent). The foliage transparency CIs were widest at the 25th percentile (7.24 percent) and narrowest at the 90th percentile (4.56 percent). Note that the negative lower bounds for crown dieback in Table 4.15 are the result of adding the "error" to an observed dieback of zero percent. As negative crown conditions are not possible, the practical lower bound for these CIs is zero percent.

Confidence intervals for the averaging-case scenario

Pair-wise comparisons of the averaging-case CIs revealed no differences among the subsets for any of the crown condition indicators (Tables 4.17, 4.18, and 4.19). The average width of the averaging-case CIs across all subsets and all percentiles was 16.46 percent for crown density, 14.15 percent for crown dieback, and 14.86 percent for foliage transparency. It should be noted that the CIs in Tables 4.18 and 4.19 include negative lower bounds for some of the crown dieback and foliage transparency percentiles. As in the best-case scenario, these negative numbers are the result of adding the "error" to a crown condition of zero percent. Again, it should be understood that negative crown conditions are not possible and therefore, the practical lower bound for these percentiles is zero.

Table 4.17. Averaging-case 90 percent confidence intervals for sweetgum crown density. LCL=lower confidence limit. UCL=upper confidence limit.

Subset	Crown Density (%)									
	10th percentile		25th percentile		50th percentile		75th percentile		90th percentile	
	LCL	UCL	LCL	UCL	LCL	UCL	LCL	UCL	LCL	UCL
7	13.83	35.72	23.58	39.39	29.21	46.38	39.16	56.19	46.75	62.07
8	19.51	36.82	27.70	45.30	37.73	51.74	38.48	54.15	48.83	65.62
9	28.08	44.44	33.20	46.89	38.30	52.01	43.38	58.41	48.37	66.81

Table 4.18. Averaging-case 90 percent confidence intervals for sweetgum crown dieback. LCL=lower confidence limit. UCL=upper confidence limit.

Subset	Crown Dieback (%)									
	10th percentile		25th percentile		50th percentile		75th percentile		90th percentile	
	LCL	UCL	LCL	UCL	LCL	UCL	LCL	UCL	LCL	UCL
7	-6.62	6.58	-6.80	6.72	-6.42	8.37	-1.84	11.85	-1.68	12.09
8	-6.62	6.58	-6.80	6.72	-6.42	8.37	-1.84	11.85	-1.68	12.09
9	-6.62	6.58	-6.80	6.72	-6.69	6.74	-2.00	11.82	-1.37	19.02

Table 4.19. Averaging-case 90 percent confidence intervals for sweetgum foliage transparency. LCL=lower confidence limit. UCL=upper confidence limit.

Subset	Foliage Transparency (%)									
	10th percentile		25th percentile		50th percentile		75th percentile		90th percentile	
	LCL	UCL	LCL	UCL	LCL	UCL	LCL	UCL	LCL	UCL
7	-1.32	15.84	3.30	16.96	8.15	21.72	8.17	21.87	9.21	26.16
8	2.80	16.63	3.90	20.03	8.30	21.73	8.78	24.93	13.11	26.80
9	-1.81	11.84	1.56	16.47	4.10	21.04	8.17	21.85	8.45	23.90

Conclusion

Based upon the averaging-case scenario CIs, no significant differences within the species were found for any of the crown condition indicators. This casts a shadow on the validity of the differences observed from the best-case CIs. Nevertheless, some intraspecies differences may exist because the two sets of CIs are based on *all* observations being either the best-case *or* averaging-case. Since a combination of the two cases unquestionably occurs in the field, the "true" CIs probably lie somewhere between the CI sets reported here. It should be noted, however, that the error incorporated in the bootstrap estimates is only part of the known error in the crown condition assessments. The best-case and averaging-case errors incorporated expected within-crew variation only. Between-crew variation also exists—more so for crown density than for crown dieback or foliage transparency (See Chapters I and II)—but no practical way of incorporating between-crew error was found. Consequently, even the averaging-case CIs represent a "best" case situation.

In addition to the uncertainty in the crown condition measurements, the "uncontrolled" environmental conditions (forest type, elevation, aspect, etc.) may have masked potential intraspecies variation. The number of observations required per subset prohibited the creation of subgroups that separated all environmental variables. It was hoped that terrain position would capture some of the variation attributable to forest type and elevation, and indeed these variables were significantly correlated (p-value <0.0001). Based upon the loblolly pine and sweetgum data utilized in Chapter III, the Spearman correlation coefficient was 0.084 between terrain position and forest type and -0.485 between terrain position and elevation.

In light of the uncertainty and possible uncontrolled variation in the data, there is little evidence to suggest that interpretations of crown condition need be concerned with intraspecies variation. A possible exception to this is loblolly pine foliage transparency. The majority of the differences within loblolly pine were found in the upper percentiles of the best-case foliage transparency CIs. Differences detected between stand origins suggest that planted trees tend to have lower (better) foliage transparency than natural stands, but this pattern was found only on flat terrain, not midslopes. Terrain position also appeared to have an impact on foliage transparency, but the effect was not consistent across stand origin. That is, for planted stands, foliage transparency was higher (poorer) on midslopes than on flatland, but for natural stands foliage transparency was highest on flatland. Further study of the differences within loblolly pine foliage transparency would be beneficial. Any such study should control as much environmental variation as possible and utilize only one field crew to eliminate between-crew variation.

CHAPTER V

AN EVALUATION OF THE CURRENT CROWN CONDITION THRESHOLD LEVELS FOR TREE HEALTH

Introduction

The USDA Forest Service Forest Inventory and Analysis (FIA) Program utilizes visual assessments of tree crowns, specifically crown density, crown dieback, and foliage transparency, to accomplish in part the forest health monitoring (FHM) mission of reporting the long-term status, changes, and trends in forest ecosystem health in the United States (USDA Forest Service 1994). Visual assessment of tree crowns has been used worldwide to measure forest health because it is generally felt that tree health and vigor are reflected in the crown condition (Anderson and Belanger 1987, Innes 1993). The size and shape of the crown affects the amount of carbohydrates produced by a tree, and therefore can have a major effect on the amount and quality of wood produced (Biging and Gill 1997). Healthy crowns are usually distributed symmetrically in a predictable manner along the stem and careful examinations for deviations from this pattern may indicate a tree undergoing stress (Waring 1987).

A single assessment of a tree crown results in the categorization of the tree as either healthy or unhealthy. The thresholds that demarcate healthy trees from unhealthy trees ideally should be based on the level at which trees are stressed to the point of biological decline. These thresholds are difficult to pinpoint, however, so the tails of statistical distributions have been used instead. Stolte et al. (1994) established thresholds by first estimating a concern threshold, i.e., the crown condition level considered to be detrimental to the future health of the tree. The cumulative (empirical) distribution function was then subdivided on each side of the concern threshold to give four overall categories of health (Figure 5.1): optimal (exceptional), nominal (acceptable), subnominal (questionable), and poor (highly undesirable). As this example illustrates, the use of statistical distributions always results in some observations designated as poor; nevertheless, statistical distributions are useful for identifying spatial and temporal changes in forest condition (Bechtold et al. 2002).

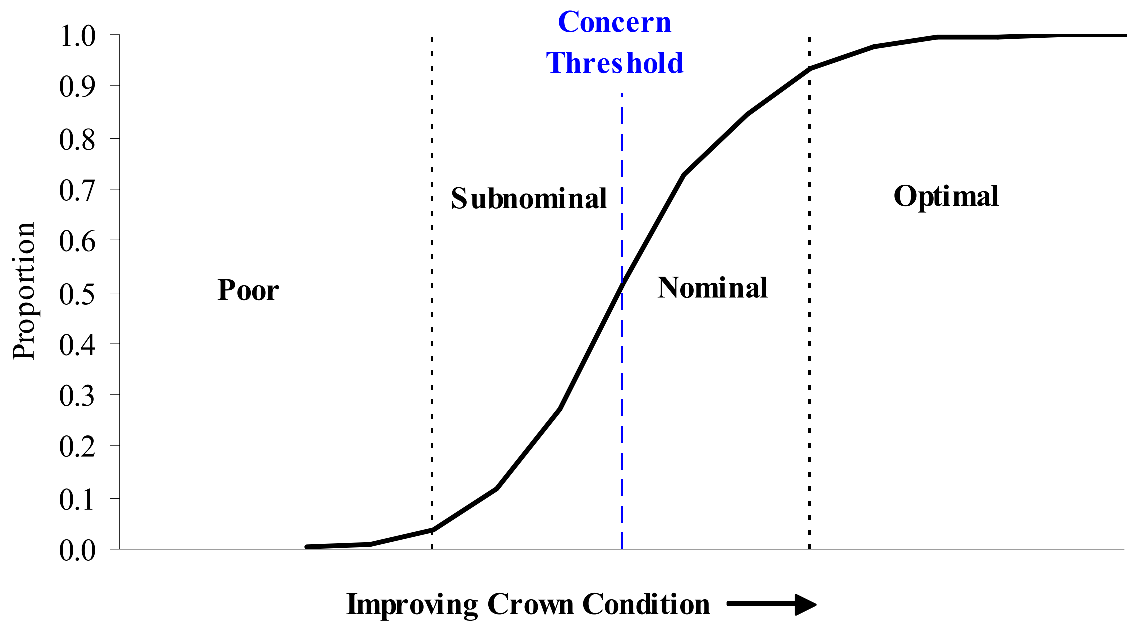


Figure 5.1. Example demarcation of crown condition thresholds based upon the four categories presented by Stolte et al. (1994).

The FIA-FHM Program has established thresholds for categorizing trees as healthy or unhealthy based upon assessments of crown density, crown dieback, and foliage transparency. (See the Introduction for definitions of crown density, crown dieback, and foliage transparency.) These thresholds are (Bechtold et al. 1992):

- crown density: good, 51-100 percent; moderate, 21-50 percent; and poor, 0-20 percent;
- crown dieback: none, 0-5 percent; light, 6-20 percent; moderate, 21-60 percent; and severe, 61-100 percent; and
- foliage transparency: normal, 0-30 percent; moderate, 31-50 percent; and severe, 51-100 percent.

Crown density, crown dieback, and foliage transparency are significantly correlated with one another (Table 5.1), but the USDA Forest Service does not assign an overall health

Table 5.1. Pearson correlation coefficients for crown density, crown dieback, and foliage transparency. All correlations are significant, $p < 0.0001$.

	Crown Density	Crown Dieback	Foliage Transparency
Crown Density	1.000	-0.213	-0.379
Crown Dieback		1.000	0.197
Foliage Transparency			1.000

rating based upon a combined score from the three indicators. Instead, any one of the indicators identifies trees potentially undergoing stress.

The “good” to “poor” categories aid data interpretation and provide general guidelines of health across all species. It is expected that the thresholds will change as further studies note differences among species (Bechtold et al. 1992); however, no adjustments have been made to date. The purpose of this paper, therefore, is to critique the crown condition indicator thresholds currently set for all species in light of the results of Chapters III and IV.

Summary of Previous Results and Threshold Critique

A gradient of expected crown conditions among species was evident in the original data, though measurement error made it difficult to confidently pinpoint species-specific differences in the crown condition indicators. In general for crown density and foliage transparency, Virginia pine had the most disparate crown conditions, and was especially distinct from sweetgum, yellow-poplar, and white oak. Crown dieback was essentially the same for all species; differences were detected at the 75th percentile only. Intraspecies differences were less pervasive as only a few percentiles among the paired comparisons were significantly different. Particularly, the significant differences occurred in the upper percentiles of loblolly pine foliage transparency. Measurement error and an insufficient number of observations to adequately categorize the data across environmental variables likely strained the discernment of intraspecies differences. Given these limitations, it would be imprudent to consider the adequacy of the current crown condition thresholds on an intraspecies level. Furthermore, since no differences were evident among the averaging-case confidence intervals, species-specific recommendations would be a dubious task as well; therefore, the critique of the current thresholds was done with the empirical distribution function (*edf*) of all species but not without consideration of species-specific deviations from this all-species average.

The all-species *edf* was based upon the same data set from which the seven select species were chosen. That is, the observations were not on plots with disturbances or on plots missing terrain positions and percent slopes. A total of 7957 observations were utilized. Included were 29 identifiable species plus trees recorded generically as hickories (*Carya* spp.). Figures 5.2-5.4 show the all-species *edf* in relation to the *edfs* of other species in the data set. The most disparate *edfs* of the seven select species illustrate that these species adequately captured the variation in the non-select species.

As stated previously, the use of statistical distributions to delineate crown condition thresholds always results in some observations designated as poor. If thresholds are set correctly, then the least desirable categories should contain a small proportion of the observations. In contrast, the remaining portion of the distribution, the "acceptable" crowns, should constitute the greatest proportion of observations. No guidelines have been given regarding the acceptable proportions to utilize; however, it seems reasonable that no more than five to ten percent of the observations should fall into the most undesirable categories. In this analysis, the proportion of observations in the poorest categories was 1.70 percent for crown density; 0.16 percent for foliage transparency; and 0.49 percent for the moderate and severe crown dieback categories combined.

While the poorest categories appear to include an acceptably small fraction of the observations, the largest proportion of the data did not necessarily fall into the best crown condition categories. The best foliage transparency and crown dieback categories included approximately 95 percent or more of the observations, but only 22.62 percent of the observations exhibited good crown density. The majority of trees (75.68 percent) had only moderate crown density suggesting that perhaps the threshold delineating good crown density is incorrectly set. Thus, adjustments to some of the thresholds are recommended to more accurately reflect the distributions of crown density, crown dieback, and foliage transparency.

Crown Density

Only 22.62 percent of the observations exhibited good crown density, which is low given that thresholds based on statistical distributions should delineate the largest proportion of observations into the best category. This seems especially evident when

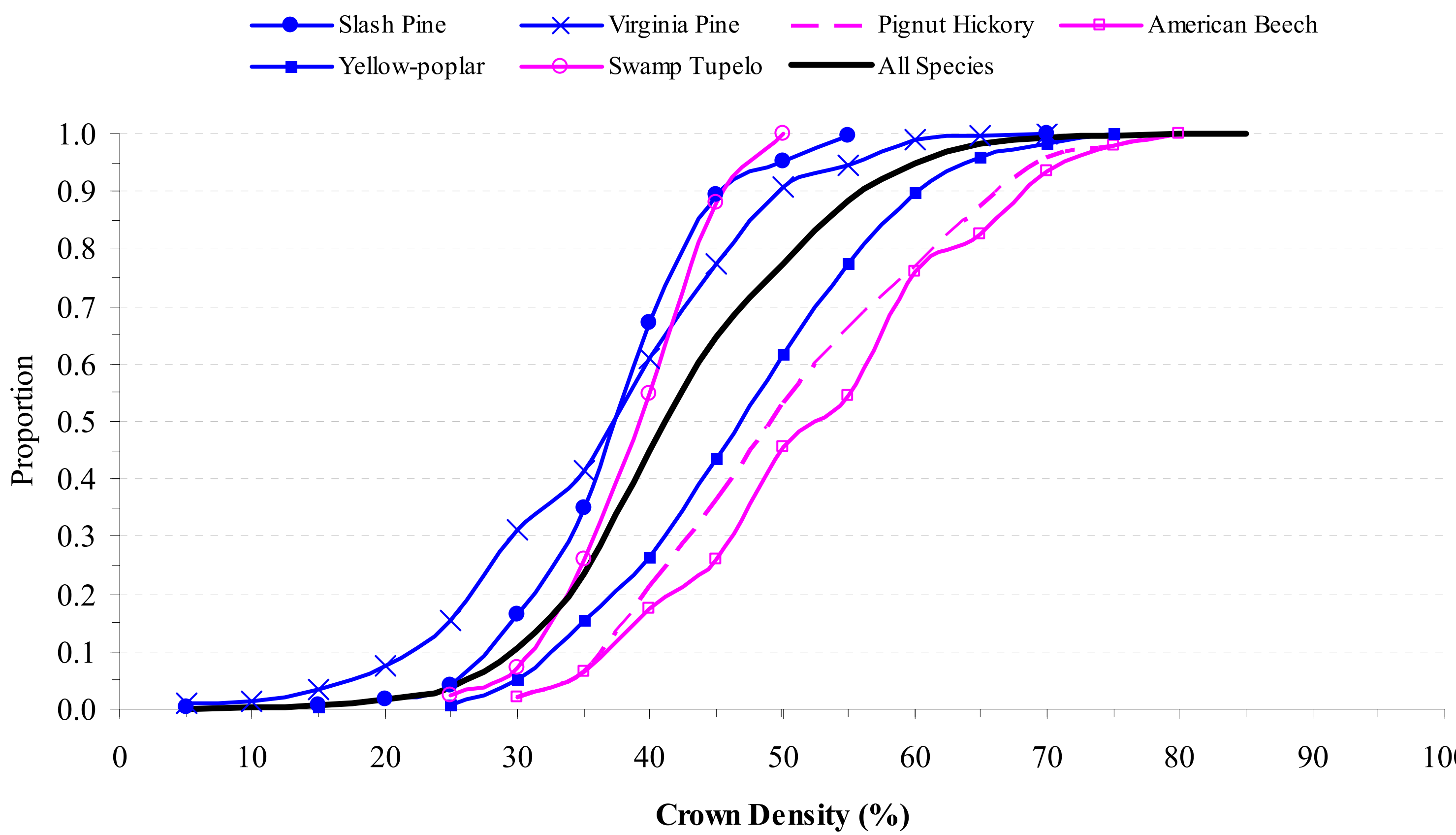


Figure 5.2. Crown density empirical distribution functions by species, including all species combined and the most disparate of the seven select species utilized in Chapter III.

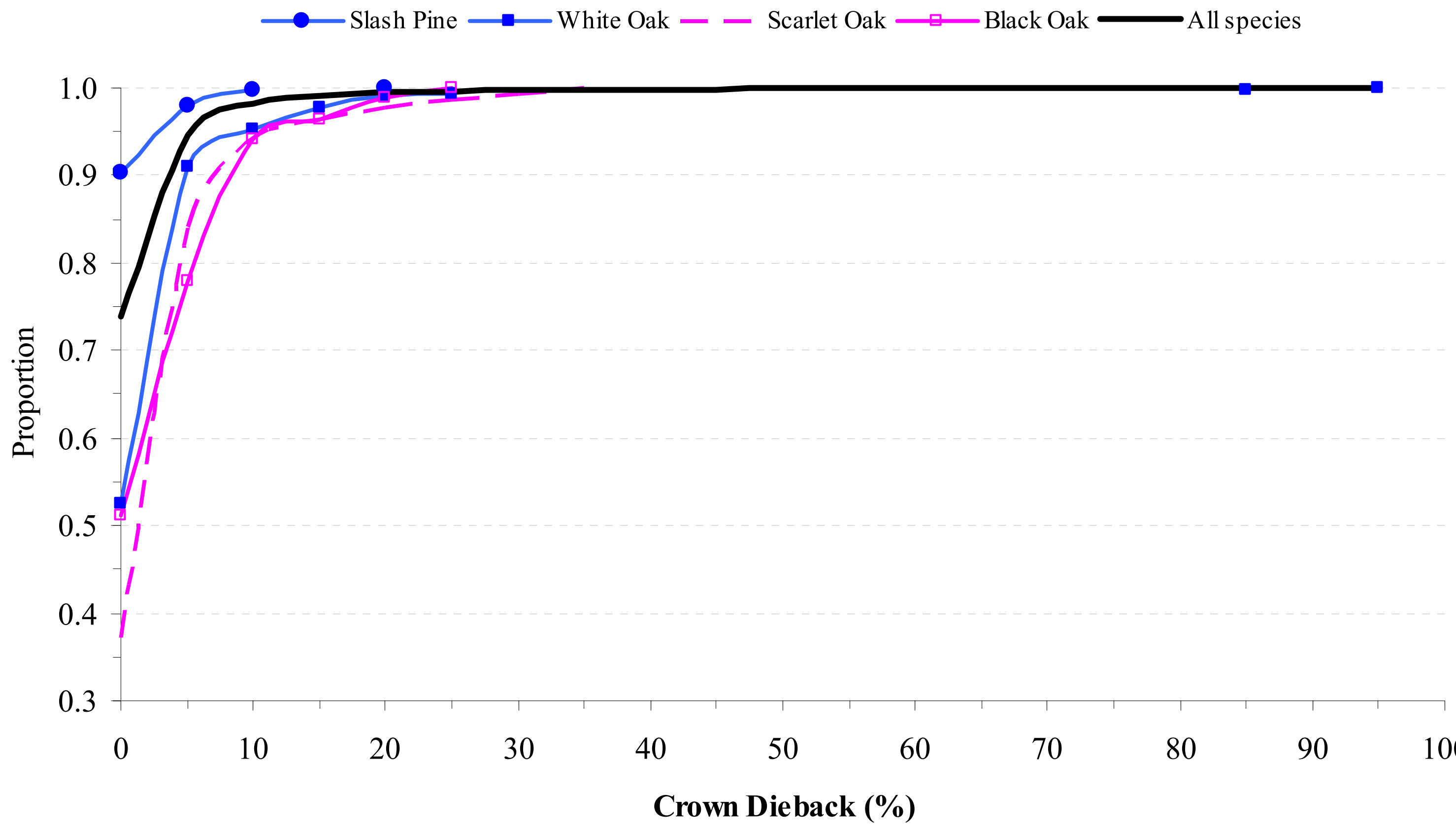


Figure 5.3. Crown dieback empirical distribution functions by species, including all species combined and the most disparate of the seven select species utilized in Chapter III.

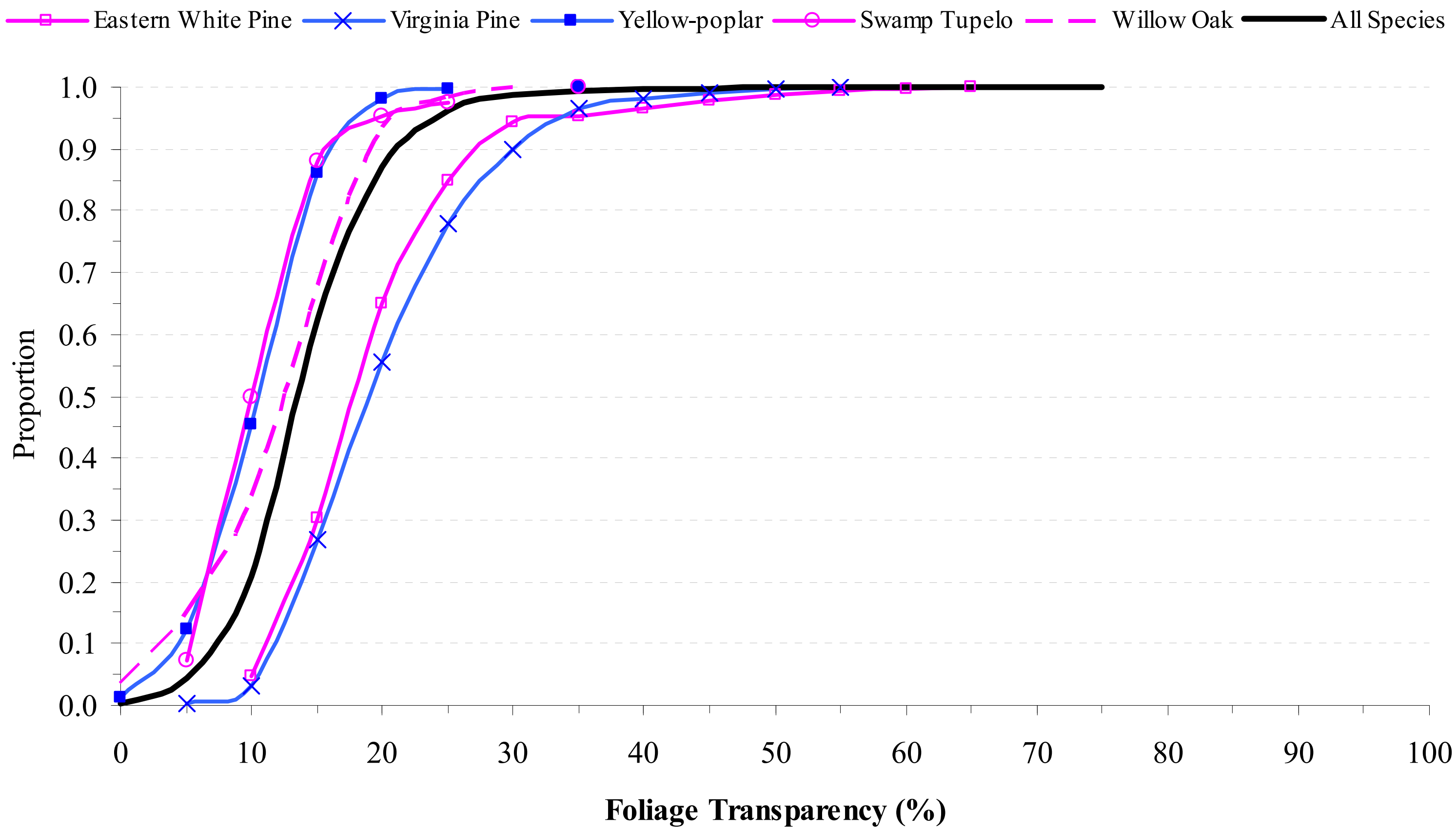


Figure 5.4. Foliage transparency empirical distribution functions by species, including all species combined and the most disparate of the seven select species utilized in Chapter III.

individual species are considered. For example, the percentage of trees in the good category ranged from a low of zero percent for swamp tupelo (*Nyssa sylvatica* var. *biflora*) to a high of 54.35 percent for American beech (*Fagus grandifolia*). In the case of swamp tupelo, all observations were in the moderate category. Alterations to the moderate class thresholds are suggested to better reflect the expected crown densities.

Given the data, it appears that both the upper and lower bounds of the moderate category need adjusting. Raising the lower bound from 20 percent to 25 or 30 percent would increase the amount of "poor" trees but not unreasonably so. At 25 percent, 3.84 percent would be classified as poor; 10.76 percent if the threshold was 30 percent. Thirty percent is deemed the acceptable level as this was the threshold of imminent mortality reported by Steinman (2000). Delineating the remainder of the distribution is not as straightforward as defining the poor crowns; however, the interquartile bounds provide guidance. The 25th and 75th percentiles were 40 and 50 percent, respectively. Setting the bounds for the moderate category as 31-40 percent and the bounds for the good category as 41-50 percent, re-labels part of the moderate crowns as "good" and effectively splits the percentage of trees in the moderate class in half. The addition of a fourth category, crown density greater than 51 percent, then delineates trees with exceptional crown density. The current and proposed thresholds and their effect on the percentage of trees in each category are given in Table 5.2.

The proposed thresholds are based upon the all-species *edf*; however, variation in crown density by species is quite large (Figure 5.2). Thus, species-specific shifts in crown density over time should be interpreted carefully. For example, American beech typically has very dense crowns, and a shift of beech trees into the moderate category would certainly indicate declining conditions since "exceptional" crowns are the norm. On the other hand, a shift of swamp tupelo trees into the moderate category might not be as alarming since moderate crown density is not atypical.

Crown Dieback

The presence of more than 20 percent crown dieback was a rare event, possibly suggesting that trees with such amounts of dieback do not survive very long. This

Table 5.2. Current and proposed categories for crown density condition, and the percentage of all observations in each category.

	Crown Density (%)		Percentage of Observations in Each Category	
	Current	Proposed	Current	Proposed
Poor	0 – 20	0 – 30	1.70	10.76
Moderate	21 – 50	31 – 40	75.68	34.21
Good	51 – 100	41 – 50	22.62	32.40
Exceptional	---	51 – 100	---	22.63

coincides with the findings of Steinman (2000) who reported that softwood trees with dieback greater than 20 percent were most likely to die within one year of assessment; the estimate was 30 percent for hardwood trees. In light of these results, it seems reasonable to establish a threshold at or near 20 percent to indicate that trees are nearing a critical level of stress, as well as a threshold beyond 30 percent to indicate ongoing stress. This can be done by moving 20 percent dieback from the light category into the moderate category, and lowering the upper bound of the moderate category from 61 percent to 35 percent. Lowering the moderate category upper bound to 35 percent is supported by the results of the North American Maple Project which indicated that crown dieback exceeding 35 percent signaled imminent mortality for sugar maple (*Acer saccharum*) (Allen et al. 1995). These slight modifications better describe the relative health of trees and do not affect the proportion of trees in each category greatly (Table 5.3). The addition of the descriptors utilized by Stolte et al. (1994)—exceptional, acceptable, questionable, and highly undesirable—is especially helpful for this crown indicator.

Foliage Transparency

With no external evidence to suggest a threshold for imminent mortality, adjusting the foliage transparency thresholds requires more improvisation than the adjustments for crown density and crown dieback. Currently, foliage transparency less than or equal to 30 percent is considered normal and outside the range of detrimental stress; however, only 1.22 percent of the trees were found to have transparency *greater* than 30 percent. As with crown dieback, this may suggest that trees cannot tolerate transparency at higher levels. Subsequently, the upper bound of the normal category should be lowered to provide a forewarning of impending decline. The 75th percentile of foliage transparency, 20 percent, provides a plausible upper limit for the normal category. Adjusting the normal/moderate threshold accordingly, modifies the percentage of trees in these categories by about 12 percent (Table 5.4).

Table 5.3. Current and proposed categories for crown dieback condition, and the percentage of all observations in each category.

	Crown Dieback (%)		Percentage of Observations in Each Category	
	Current	Proposed	Current	Proposed
None (Exceptional)	0 – 5	0 – 5	94.69	94.69
Light (Acceptable)	6 – 20	6 – 19	4.82	4.41
Moderate (Questionable)	21 – 60	20 – 35	0.39	0.66
Severe (Highly Undesirable)	61 - 100	36 – 100	0.10	0.24

Table 5.4. Current and proposed categories for foliage transparency condition, and the percentage of observations in each category.

	Foliage Transparency (%)		Percentage of Observations in Each Category	
	Current	Proposed	Current	Proposed
Normal (Acceptable)	0 – 30	0 – 20	98.78	86.96
Moderate (Questionable)	31 – 50	21 – 40	1.06	12.72
Severe (Highly Undesirable)	51 – 100	41 – 100	0.16	0.31

Conclusion

Modifications to the current thresholds were made to better partition the crown conditions into categories ranging from exceptional to highly undesirable. Most of the modifications centered on the moderate thresholds and resulted in only small changes to the percentage of observations in each category. Utilizing statistical distributions to set crown condition thresholds for health may not always correctly identify the trees undergoing stress; however, such thresholds can delineate crown conditions outside the normal range. This provides meaningful insight into forest conditions especially when the distributions are examined over time. It is important to remember, though, that the proposed (and current) thresholds are not absolute, since a range of expected crown conditions exists across species. Discretion must be exercised when declining or improving forest conditions are identified with these categories.

CONCLUSION

The USDA Forest Service Forest Inventory and Analysis (FIA) and Forest Health Monitoring (FHM) Programs have much invested in the visual assessment of tree crown condition. While the relationship between crown condition and tree vigor is not yet fully understood, such assessments are useful in identifying potentially unhealthy forest conditions. This research evaluated and described inter- and intra-species differences in three crown condition indicators, and critiqued the thresholds of health set for each of these indicators. In addition, the quality of the crown density indicator was addressed, and an attempt to estimate between-crew variation was made. The analyses herein utilized FIA Phase 3 data from six states in the southeastern United States: Alabama, Georgia, North Carolina, South Carolina, Tennessee, and Virginia. Interspecies differences were studied among slash pine, loblolly pine, Virginia pine, red maple, sweetgum, yellow-poplar, and white oak. Intraspecies differences were examined for loblolly pine and sweetgum trees in Alabama and Georgia.

Data quality of the crown density indicator

Several factors are known to influence an observer's ability to make reliable visual assessments of tree crowns. These factors range from a lack of training to the dimensions of the tree crown itself. Observer bias reduces data quality and may lead to incorrect conclusions about the health of the forest. The FIA-FHM Program has established an adequate Quality Assurance Plan to monitor the quality of the ongoing forest health monitoring; however, the crown density indicator repeatedly fails to meet the established measurement quality objective. Attempts to effectively predict between-crew variation in the crown density assessments were unsuccessful. The between-crew differences noted for the current data set were not unlike the results of Solberg and Strand's (1999) study in Norway; therefore, it may be that the expected quality of this data is too high. There are options available for improving the quality of the crown density assessments. These include improving field crew training sessions, reducing the number of rating classes, lowering the measurement quality objective, and/or changing how crown density is measured altogether, e.g. by making use of advancing digital imaging and remote sensing technologies.

Despite the poor repeatability of the crown density indicator, it and the other crown condition indicators provide adequate, albeit rough, assessments of forest health trends and should not be abandoned. Recall that within the FHM Program the detection monitoring stage (now under the direction of FIA) works in tandem with the evaluation monitoring phase. That is, forests with unmistakably declining conditions, as discovered during detection monitoring, are further scrutinized through intensified surveys. It is through the intensified surveys of the evaluation monitoring process that the extent and severity of undesirable changes in forest health are verified. Thus in the end, the crown condition assessments are not the sole factor supporting the presence of declining forest health. All the same, between-crew variation cannot be ignored and should be recognized as changes and trends in the crown condition indicators are investigated.

Interspecies differences in tree crowns

Tree crown form reflects inherent physiological traits of the tree as well as past and present external influences exerted thereon. Tree species captures the inherent physiological traits and also impacts the response of the crown to external influences. Subsequently, it is assumed that there are quantifiable differences in crown form among species, but prior to this research relatively few had been explicitly identified, particularly in context of the three crown condition indicators utilized by the FIA and FHM Programs.

A clear gradient of expected crown conditions was indeed found among the species examined herein, but uncertainty in the data made it difficult to confidently pinpoint species-specific differences for the three FIA crown condition indicators. Assuming limited measurement error in the data (i.e. the “best-case” scenario), the greatest disparity among species was found in crown density. Dissimilarity was apparent between hardwood and softwood crown densities in general, but only scattered differences were found among the species in each group. In terms of foliage transparency Virginia pine was the most dissimilar overall. Virginia pine was different than sweetgum, yellow-poplar, and white oak at all of the percentiles examined and different than red maple, loblolly pine and slash pine at almost all of the percentiles. No major differences were found among the species in terms of crown dieback.

Given the gradient of expected crown conditions among species, separating the species for data interpretation as well as data analysis is recommended. Comparative statements about crown condition among species can be made in relative terms only, because it is evident that some species tend to have relatively poorer crowns than others. If a species exhibits generally poorer crown conditions it may not necessarily be in poorer health. Though this may well be true, additional research is needed to determine if species with, for example, less dense crowns actually have lower growth rates than species with denser crowns.

Intraspecies differences in tree crowns

Stand origin and terrain position were investigated as environmental factors influencing intraspecies differences in tree crowns; however, relatively little variation was found within the two species examined. Differences were noted for loblolly pine foliage transparency suggesting that stand origin and terrain position influence this indicator, though the evidence was not overwhelmingly supportive or consistent. Few outstanding differences were found within the sweetgum crowns. This signifies that the environmental conditions considered herein have little impact on the crown appearance of sweetgum trees.

Measurement error and an insufficient number of observations to adequately categorize the data across environmental variables likely strained the discernment of intraspecies differences. The intent of the FHM Program is to monitor and detect forest health trends on national, regional, and state levels. Thus perhaps, examining the crowns on such a fine scale placed unreasonable expectations on the data. Ideally, intraspecies differences in crown condition should be examined through smaller, more controlled inventories targeting a specific set of environmental conditions. In addition, sweetgum and loblolly pine are very plastic species in that they grow well in a wide variety of environmental conditions. This adaptability may also attribute to the lack of intraspecies differences for these two species.

Review of the analytical methodology

The species' distributions were compared by examining the 10th, 25th, 50th, 75th, and 90th percentiles of the empirical distribution functions for each crown condition indicator. In order to determine statistically significant differences among the species at these various percentiles, a measure of standard error was needed; however, no natural estimate for the variance of percentiles exists (Hall and Martin 1989). Therefore, bootstrapping was utilized to calculate two-sided 90 percent confidence intervals for each percentile with the percentile confidence interval method (Lunneborg 2000). Random error was added to the percentile estimates in each bootstrap resample to capture the potential within-crew variation in the crown assessments. Two confidence interval sets were generated, one with random errors distributed Uniform (-2.5, +2.5) and one with random errors distributed Uniform (-7.5, +7.5).

Two species were declared significantly different at a percentile level if their confidence intervals for the given percentile did not overlap. Using overlapping confidence intervals to determine statistical significance is, under normal theory, a "valid but underpowered test of the hypothesis of no difference" (Mulla and Cole 2004); nonetheless, the overlapping confidence interval approach was utilized in this research. Additional analyses indicated that few changes in the outcomes of Chapters III and IV would have resulted if the standard method had been applied instead. For example, any species that was not declared significantly different from another species because one or two of the five best-case percentile confidence intervals overlapped were reevaluated using the standard method. Of the eight comparisons reexamined for crown density and foliage transparency, only one conclusion was "incorrect," that was between Virginia pine and red maple at the 75th percentile. Consequently, if the standard method had been applied instead of the overlapping method, Virginia pine and red maple could have been declared significantly different at all percentile levels. The few intraspecies comparisons selected for reevaluation were those that would have declared the tails of the distributions completely different from one another. For example, the 25th percentiles of sweetgum subsets nine and seven were significantly different under the overlapping method, but the 10th percentiles were not different. Thus, the 10th percentile was reexamined with the standard method, but still no difference was detected. While only a small proportion of the total comparisons were reexamined, the outcomes suggest that the overall best-case scenario results were not compromised by the use of the overlapping method.

Recommended changes to the crown condition thresholds

The critique of the current crown condition thresholds was done with the empirical distribution function of all species but not without consideration of species-specific deviations from the all-species average. Modifications to the current threshold levels were recommended for all three crown condition indicators: the moderate crown density category was divided in two and a new category was added to accommodate the densest crowns (Figure 35). In addition, the thresholds bounding the moderate categories for crown dieback and foliage transparency were altered because only a small proportion of the trees were found beyond the current thresholds (Figures 36 and 37). The proposed thresholds are:

- crown density: exceptional, 51-100 percent; good, 41-50 percent; moderate, 31-40 percent; and poor, 0-30 percent;
- crown dieback: none, 0-5 percent; light, 6-19 percent; moderate, 20-35 percent; and severe, 36-100 percent; and
- foliage transparency: normal, 0-20 percent; moderate, 21-40 percent; and severe, 41-100 percent.

The suggested changes resulted in only small adjustments to the percentage of observations in each category but better reflect the distribution of observations across the range of the crown conditions. Furthermore, the modified thresholds offer improved

Current Thresholds

Proposed Thresholds

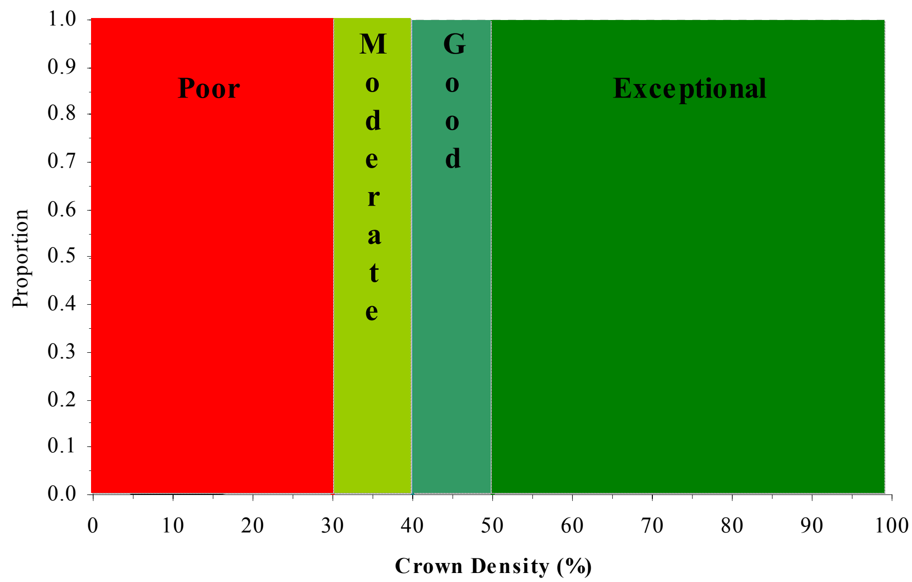
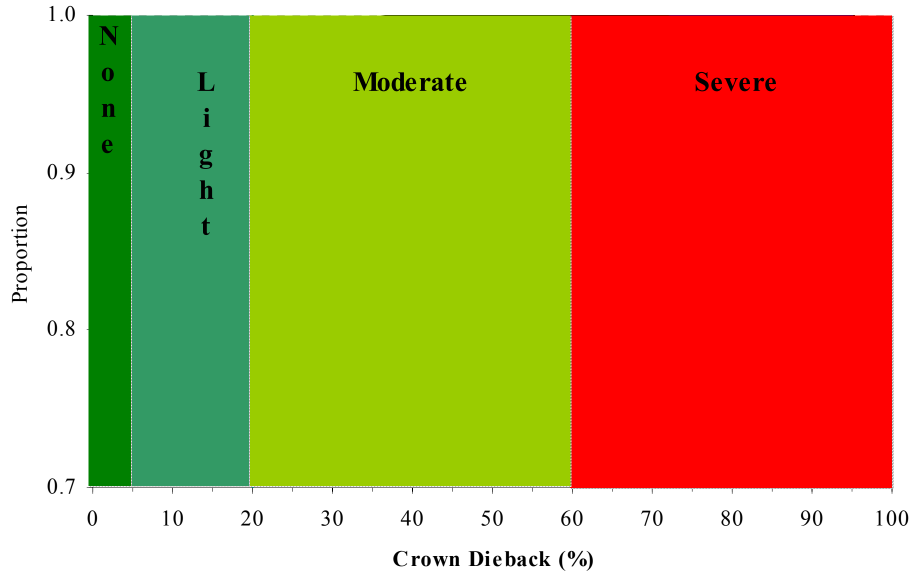


Figure 35. Current and proposed crown condition thresholds for crown density.

Current Thresholds



Proposed Thresholds

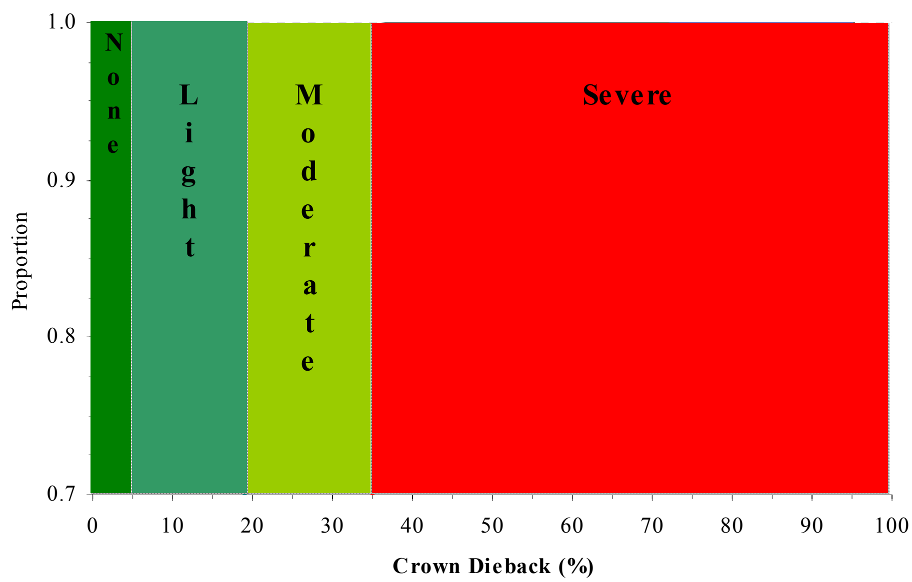
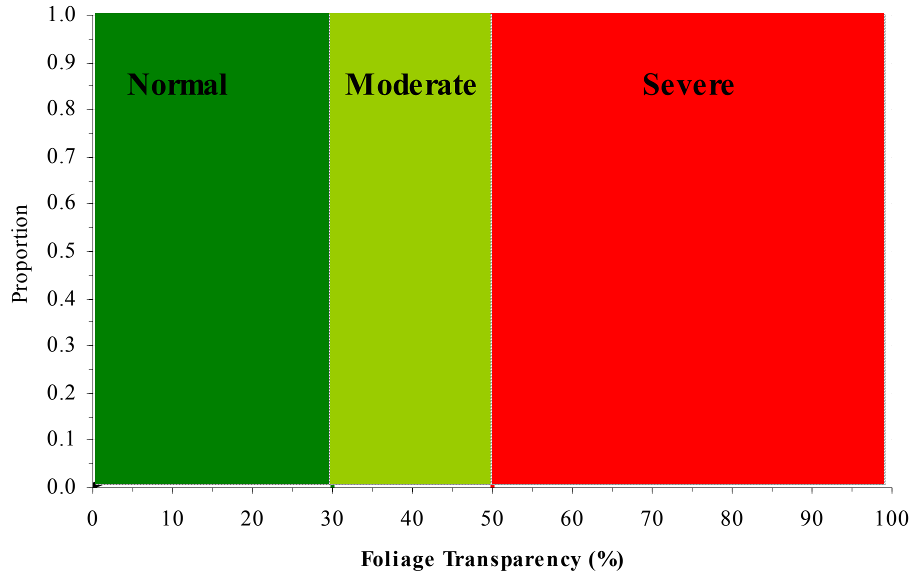


Figure 36. Current and proposed crown condition thresholds for crown dieback.

Current Thresholds



Proposed Thresholds

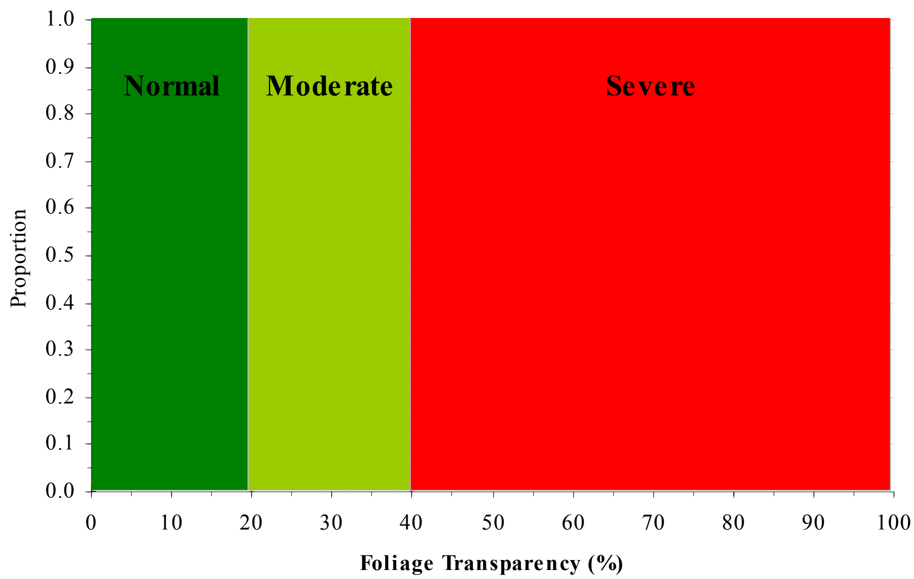


Figure 37. Current and proposed crown condition thresholds for foliage transparency.

warnings of stress or impending mortality. This was the particular intent for the proposed changes to the moderate-severe threshold of crown dieback and for the downward shift of the foliage transparency moderate category.

Suggestions for further research

The crown condition indicators provide adequate, albeit rough, assessments of forest health trends and should not be abandoned due to data quality issues. Instead, efforts should be taken to improve the repeatability of the assessments, particularly for crown density. Advancing digital imaging and remote sensing technologies may be the most promising avenues for improving crown density assessments; however, the practicality of utilizing such technologies on a nation-wide network of plots needs to be considered. Factors limiting the feasibility of these technologies include:

- the scale of the FIA and FHM Programs – the cost of providing equipment for multiple crews in each state,
- remote plot locations – the ability to transport the equipment safely to the plot without undue hardship on the field crew,
- plot conditions – dense understories and closed canopy conditions, and
- post- processing of the data – defining algorithms to analyze and summarize the collected data.

Pilot programs initiated in one or more states could address the above factors and study the cost-benefit ratios of employing new technologies.

In addition to improving the repeatability of the crown condition assessments, further understanding of the relationships between the crown condition indicators and growth, mortality, and environmental conditions (e.g. atmospheric pollution) is needed. In general, visual assessments of tree crowns in the US were begun in response to growing concern in the mid 1980s that acidic deposition and other pollutants were damaging forests. Now incorporated into the FIA Program, the crown condition indicators behave as both response and predictor variables: as response variables to atmospheric (or other environmental) changes, and as predictor variables of tree growth and mortality. Both perspectives are equally valid; however, utilizing crown condition to predict tree growth and mortality is considered the superior role by some individuals. Unfortunately, two issues currently complicate the use of the crown condition data for this purpose.

The first issue is data quality. Schreuder and Thomas (1991) note that effective predictor variables are those measured with accuracy, i.e. with small (and preferably known) error. From the data and analysis presented in Chapter II, it is evident that crown density does not meet this prerequisite. Thus, improvements in the repeatability of crown density are of utmost importance if it is to be used as a predictor of tree growth and/or mortality. The second issue is that of repeated measurements. Detection monitoring is a relatively young program in the US, and not all states have yet established the FIA Phase 3 plots. Furthermore, because definitions and data collection protocols have stabilized only in recent years, usable repeated measurements are just now emerging from the initial detection monitoring plots. As the repeated measurements are made available, modeling the relationship between crown condition and tree growth and/or mortality should begin.

Results of the predictive models just described will allow the crown condition thresholds to be adjusted so that they better reflect the crown condition levels at which trees are stressed to the point of biological decline. While these productivity thresholds are of primary concern, Stolte et al. (1994) suggest that thresholds related to aesthetics also address a relevant societal value. Aesthetic thresholds may be just as important as forest productivity thresholds since “the visual environment is the filter through which the public encounters and evaluates both forests and forestry” (Hull et al. 2000). Sheppard et al. (2004) report that there is a strong correlation between the aesthetic beauty of forest landscapes and their acceptability to the public; therefore, aesthetic thresholds should demarcate the levels of defoliation and dieback considered unhealthy, i.e. unacceptable, by the public.

Most people have an intuitive idea of what constitutes a healthy ecosystem and believe they “know it when they see it;” therefore, a survey utilizing reference photographs of forests (or trees) with varying degrees of defoliation and dieback could establish thresholds delineating public perception of healthy forests. Indeed, Sheppard et al. (2004) note that studies of this type have been conducted, but still there is no widely understood standard for how a socially acceptable forest should appear (Hull et al. 2000). As a result, new studies should be initiated to examine the relationship between forest health and aesthetics; and to the extent possible, such studies should specifically focus on the FIA Phase 3 crown condition indicators.

In closing, visual assessment of crown condition is an acceptable and relatively easy way to monitor forest health, though for the most part, the specific relationships between crown condition and tree vigor remain unidentified. Since these relationships are necessary to our understanding of tree (and forest) health, future research should place its emphasis here. Indeed, there is much to be gained from the continued assessment of the crown condition indicators.

LITERATURE CITED

Allen, D.C., A.W. Molloy, R.R. Cooke, D. Lachance, and C. Barnett. 1995. North American maple project: seven year report. USDA For. Serv. 57 p.

Anderson, R.L. and R.P. Belanger. 1987. A crown rating method for assessing tree vigor of loblolly and shortleaf pines. P. 538-5543 in Proc. of the fourth biennial southern silvicultural research conference, Phillips, D. (ed.). USDA For. Serv. Gen. Tech. Rep. SE-42.

Baker, W.L. 1941. Effect of gypsy moth defoliation on certain forest trees. Journal of Forestry. 39:1017-1022.

Bechtold, W.A., W.H. Hoffard, and R.L. Anderson. 1992. Summary report: forest health monitoring in the South, 1991. USDA For. Serv. Gen. Tech. Rep. SE-81.

Bechtold, W.A., S.J. Zarnoch, and M.E. Schomaker. 2002. Standardization, residualization, and adjusted statistical thresholds for forest health indicators. National Forest Health Monitoring workshop poster. http://www.na.fs.fed.us/spfo/fhm/posters/posters02/posters02.htm. Site visited May 2004.

Biging, G.S. and S.J. Gill. 1997. Stochastic models for conifer tree crown profiles. Forest Science. 43(1):25-34.

Bradley, J.V. 1968. Distribution-free statistical tests. Englewood Cliffs, NJ: Prentice-Hall, Inc. 388 p.

Burkman, W.G., and W.A. Bechtold. 2000. Has Virginia pine declined? The use of Forest Health Monitoring and other information in the determination. P. 258-264 in Proc. of the IUFRO conference Integrated tools for natural resources inventories in the 21st century, Hansen, M. and T. Burk (eds.). USDA For. Serv. Gen. Tech. Rep. NC-212. 744 p.

Burkman, W.G., I. Millers, and D. Lachance. 1991. Quality assurance/quality control implementation and evaluation in the North American Sugar Maple Decline Project. P. 29-44 in Research management for the future, Burns, D.P. (tech. coord.). USDA For. Serv. Gen. Tech. Rep. NE-157.

Caro, T.M, R. Roper, M. Young, and G.R. Dank. 1979. Inter-observer reliability. Behaviour. 39(3-4):303-315.

Carpenter, J. and J. Bithell. 2000. Bootstrap confidence intervals: when, which, what? A practical guide for medical statisticians. Statistics in Medicine. 19:1141-1164.

Clark, N., S. Lee, W. Bechtold, and G. Reams. 2004. Crown assessment of urban street trees using ground-based digital imaging. National Forest Health Monitoring workshop poster. http://www.na.fs.fed.us/spfo/fhm/posters/posters04/posters04.htm. Site visited May 2004.

Cline, S.P., W.G. Burkman, and C.D. Geron. 1989. Use of quality control procedures for assessing variation in measurements of forest canopy condition. P. 379-394 in Effects of air pollution on western forests, Olson, R.K. and A.S. Lefohn (eds). Pittsburgh, PA: Air and Waste Management Association.

Cline, S.P. (ed.). 1995. Forest health monitoring [microform]: quality assurance project plan for detection monitoring project/Environmental Monitoring and Assessment Program. EPA/620/R-95/002. Washington, DC: US Env. Protection Agency. various p.

Conover, W.J. 1999. Practical nonparametric statistics, 3rd edition. New York: John Wiley and Sons, Inc. 584 p.

D'Agostino, R.B., and M.A. Stephens. 1986. Graphical analysis. P. 7-62 in Goodness-of-fit techniques, D'Agostino, R.B. and M.A. Stephens (eds.). New York: Marcel Dekker. 560 p.

Deetlefs, P.P. du T. 1954. The relationship between stand density, crown size and basal area growth in stands of *Pinus taeda* in the native habitat of this species. South African Forestry Association Journal. 24:1-28.

DiCiccio, T.J. and B. Efron. 1996. Bootstrap confidence intervals. Statistical Science. 11(3):189-228.

Dixon, P.M. 1993. The bootstrap and the jackknife: describing the precision of ecological indices. P. 290-318. in Design and analysis of ecological experiments, Scheiner, S.M. and J. Gurevitch (eds.). New York: Chapman and Hall, Inc. 445 p.

Efron, B. 1979. Bootstrap methods: another look at the jackknife. The Annals of Statistics. 7:1-26.

Efron, B. 1982. The Jackknife, the bootstrap, and other resampling plans. CBMS 38, Society for Industrial and Applied Mathematics-NSF. Philadelphia, PA.

Eyre, F.H. (ed.). 1980. Forest cover types of the United States and Canada. Society of American Foresters. 148 p.

Farmer, R.E., Jr. 1976. Relationships between the genetic differences in yield of deciduous tree species and variation in canopy size, structure, and duration. P. 119-137 in Tree physiology and yield improvement, Cannell, M.G.R. and F.T. Last (eds.). New York: Academic Press. 567 p.

Ferretti, M. 1997. Forest health assessment and monitoring – issues for consideration. Environmental Monitoring and Assessment. 48:45-72.

Ferretti, M. F. Bussoitti, E. Cenni, and A. Cozi. 1999. Implementation of quality assurance procedures in the Italian programs of forest condition and monitoring. Water, Air, and Soil Pollution. 116:371-376.

Fisher, J.B. 1986. Branching patterns and angles in trees. P. 493-523 in On the economy of plant form and function, Givnish, T.J. (ed.). New York: Cambridge University Press. 717 p.

Gertner, G., and M. Köhl. 1995. Correlated observer errors and their effects on survey estimates of needle-leaf loss. Forest Science. 41(4):758-776.

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

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

Gross, H.L. 1972. Crown deterioration and reduced growth association with excessive seed production by birch. Canadian Journal of Botany. 50:2431-2437.

Guttenberg, S. 1953. Loblolly crown length – clue to vigor. USDA For. Serv. So. For. Exp. St. Southern Forestry Notes No. 88.

Hall, P., and M.A. Martin. 1989. A note on the accuracy of bootstrap percentile method confidence intervals for a quantile. Statistics and Probability Letters. 8(3):197-200.

Hall, P., and M.A. Martin. 1996. Comment on Bootstrap confidence intervals. Statistical Science. 11(3): 212-214.

Hallé, F., R.A.A. Oldeman, and P.B. Tomlinson. 1978. Tropical trees and forests: an architectural analysis. New York: Spinger-Verlag. 441 p.

Helms, J.A. 1976. Factors influencing net photosynthesis in trees: an ecological viewpoint. P. 55-78 in Tree physiology and yield improvement, Cannell, M.G.R. and F.T. Last (eds.). New York: Academic Press. 567 p.

Henning, J.G., and P.J. Radtke. 2003. Gathering 3-dimensional forest canopy data using a ground-based laser imaging device. P. 28-35 in Proc. of the IUFRO symposium on statistics and information technology in forestry, September 8-12, 2002. Blacksburg, VA.

Horn, H.S. 1971. The adaptive geometry of trees. Princeton, NJ: Princeton University Press. 144 p.

Houston, D. 1981. Stress triggered tree diseases: the diebacks and declines. USDA For. Serv. Pub. NE-INF-41-81.

Hull, R.B, D.P Robertson, G.J. Buyhoff, and A. Kendra. 2000. What are we hiding behind the visual buffer strip? Journal of Forestry. 98(7):34-38.

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

Innes, J.L. 1993. Forest health: its assessment and status. Oxon, UK: CAB International. 677 p.

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

Juknys, R. and A. Augustaitis. 1998. Indicators of crown and their application in forest health monitoring. Baltic Forestry. 2:51-58.

Kauffmann, M.R. and R.K. Watkins. 1990. Characteristics of high- and low-vigor lodgepole pine trees in old-growth stands. Tree Physiology. 7(1/4):239-246.

Kenk, G. 1993. Growth in "declining" forests of Baden-Württemberg (Southwestern Germany). P. 202-250 in Forest decline in the Atlantic and Pacific region, Huettl, R.F. and D. Mueller-Dombois (eds.). Berlin; New York: Springer-Verlag. 366 p.

King, D.A. and J.H. Maindonald. 1999. Tree architecture in relation to leaf dimensions and tree stature in temperate and tropical rain forests. The Journal of Ecology. 87(6):1012-1024.

Kuuluvainen, T. and D.G. Sprugel. 1996. Examining age- and altitude-related variation in tree architecture and needle efficiency in Norway spruce using trend surface analysis. Forest Ecology and Management. 88:237-247.

Lawrence, J. and C. Palmer. 1996. Ecological quality assurance: a Canadian perspective. P. 172-181 in North American Workshop on Monitoring for Ecological Assessment of Terrestrial and Aquatic Ecosystems, Bravo, C.A. (ed.). USDA For. Serv. Gen. Tech. Rep. RM-284.

Leckie, D., F. Gougeon, D. Hill, R. Quinn, L. Armstrong, and R. Shreenan. 2003. Combined high-density lidar and multispectral imagery for individual tree crown analysis. Canadian Journal of Remote Sensing. 29(5):633-649.

Lewis T.E., D.L. Cassell, and K.W. Stolte. 1994. Section 1 Introduction in Forest health monitoring: southeast loblolly/shortleaf pine demonstration interim report, Lewis, T.E. and B.L. Conkling (eds.). US Environmental Protection Agency Rep. EPA/620/R-94/006.

Lunneborg, C.E. 2000. Data analysis by resampling: concepts and applications. Pacific Grove, CA: Duxbury. 568 p.

McRoberts, R.E., W.H. McWilliams, G.A. Reams, T.L. Schmidt, J.C. Jenkins, K.P. O'Neill, P.D. Miles, and G.J. Brand. 2004. Assessing sustainability using data from the Forest Inventory and Analysis Program of the United States Forest Service. Journal of Sustainable Forestry. 18(1): 23-46.

Metzger, J.M. and R. Oren. 2001. The effect of crown dimensions on transparency and the assessment of tree health. Ecological Applications. 11(6):1634-1640.

Millers, I., R. Anderson, W. Burkman, and W. Hoffard. 1992. Crown condition rating guide. USDA For. Serv. State and Private Forestry.

Millers, I., D. Shriner, and D. Rizzo. 1989. History of hardwood decline in the Eastern United States. USDA For. Serv. Gen. Tech. Rep. NE-126.

Mitchell, S.K. 1979. Interobserver agreement, reliability, and generalizability of data collected in observational studies. Psychological Bulletin 86(2):376-390.

Mulla, Z.D., and S.R. Cole. 2004. RE: Epidemiology of salmonellosis in California, 1990-1999: morbidity, mortality, and hospitalization costs. American Journal of Epidemiology. 159(1):104.

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

Oliver, C.D. and B.C. Larson. 1996. Forest stand dynamics, update edition. New York: John Wiley and Sons, Inc. 520 p.

Polansky, A.M. 1999. Upper bounds on the true coverage of bootstrap percentile type confidence intervals. The American Statistician. 53(4):362-369.

Polansky, A.M. 2000. Stabilizing bootstrap-t confidence intervals for small samples. Canadian Journal of Statistics. 28:501-516.

Pollard, J.E. and W. Smith. 1999. Forest Health Monitoring 1998 plot component quality assurance report, Volume I. USDA For. Serv. National Forest Health Monitoring Program, Research Triangle Park, NC 27709.

Pollard, J.E. and W.D. Smith. 2001. Forest Health Monitoring 1999 plot component quality assurance report. USDA For. Serv. National Forest Health Monitoring Program, Research Triangle Park, NC 27709.

Popescu, S.C., R.H. Wynne, and R.F. Nelson. 2003. Measuring individual tree crown diameter with lidar and assessing its influence on estimating forest volume and biomass. Canadian Journal of Remote Sensing. 29(5):564-577.

Price, T.S., C. Doggett, J.M. Pye, and B. Smith, (eds.). 1998. A history of southern pine beetle outbreaks in the Southeastern United States. Georgia Forestry Commission, Southeastern Forest Insect Working Group.

Reams, G.A., N. Clark, and J. Chamberlain. [In press]. Monitoring the sustainability of the southern forest. in Southern forest science: past, present, and future, Rauscher, H.M. and K. Johnsen (eds.). USDA For. Serv. Gen. Tech. Rep.

Remphrey, W.R., C.G. Davidson, and M.J. Blouw. 1987. A classification and analysis of crown form in green ash (*Fraxinus pennsylvanica*). Canadian Journal of Botany. 65:2188-2195.

Reynolds, M.R., Jr., T.E. Burk, W. Huang. 1988. Goodness-of-fit tests and model selection procedures for diameter distribution models. Forest Science. 34(2):373-399.

Riitters, K. and B. Tkacz. 2004. The US Forest Health Monitoring Program. P. 669-683 in Environmental Monitoring, Wiersma, B. (ed.). Boca Raton, FL: CRC Press.

Schenker, N., and J.F. Gentleman. 2001. On judging the significance of differences by examining the overlap between confidence intervals. The American Statistician. 55(3):182-186.

Schreuder, H.T., and C.E. Thomas. 1991. Establishing cause-effect relationships using forest survey data. Forest Science. 37(6):1497-1512.

Sheppard, S.R., C. Achiam, and R.G. D'Eon. 2004. Aesthetics: are we neglecting a critical issue in certification for sustainable forest management? Journal of Forestry. 102(5):6-11.

Sherwood, R.T., C.C. Berg, M.R. Hoover, and K.E. Zeiders. 1983. Illusions in visual assessment of Stagonospora leaf spot of orchardgrass. Phytopathology. 73:173-177.

Solberg, S. and L. Strand. 1999. Crown density assessments, control surveys and reproducibility. Environmental Monitoring and Assessment. 56:75-86.

Steinman, J. 2000. Tracking the health of trees over time on forest health monitoring plots. P. 334-339 in Proc. of the IUFRO conference Integrated tools for natural resources inventories in the 21st century, Hansen, M. and T. Burk (eds.). USDA For. Serv. Gen. Tech. Rep. NC-212. 744 p.

Stephens, M.A. 1986. Tests based on EDF statistics. P. 97-193 in Goodness-of-fit techniques, D'Agostino, R.B. and M.A. Stephens (eds.). New York: Marcel Dekker. 560 p.

Stine, R. 1989. An introduction to bootstrap methods. Sociological Methods and Research. 18(2-3):243-291.

Sterck, F.J., F. Bongers, and D.M. Newbery. 2001. Tree architecture in a Bornean lowland rain forest: intraspecific and interspecific patterns. Plant Ecology. 153:279-292.

Stokes, M.E., C.S. Davis, and G.G. Koch. 2000. Categorical data analysis using the SAS System, second edition. Cary, NC: SAS Institute, Inc.

Stolte, K.W., R.N. Binns, and T.R. Stockton. 1994. Crown condition. P. 4.1-4.32 in Forest health monitoring [microform]: southeast loblolly/shortleaf pine demonstration interim report, Lewis, T.E. Lewis and B.L. Conkling (eds.). EPA/620/R-94/006. Washington, DC: US Environmental Protection Agency.

Stoyenoff, J., J. Witter, and B. Leutscher. 1998. Forest health in the North Central states. Ann Arbor, MI: Univ. of MI, School of Natural Resources. Unnumbered publication.

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

Taylor, J.K. 1988. Quality control data. in Proceedings of the first ecological quality assurance workshop; Corvallis, Oregon. US Environmental Protection Agency.

USDA Forest Service. 1990. Silvics of North America: 1. Conifers; 2. Hardwoods, Burns, R.M, and B.H. Honkala (tech. coords.). Agriculture Handbook 654. Washington, DC: USDA For. Serv. 877 p.

USDA Forest Service. 1994. Forest health monitoring: A national strategic plan. USDA For. Serv. Southern Region. 13 p.

USDA Forest Service. 1998. Quality assurance. Forest Health Monitoring Fact Sheet Series.

USDA Forest Service. 1999. Forest Health Monitoring 1999 Field Methods Guide. USDA For. Serv. National Forest Health Monitoring Program, Research Triangle Park, NC 27709. various pp.

USDA Forest Service. 2002a. Forest inventory and analysis national core field guide, FIA Phase 3 Crowns: measurements and sampling, version 1.6. USDA For. Serv. Washington Office. http://fia.fs.fed.us/library.htm#manuals. Site visited May 2004.

USDA Forest Service. 2002b. Enhanced FIA implementation status. USDA For. Serv. Forest Inventory and Analysis. http://fia.fs.fed.us/news.htm. Site visited May 2002.

Valentine, J. and A.B. Ismail. 1983. The efficiency of visual assessment for yield and its components in winter oat rows. Annals of Applied Biology. 102:551-556.

Virginia Tech. 2004. Tree fact sheets. Virginia Tech, Department of Forestry. http://www.cnr.vt.edu/dendro/dendrology/syllabus/biglist_frame.htm. Site visited June 2004.

Vissage, J.S. and W.H. Hoffard. 1997. Summary report: forest health monitoring in the South, 1992. USDA For. Serv. Res. Bul. SO-195. 27 p.

Waring, R.H. 1987. Characteristics of trees predisposed to die. BioScience. 37(8):569-574.

Wolfe, R., and J. Hanley. 2002. If we're so different, why do we keep overlapping? When 1 plus 1 doesn't make 2. Canadian Medical Association Journal (electronic). 166(1). http://www.cmaj.ca/cgi/content/full/166/1/65. Site visited July 2004.

APPENDIX A

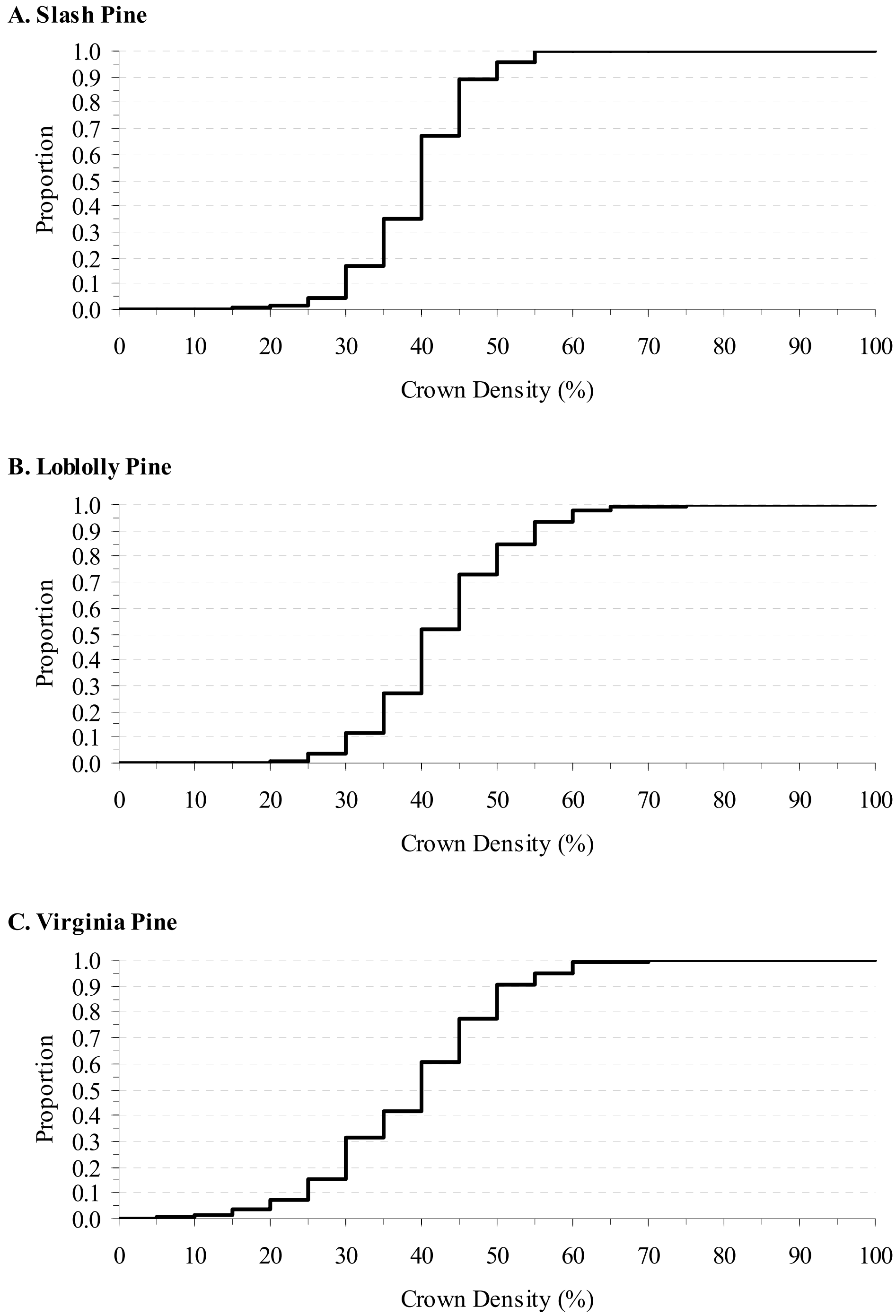
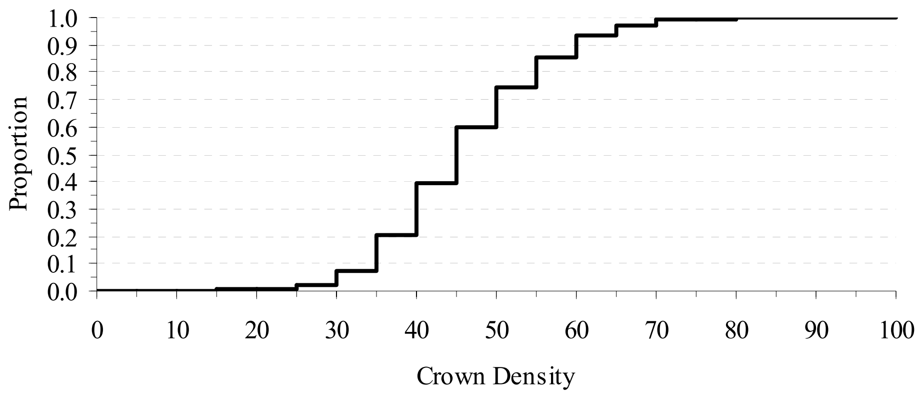
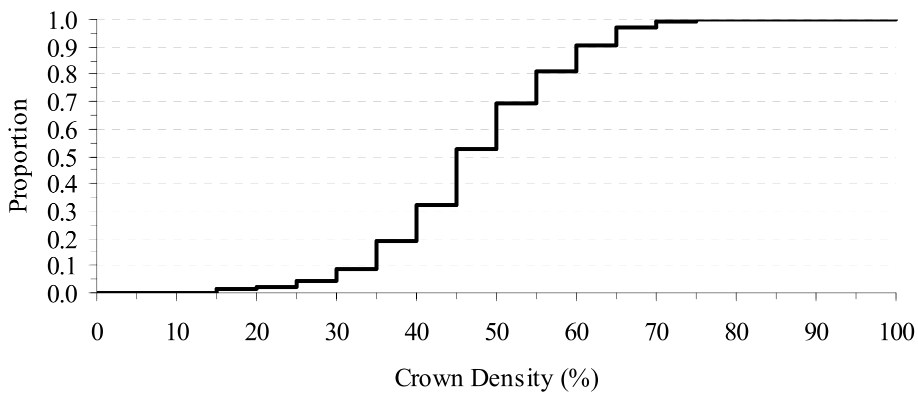


Figure A.1. Crown density empirical distribution functions by species. (A) slash pine. (B) loblolly pine. (C) Virginia pine. (D) red maple. (E) sweetgum. (F) yellow-poplar. (G) white oak.

D. Red Maple



E. Sweetgum



F. Yellow-poplar

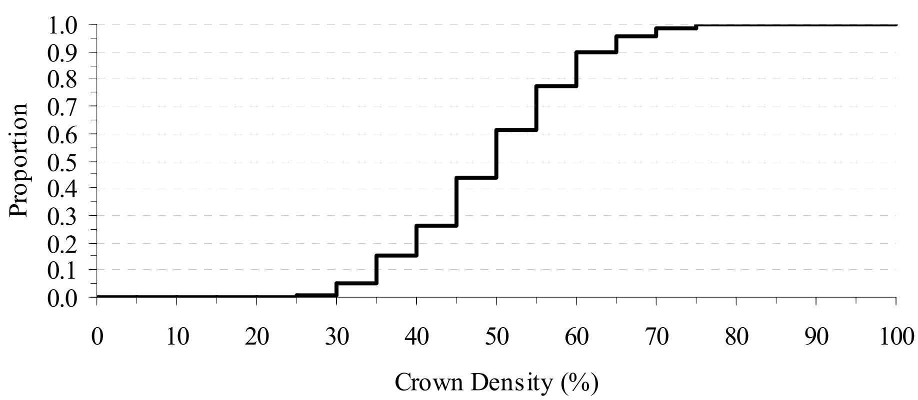


Figure A.1. Continued.

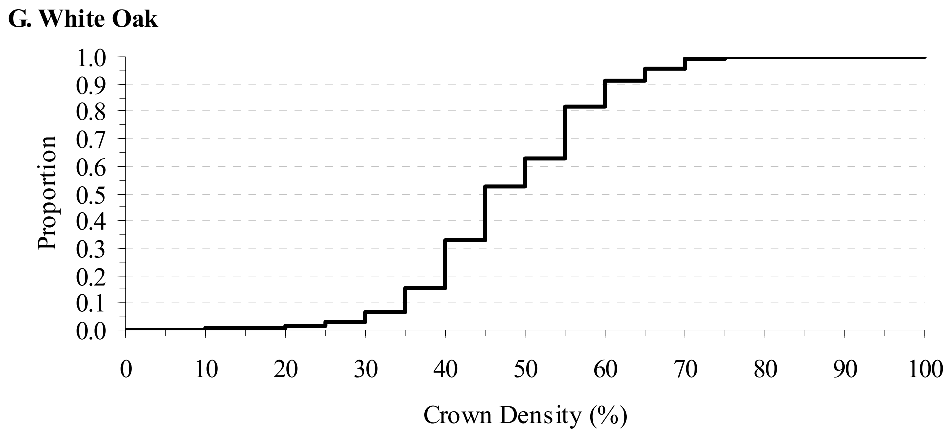


Figure A.1. Continued.

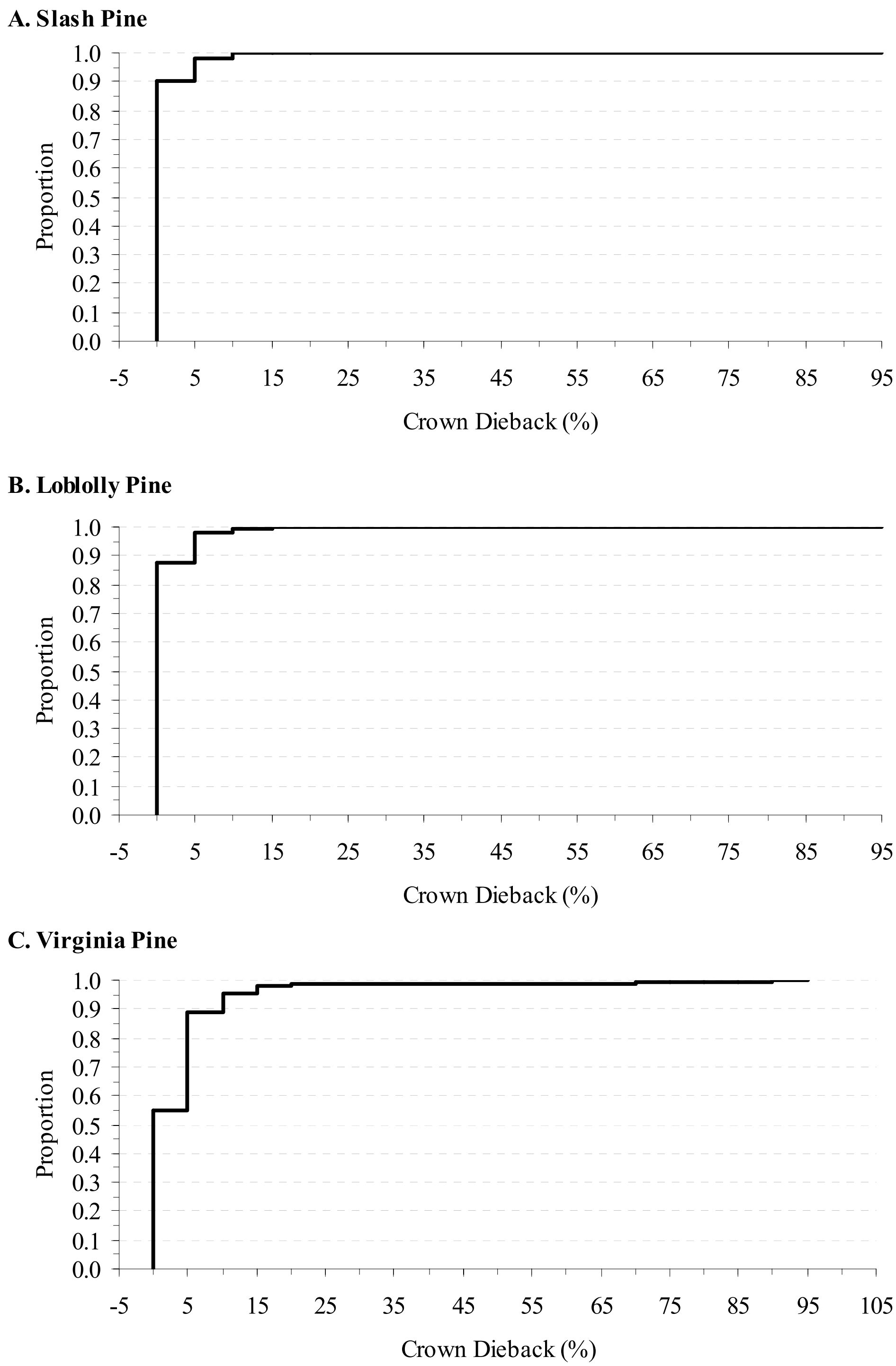
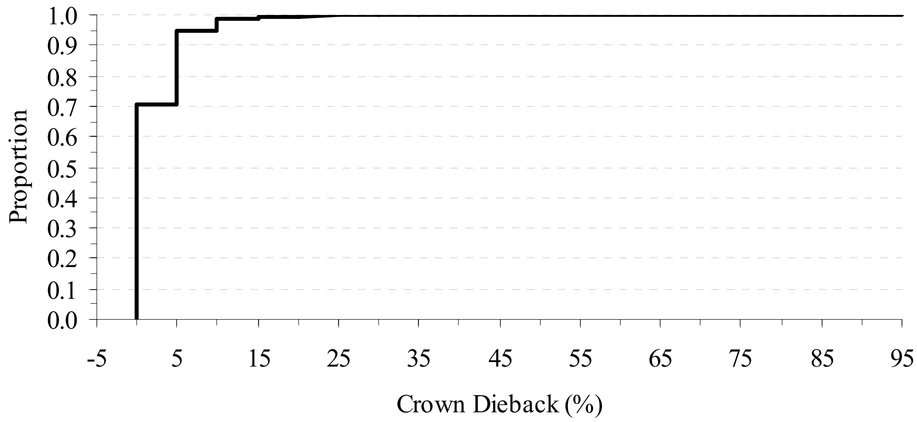
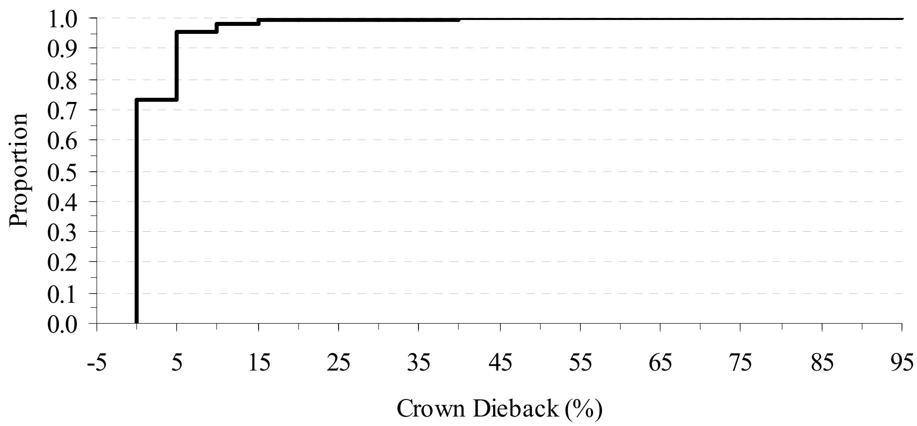


Figure A.2. Crown dieback empirical distribution functions by species. (A) slash pine. (B) loblolly pine. (C) Virginia pine. (D) red maple. (E) sweetgum. (F) yellow-poplar. (G) white oak.

D. Red Maple



E. Sweetgum



F. Yellow-poplar

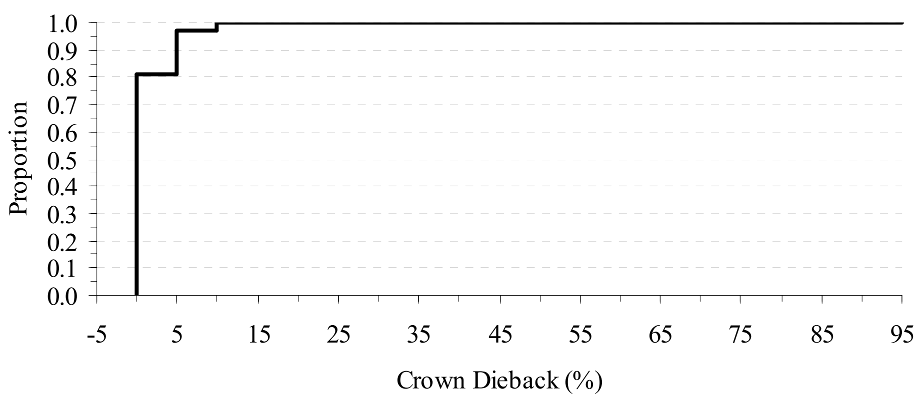


Figure A.2. Continued.

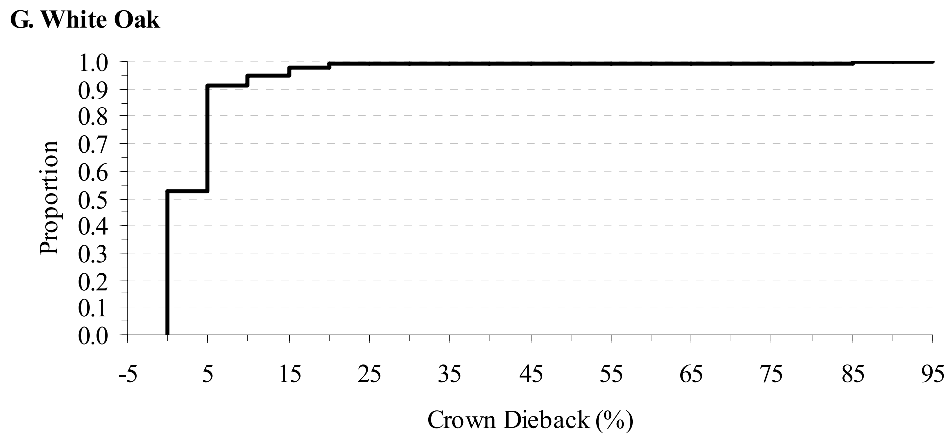


Figure A.2. Continued.

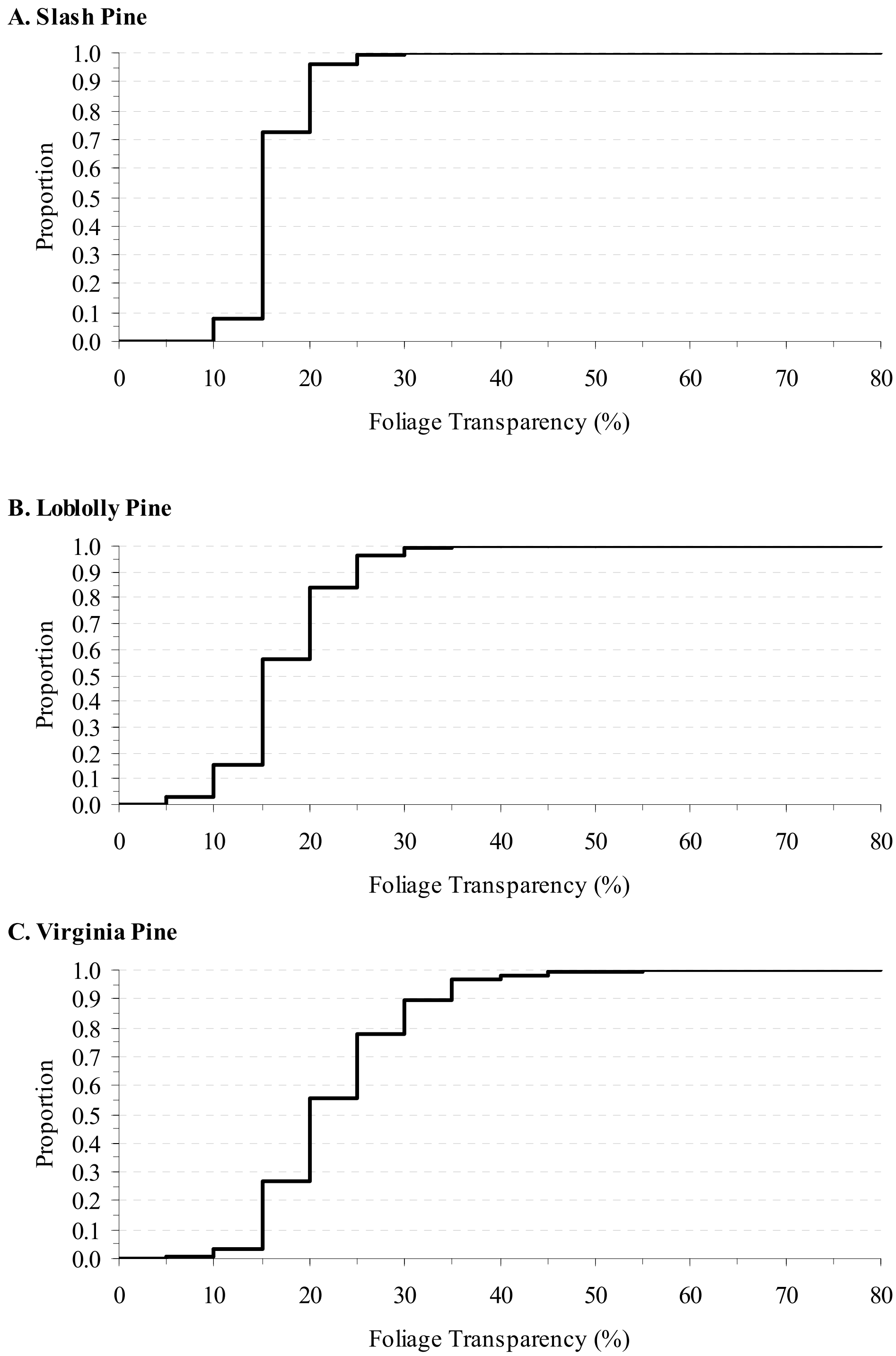
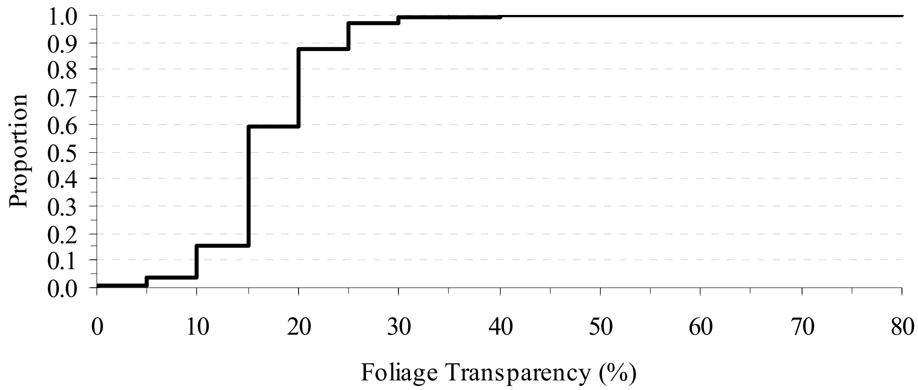
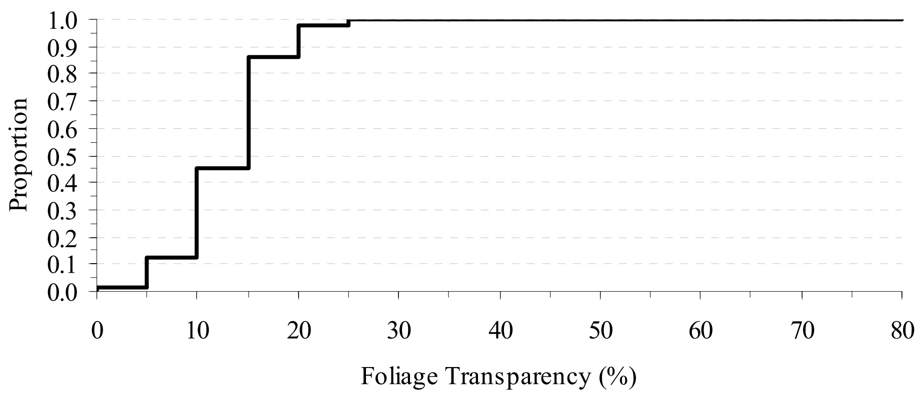


Figure A.3. Foliage transparency empirical distribution functions by species. (A) slash pine. (B) loblolly pine. (C) Virginia pine. (D) red maple. (E) sweetgum (F). yellow-poplar. (G) white oak.

D. Red Maple



E. Sweetgum



F. Yellow-poplar

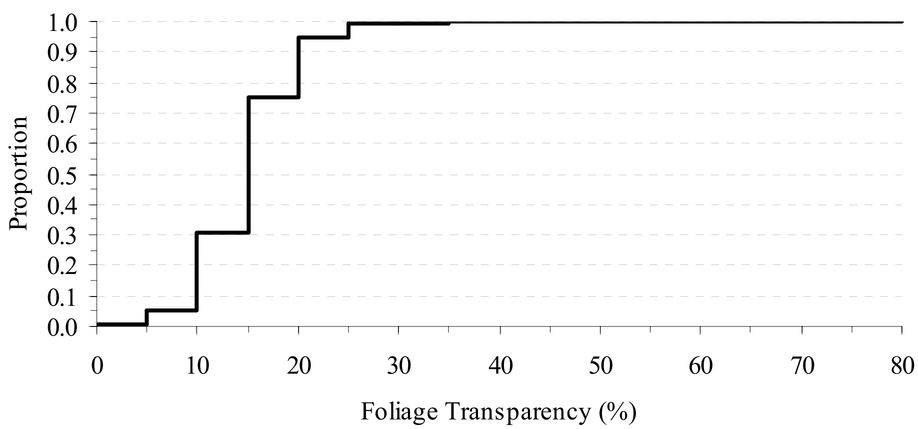


Figure A.3. Continued.

G. White Oak

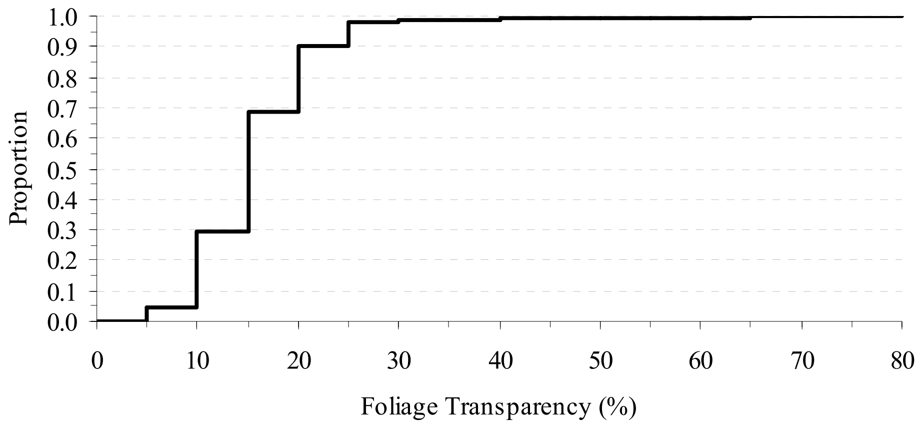
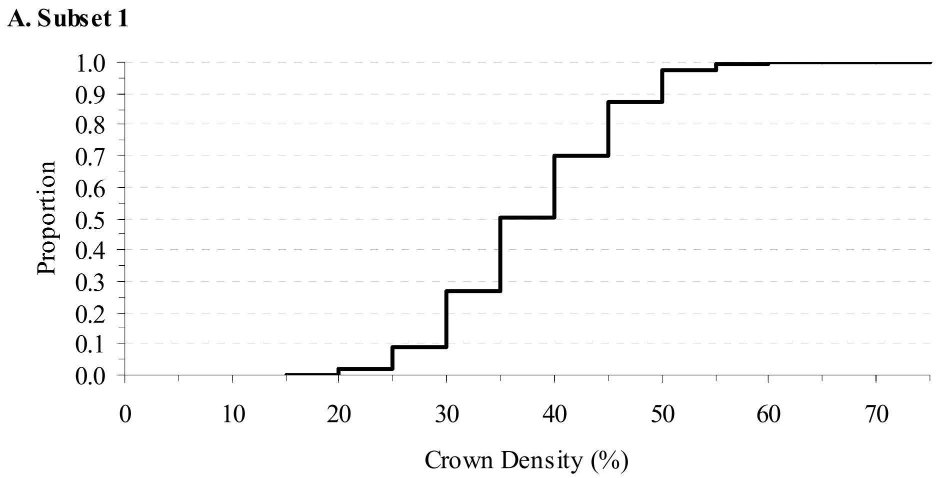
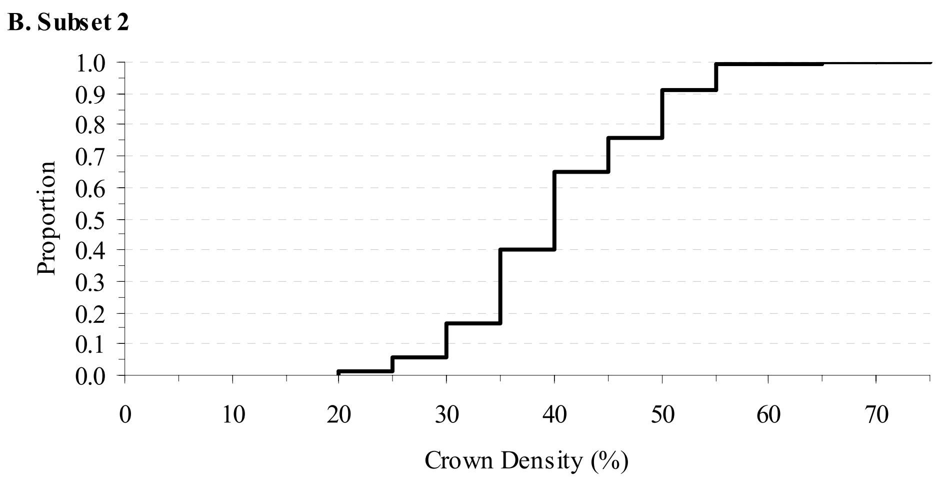


Figure A.3. Continued.

APPENDIX B





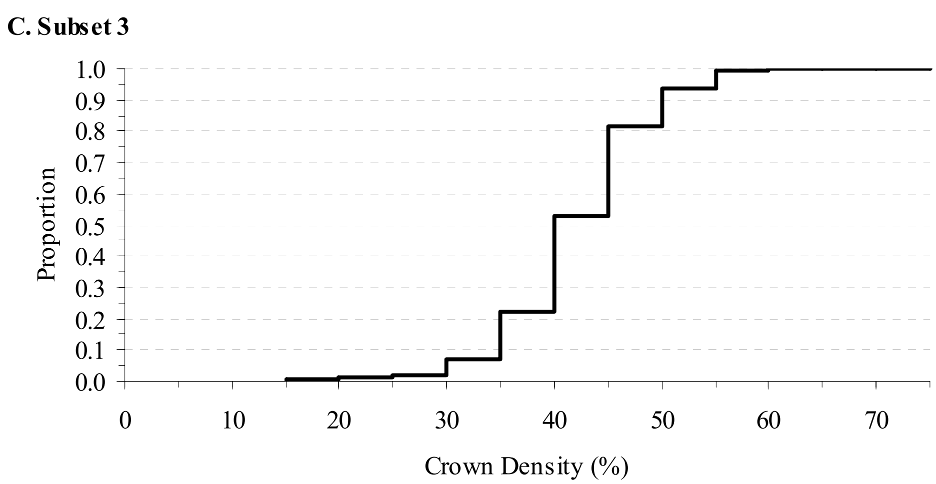
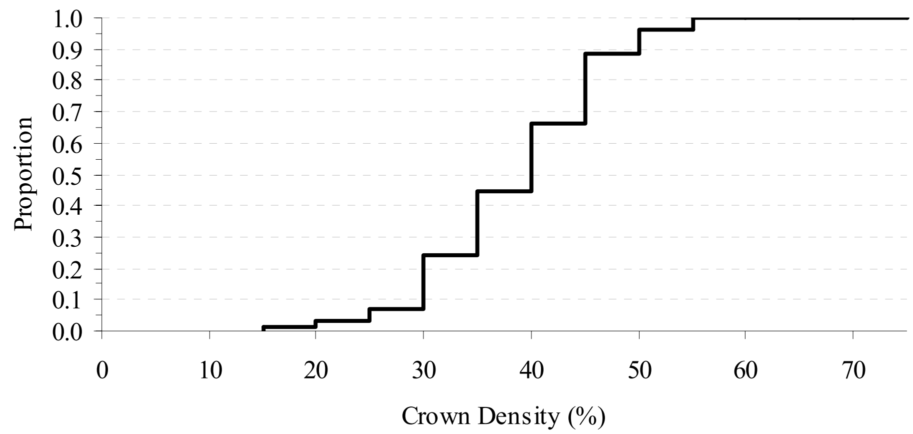
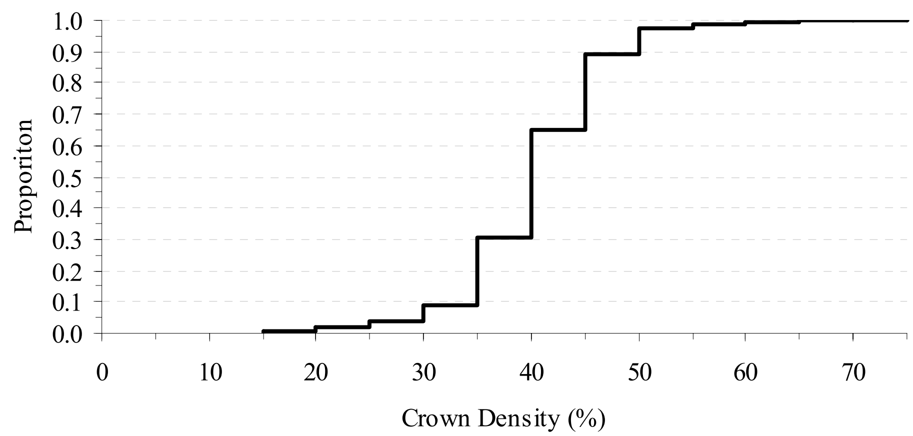


Figure B.1. Crown density empirical distribution functions by loblolly pine subset. (A) Subset 1. (B) Subset 2. (C) Subset 3. (D) Subset 4. (E) Subset 5. (F) Subset 6. Subset definitions are given in Table 4.1 (page 95).

D. Subset 4



E. Subset 5



F. Subset 6

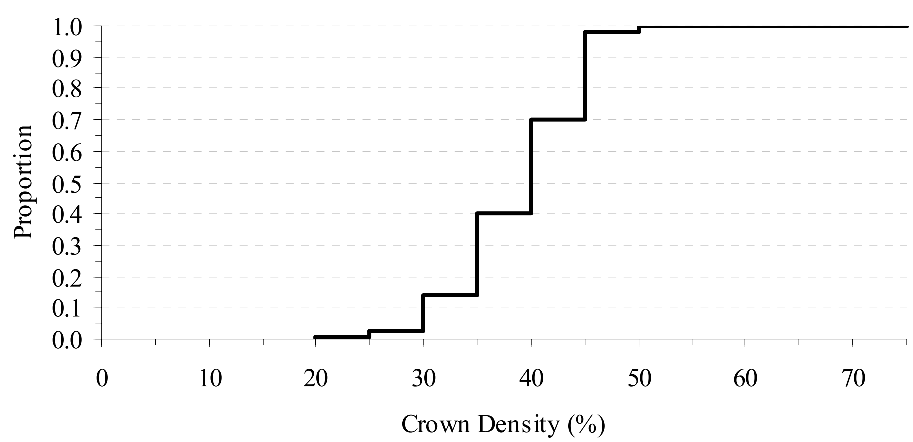
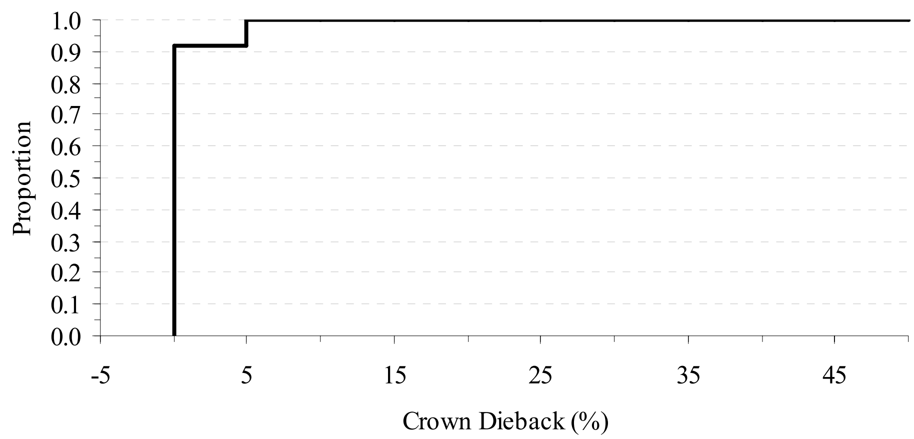
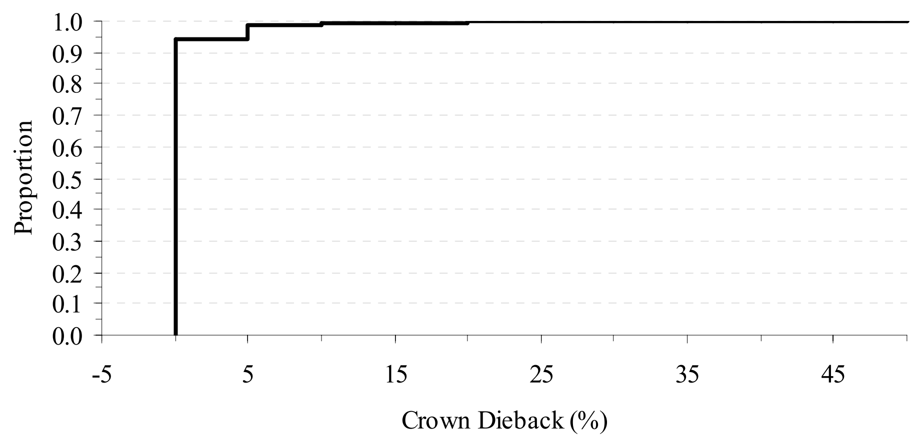


Figure B.1. Continued.

A. Subset 1



B. Subset 2



C. Subset 3

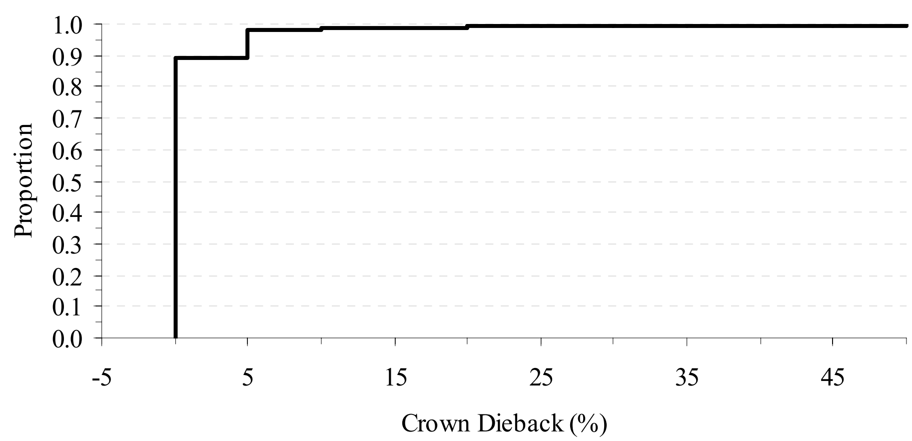
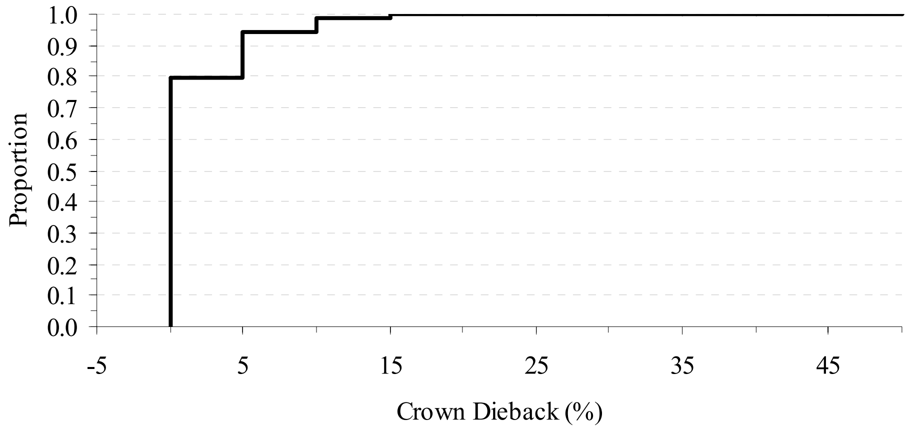
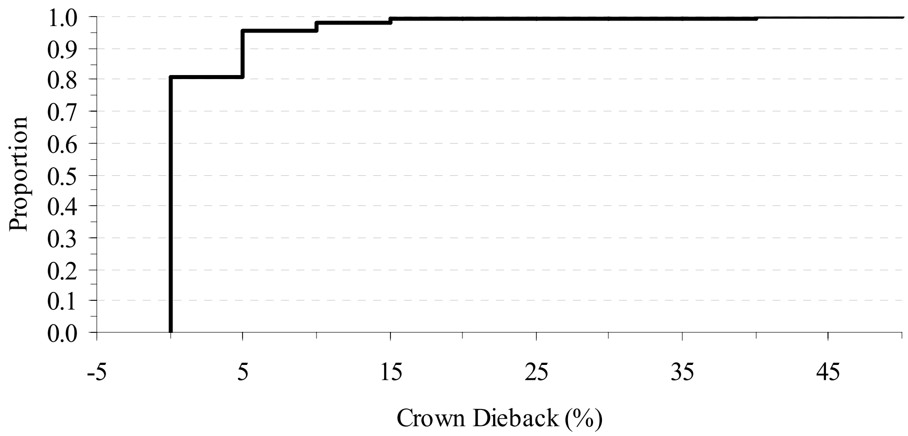


Figure B.2. Crown dieback empirical distribution functions by loblolly pine subset. (A) Subset 1. (B) Subset 2. (C) Subset 3. (D) Subset 4. (E) Subset 5. (F) Subset 6. Subset definitions are given in Table 4.1 (page 95).

D. Subset 4



E. Subset 5



F. Subset 6

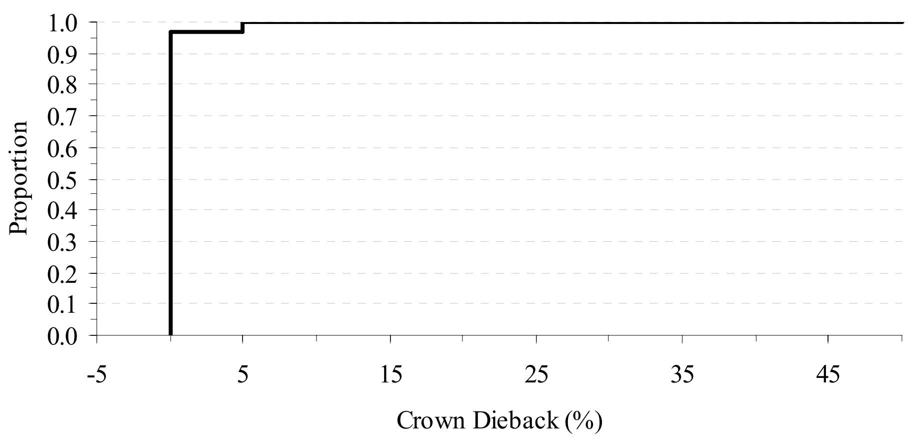


Figure B.2. Continued.

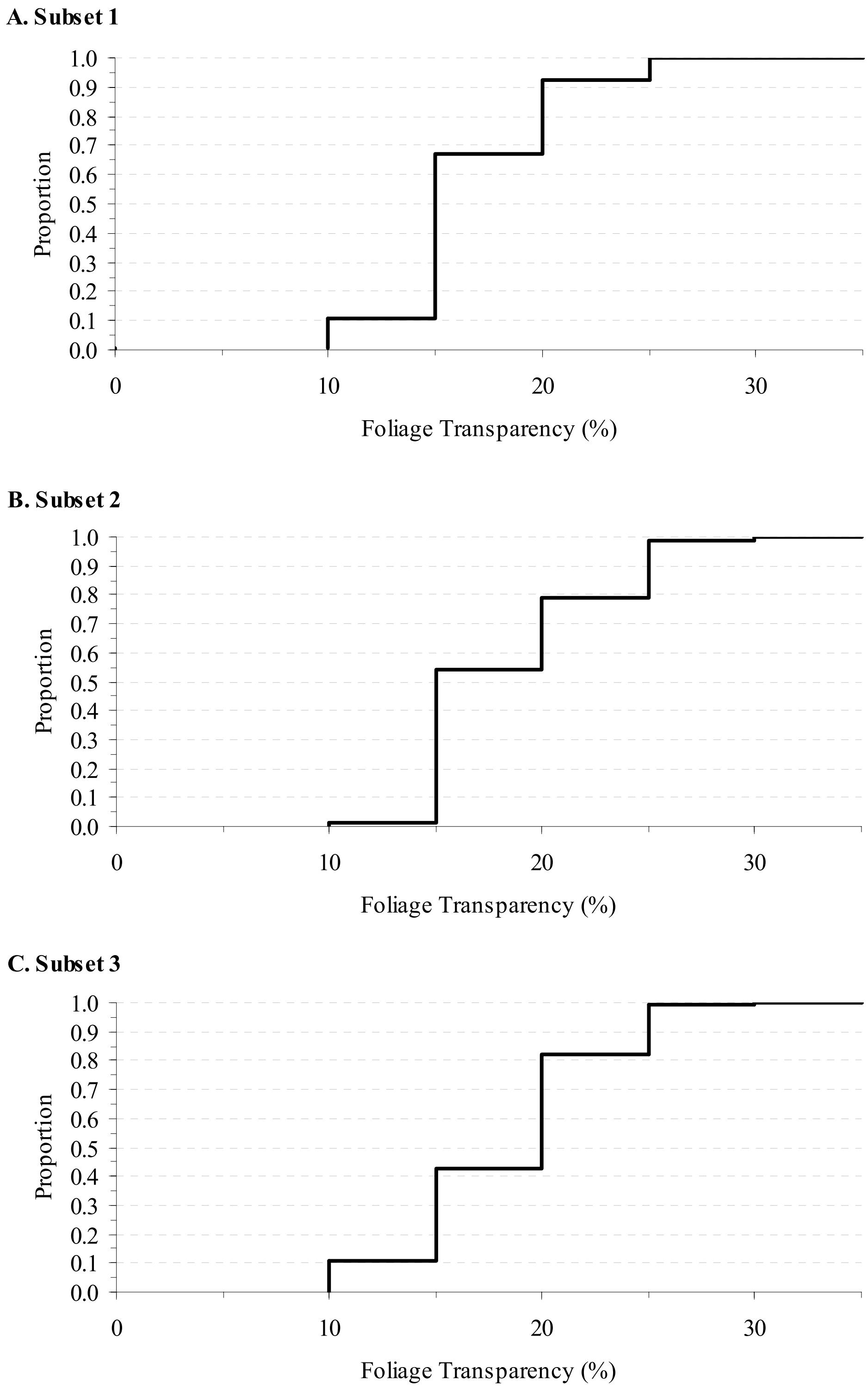
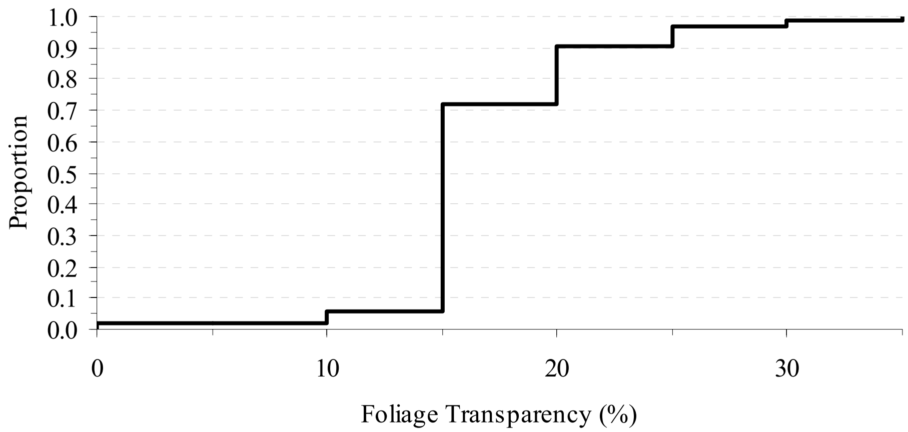
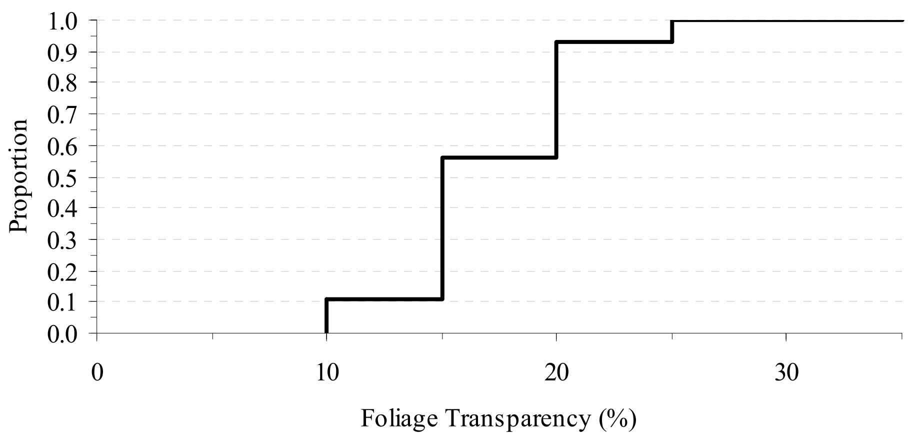


Figure B.3. Foliage transparency empirical distribution functions by loblolly pine subset. (A) Subset 1. (B) Subset 2. (C) Subset 3. (D) Subset 4. (E) Subset 5. (F) Subset 6. Subset definitions are given in Table 4.1 (page 95).

D. Subset 4



E. Subset 5



F. Subset 6

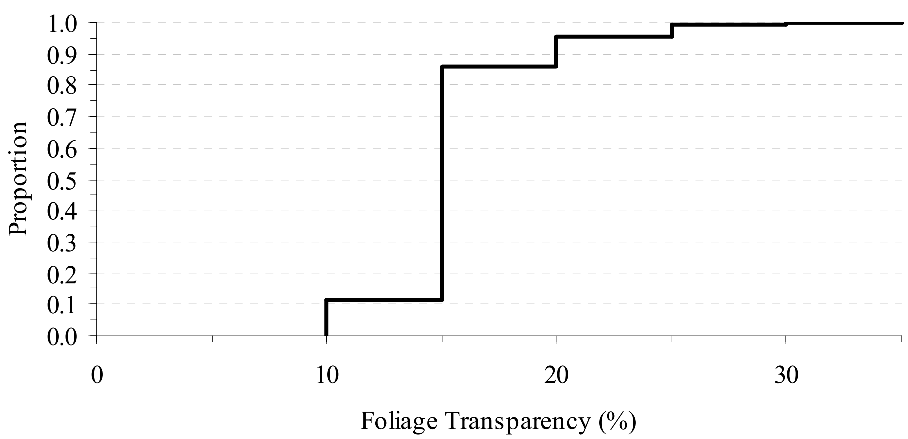


Figure B.3. Continued.

APPENDIX C

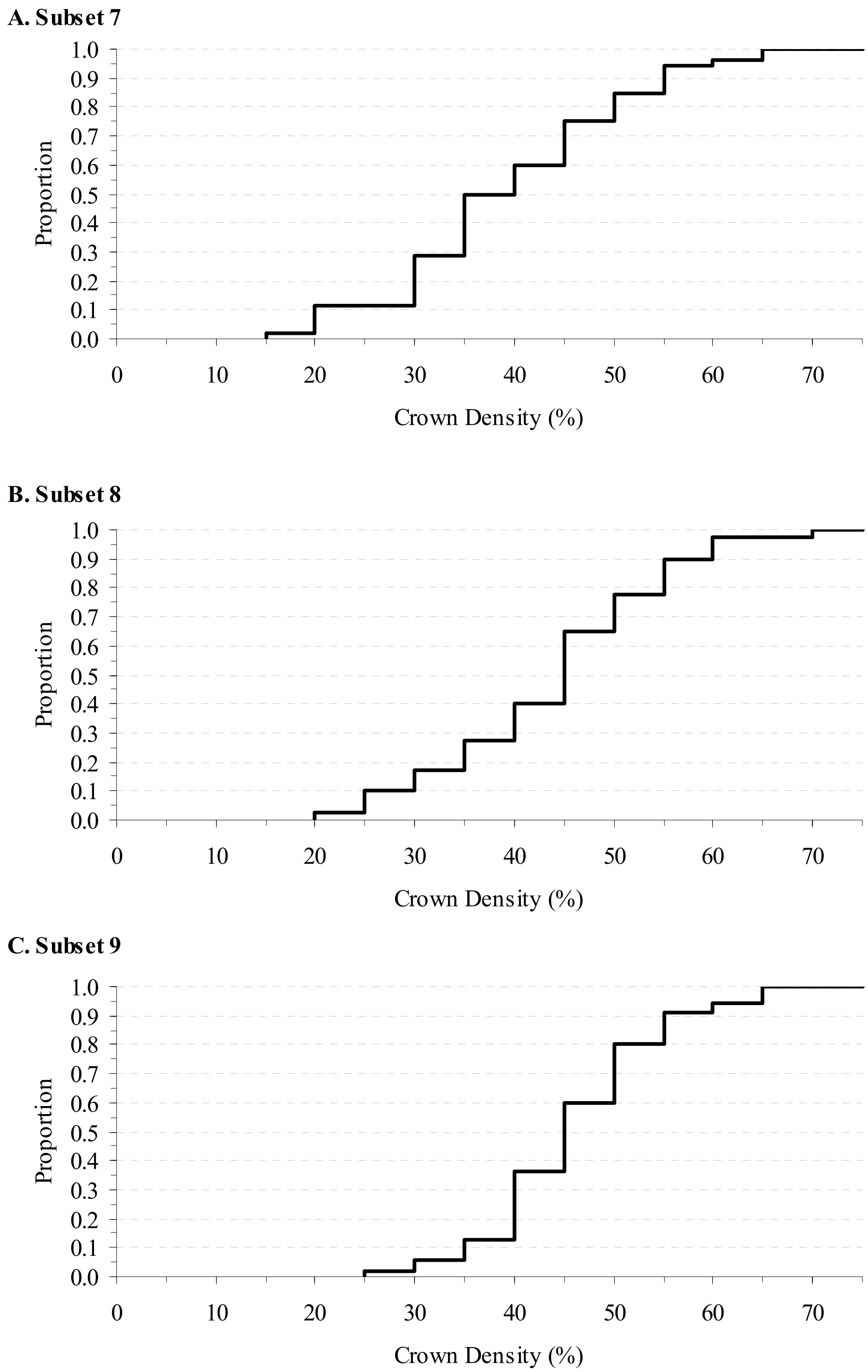


Figure C.1. Crown density empirical distribution functions by sweetgum subset. (A) Subset 7. (B) Subset 8. (C) Subset 9. Subset definitions are given in Table 4.1 (page 95).

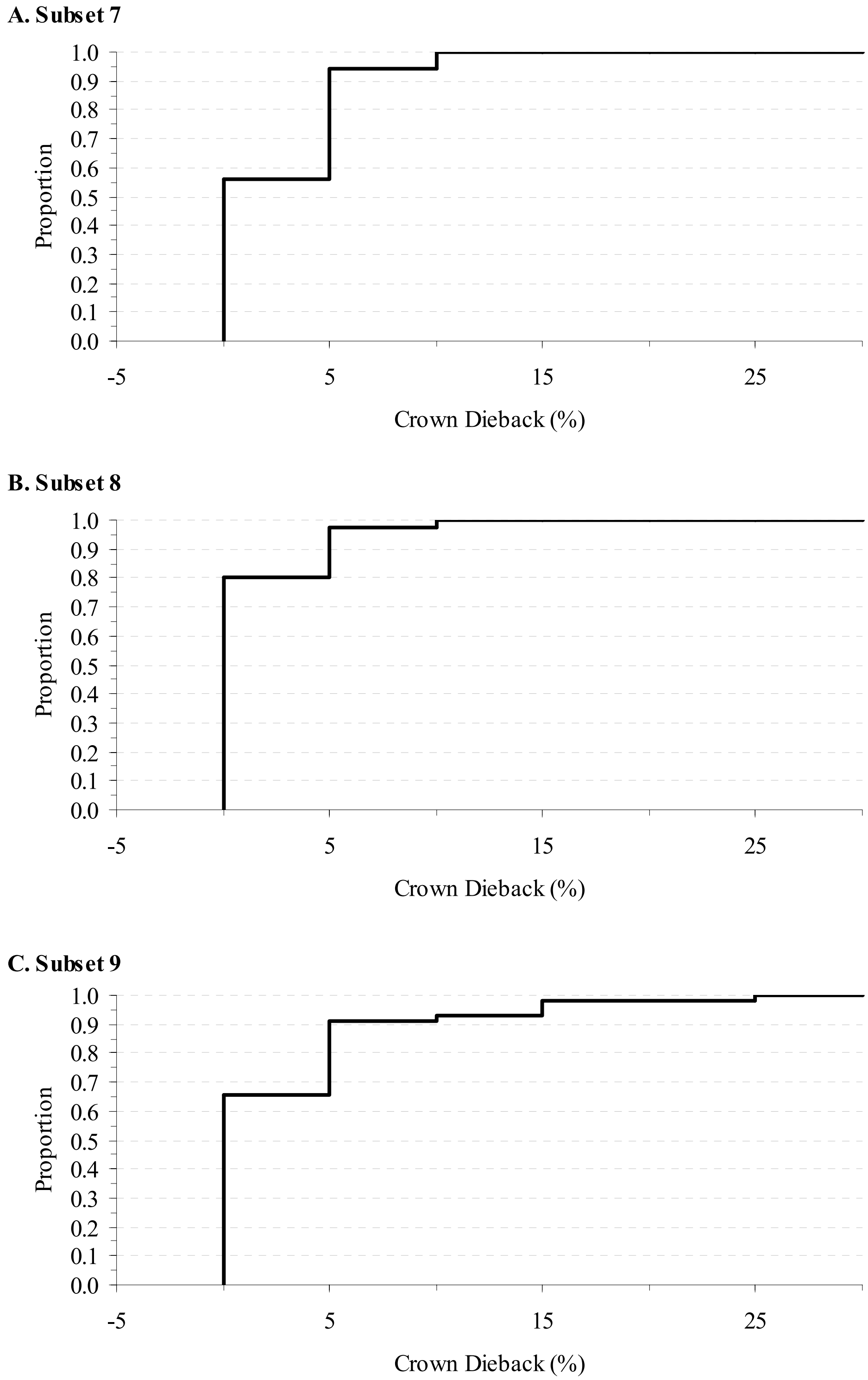


Figure C.2. Crown dieback empirical distribution functions by sweetgum subset. (A) Subset 7. (B) Subset 8. (C) Subset 9. Subset definitions are given in Table 4.1 (page 95).

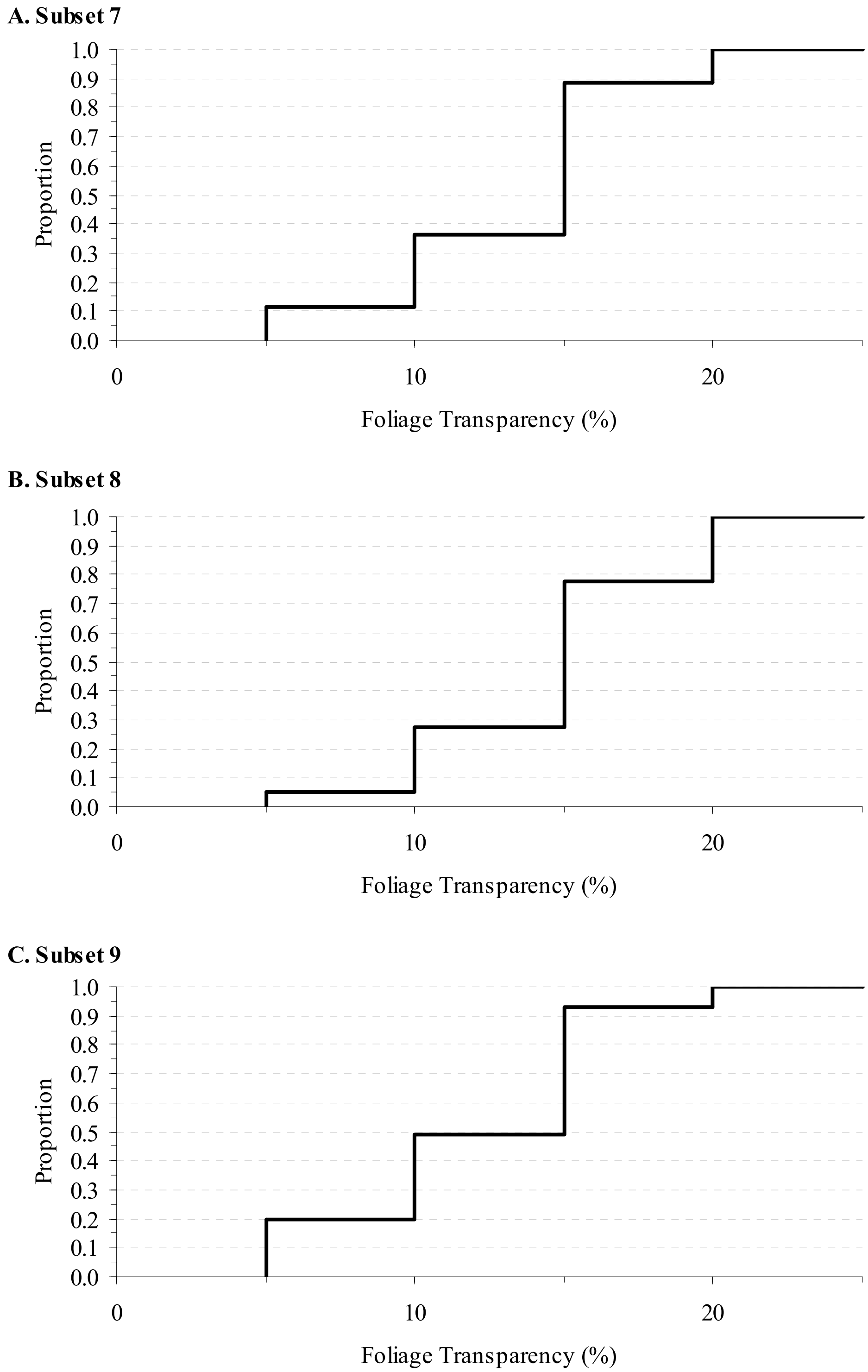


Figure C.3. Foliage transparency empirical distribution functions by sweetgum subset. (A) Subset 7. (B) Subset 8. (C) Subset 9. Subset definitions are given in Table 4.1 (page 95).

VITA

KaDonna Cheryl Randolph was born February 3, 1975, in Murray, Kentucky. She graduated as valedictorian from Calloway County (KY) High School in 1993. Following high school she attended the University of Kentucky and received a Bachelor of Science in Forestry in May 1997. After working as Plantation Productivity Intern and temporary employee with Westvaco Corporation in Wickliffe, Kentucky, she attended Purdue University and earned a Master of Science in Forestry in May 2000. KaDonna then worked for the Cooperative Forestry Research Unit at the University of Maine, Orono, where she co-developed ThinME, a commercial thinning guide for Maine spruce-fir forests. KaDonna began her doctoral pursuit at the University of Tennessee, Knoxville, in August 2001, and is presently Mathematical Statistician with the USDA Forest Service, Forest Inventory and Analysis Research Work Unit in Knoxville, Tennessee.