Using crown condition variables as indicators of forest health

S.J. Zarnoch, W.A. Bechtold, and K.W. Stoke

Abstract: Indicators of forest health used in previous studies have focused on crown variables analyzed individually at the tree level by summarizing over all species. This approach has the virtue of simplicity but does not account for the three-dimensional attributes of a tree crown, the multivariate nature of the crown variables, or variability among species. To alleviate these difficulties, we define composite crown indicators based on geometric principles to better quantify the entire tree crown. These include crown volume, crown surface area, and crown production efficiency. These indicators were then standardized to a mean of 0 and variance of 1 to enable direct comparison among species. Residualized indicators, which can also be standardized, were defined as the deviation from a regression model that adjusted for tree and plot conditions. Distributional properties were examined for the three composite crown indicators and their standardized-residualized counterparts for 6167 trees from 250 permanent plots distributed across Virginia, Georgia, and Alabama. Comparisons between the composite crown indicators and their associated standardized residual indicators revealed that only two or three plots were jointly classified as poor by both when thresholds were set at the lower 5 percentiles of statistical distributions. In contrast, 19-21 other plots were classified differently, emphasizing that different aspects of crown condition are being summarized when the raw values are adjusted and standardized. Generally, crown volume and crown surface area behaved similarly, while crown production efficiency was substantially different.

Résumé : Les indicateurs de l’état de santé des forêts utilisés dans les études antérieures sont surtout fonction des variables du houppier qui sont analysées individuellement à l’échelle de l’arbre en regroupant toutes les espbces. Cette approche a l’avantage d’être simple mais ne tient pas compte des attributs tridimensionnels du houppier, de la nature multivariée des variables du houppier ni de la variabilité interspécifique. Pour remédier à ces inconvénients, nous avons défini des indicateurs composites du houppier basés sur des principes géométriques de façon à mieux quantifier la totalité du houppier. Ceux-ci comprennent le volume, la superficie et la productivité du houppier. Ces indicateurs ont ensuite été standardisés, c’est-à-dire ramenés à une moyenne nulle et une variance unitaire, afin de permettre une comparaison directe entre les espbces. Des indicateurs de déviation, qui peuvent aussi être standardisés, ont été définis comme étant l’écart d’un modèle de régression ajusté aux conditions des arbres et des places-Cchantillons. Les propriétés des distributions ont été examinées pour les trois indices composites du houppier et les indicateurs de déviation standardisés correspondants de 6167 arbres provenant de 250 places-Cchantillons permanentes distribuées à travers la Virginie, la Géorgie et l’Alabama. La comparaison entre les indicateurs composites du houppier et leurs indicateurs de déviation standardisés respectifs montre que seules deux à trois places-Cchantillons sont classées comme pauvre en m&me temps par les deux lorsque les seuils sont fixés au cinquième centile inférieur des distributions statistiques. À l’opposé, de 19 à 21 places-Cchantillons sont classées de façon différente, faisant ressortir le fait que différents aspects de l’état des houppiers sont regroupés lorsque les valeurs brutes sont ajustées et standardisées. En général, le volume et la superficie du houppier se comportent de façon similaire alors que la productivité du houppier se démarque substantiellement.

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Introduction

Measurements of tree crowns have been used extensively as indicators of‘ the health and vigor of forest trees. When natural or anthropogenic stresses impact a forest, the first signs of deterioration are often observed in the tree crowns. Because tree crowns form a basic part of the structural architecturc of a forest ecosystem, they directly affect the composition, processes, and vigor of the understory floral and faunal components of the forest. Specifically, tree crowns have an important role in the regulation of solar energy, nutrient recycling, precipitation distribution, and moisture retention of a forest.

Net primary production originates at the tree crown, and its dimensions are reflective of the general health of the tree. Large dense crowns have been associated with vigorous growth rates, while trees with small, sparsely foliated crowns are in a state of decline, showing little or no growth. Kramer (1966) showed that tree crowns affect growth and survival, while Hamilton (1969) illustrated the dependence of tree volume increment on crown dimensions. Smith

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(1986) found that trees exhibiting the greatest height growth are usually the largest in all dimensions, including crown size.

Recently, much research has been directed at the effects of tree diseases and climatic stresses on tree crowns. Studies have demonstrated the association of crown condition to the basal area growth of loblolly pine (*Pinus taeda* L.) (Oak and Tainter 1988; Jacobi et al. 1988) and shortleaf pine (*Pinus echinata* P. Mill.) located on littleleaf disease sites (Zarnoch et al. 1994). Young loblolly pine needle retention, which directly affects crown condition, can be shortened up to 2 months in dry years (Dougherty et al. 1990; Hennessey et al. 1992; Dougherty et al. 1995). Similar observations have been reported for Monterey pine (*Pinus radiata* D. Don) in Australia, where peak needlefall occurred 3-6 months sooner under summer drought conditions (Raison et al. 1992). Research has also been conducted on the response of tree crown conditions to natural and induced variations in throughfall and soil moisture (Leininger 2002). In addition to climate, pollutants have also been shown to impact crown condition.

The effect of stress on tree crown condition is manifested not only through foliage mass but also through foliage distribution along the tree bole. The vertical distribution of foliage within the crown has been related to stand and site conditions. Schreuder and Swank (1974) used the Weibull distribution to quantify the crown profile. Cole and Jensen (1982) formulated models that track vertical crown development of lodgepole pine (*Pinus contorta* Dougl. ex Loud. var. *latifolia* Engelm.). Vose (1988) fit crown profile models to plantation loblolly pines growing under various nitrogen and phosphorus fertilizer regimes.

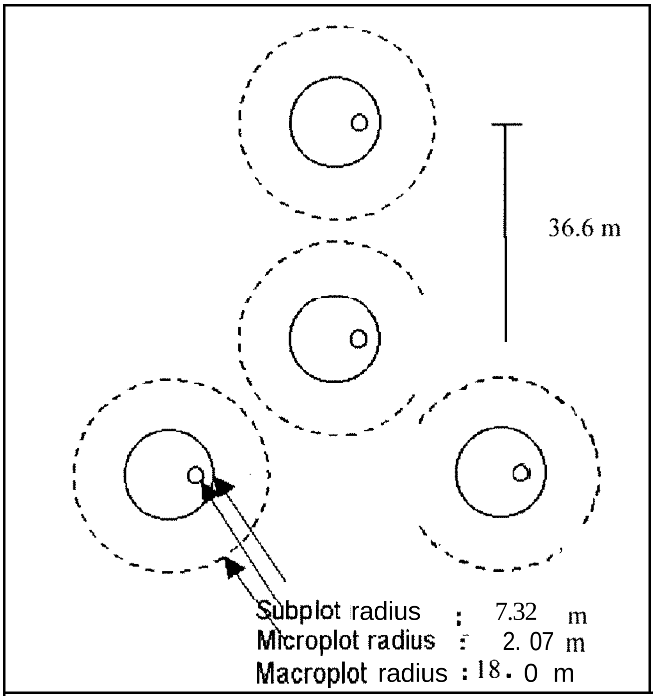
Recognizing that quantification of crown condition is fundamental to the evaluation of forest health, the USDA Forest Health Monitoring (FHM) Program has developed a series of crown condition indicators. The purpose of these indicators is to establish baseline conditions, evaluate change over time, and correlate crown conditions with natural and anthropogenic factors associated with forest health. Although average crown condition is useful as a baseline in forest health monitoring, it is the individual outlier observations that are of interest in detecting abnormal trees and stands. In addition, identifying such outliers from among many species inhabiting diverse stand conditions requires a standardization and adjustment of the crown variables. To help address these issues, this research was conducted with the following objectives: (i) describe the crown measurements recorded for each sampled tree (i.e., absolute crown indicators), *(ii)* describe the composite crown indicators derived from the absolute crown indicators, and *(iii)* develop standardized and residualized crown composite indicators, illustrate their distributional properties, and discuss their advantages.

Crown indicators

Sampling method

FHM tree crown data are gathered through the USDA Forest Service Forest Inventory and Analysis (FIA) Program. FIA maintains a network of permanent ground plots systematically distributed across the United States at an intensity of approximately one plot per 2429 ha. All plots are used for standard inventory purposes, but approximately 1/16 also serve as FHM plots, where crown indicators and additional measurements related to forest health are measured. For more information, visit the National FIA website at www.fia.fs.fed.us.

Fig. 1. FIA plot design where each plot consists of four macroplots, subplots, and microplots



FIA plots are clusters of four points spaced 36.6 m apart (Fig. 1). Each point is surrounded by a 7.32-m fixed-radius subplot where trees 12.7 cm or larger in diameter at breast height (DBH) are measured. All four subplots sample approximately 0.067 ha in total. Each subplot contains a 2.07-m fixed-radius microplot where saplings 2.54-12.69 cm DBH are measured. All four microplots sample approximately 0.0054 ha in total.

Repeatable field measurements of crown indicators are dependent on the ability to identify precisely where the crown begins on individual trees. Since sapling crowns are not fully formed and change rapidly, crown indicators are recorded only for trees 12.7 cm DBH and larger.

Two levels of crown indicators are used in the evaluation of crown condition (Table 1). The absolute crown indicators, explained in the next section, are the actual measurements recorded in the field at each plot. More detail regarding these variables is available from the FIA field methods guide (USDA Forest Service 1999). The second level consists of the composite crown indicators that are formed by combining some of the absolute crown indicators along with tree height into measures of crown volume, surface area, and production efficiency.

Absolute crown indicators

The absolute crown indicators are based on an average of field measurements from two crew members standing ap-

Table 1. Summary of crown indicator levels and their associated indicators.

Indicator level	Indicator name	Acronym	Bounds
Absolute crown indicators	Live crown ratio	LCR	0≤LCR≤100
	Crown class	CCL	1≤CCL≤5
	Crown light exposure	CEXP	0≤CEXP≤5
	Crown position	CPOS	1≤CPOS≤4
	Crown diameter	CDIA	CDIA≥0
	Crown density	CDEN	0≤CDEN≤100
	Crown dieback	CDBK	0≤CDBK≤100
	Foliage transparency	FTRAN	0≤FTRAN≤100
Composite crown indicators	Composite crown volume	CCV	CCV≥0
	Composite crown surface area	CCSA	CCSA≥0
	Crown production efficiency	CEFF	CEFF≥0

proximately 90° apart and one half to one tree length from the base of the tree.

Live crown ratio

Live crown ratio (LCR) is the percentage of the total tree height supporting live green foliage. Live crown ratio is recorded in five-percent classes and coded as 0, 05, 10, ... 100, where the code is the percentage of the upper limit of the class (i.e., code OS is l-S%).

Live crown ratio provides an estimate of the photosynthetic capacity of a tree. Larger live crown ratios are generally associated with healthier, faster growing trees. Dolph (1988) related crown ratio and crown density to the growth and survivorship of western conifers. Dyer and Burkhart (1987) concluded that live crown ratio was related to tree vigor and response to thinning. Van Laar (I 969) found that live crown ratio of Monterey pine in South Africa was related significantly to tree diameter growth.

Crown class

The crown class (CCL) rating is based on the amount of sunlight the crown receives and the proximity to neighboring trees. The five crown classes recognized are those typically used in forestry and consist of open grown, dominant, codominant, intermediate, and overtopped (Smith 1986). An important value of crown class is its utility in post-stratification during data analysis. One traditional use of such poststratification is in the development of site index equations, which are based on the mean height of the dominant and codominant trees on a plot. Further examples are the crown and basal area relationships that have been developed for open-grown southern pines (Smith et al. 1992) and the crown class transition rates and associated mortality that have been analyzed for northern red oak (*Quercus rubra* L.) (Ward and Stephens 1994).

Crown light exposure

Although crown class is widely used in many forestry applications, it is deficient in that it confounds the amount of light received by a tree with that tree's relative position in the canopy (Bechtold 2003). Trees in the overstory may receive little light in dense stands, and trees in the understory may receive full light in sparse stands. Crown light exposure (CEXP) is designed to quantify light exposure without regard to canopy position. A value is assigned by dividing the tree crown into five segments: four vertical sides and the top. The number of segments receiving light is then counted, resulting in a value that ranges from 0 to 5. For a side to be counted, at least one third of the tree length on that side must have live foliage exposed to direct light. Trees are rated based on amount of light received with the sun directly overhead. The crown light exposure variable can be used to estimate illuminated crown surface area, i.e., the amount of crown surface area that is readily available for photosynthesis.

Crown position

Crown position (CPOS) is designed to quantify the vertical position of a tree relative to the forest stand without regard to light exposure. First, an overstory canopy zone is delineated by using the average crown length as determined by the live crown ratio of overstory trees. The bottom of the zone is the average height of the live crown bases, while the top is the average height of live crown tops. Individual trees are then assigned to one of the following categories.

(1) Superstory: the live crown top must be at least twice the height of the top of the overstory canopy zone.
(2) Overstory: the live crown top is above the middle of the overstory canopy zone.
(3) Understory: the live crown top is at or below the middle of the overstory canopy zone.
(4) Open canopy: an overstory canopy zone is not present because the tree crowns in this stand are not fully closed (<50% crown cover). Most of the trees are not competing with each other for light. Once a stand is determined to be open grown, all trees in that stand are usually recorded as open canopy.

Crown diameter

Crown diameter (CDIA) is defined as the average of the widest axis of the crown and its perpendicular axis. It is measured by standing under the estimated drip-line of the crown at the ends of each of these axes and measuring the horizontal distances to the nearest 0.3 m. As with live crown ratio, trees with large crown diameters have more foliage for photosynthesis and, hence, a greater potential for carbon fixation.

The relationship between crown diameter, tree size, and productivity has been illustrated by several studies. Bonner (1964) found a strong relationship between crown diameter and DBH for lodgepole pine. Sprinz and Burkharl (1987) found that various tree stem and stand dimensions for unthinned loblolly pine were related to crown growth. In particular, crown diameter was a good predictor of DBH, tree basal area growth, and radial increment. Cole and Lorimer (I 994) demonstrated that individual tree basal area growth rates of sugar maple (*Acer saccharum* Marsh.), white ash (*Fraxinus americana* L.), and American basswood (*Tiliu americana* L.) were best predicted by crown projection area of the exposed portion of the crown, which is highly dependent on crown diameter.

Crown density

Crown density (CDEN) estimates the crown condition of each tree relative to its potential by determining the percentage of light blocked by branches, foliage, and reproductive structures (i.e., cones, acorns, etc.). The key to crown density estimates is in determining the symmetric crown outline upon which the estimates are based. To determine this outline, one selects the widest, fullest side of the crown and projects the crown outline from the point on the tree stem used for the base of live crown ratio to the top of the tree crown. Missing or broken tops, dieback, and open areas in the crown are included in this outline. The other side of the crown is simply a mirror image of this outline, yielding a symmetric crown outline. Crown density is then estimated as the average percentage of light that is blocked out by the total symmetrical crown outline. For instance, if a tree has a perfectly symmetrical crown and dense foliage such that no light is coming through the crown outline, crown density would be 100. Alternatively, if the crown is completely defoliated, the crown density would be very low, say 5, because very little light is being blocked out by any remaining branches and reproductive structures still attached to the crown portion of the tree. Crown density is recorded in five-percent classes and coded as 0, 05, 10 ,..., 100.

Generally, trees with less than full crowns have reduced growth compared with trees with full, symmetrical crowns as shown by Anderson and Belanger (1987). They also reported positive correlations between crown density and DBH growth for dominant and codominant loblolly and shortleaf pine in natural stands. Grano (1957) showed that loblolly pine seed trees with dense crowns grew faster than trees with average or sparse crowns. Belanger et al. (1991) also established positive correlations between crown density and DBH growth for loblolly pine. Horntvedt (1993) related crown density of individual Norway spruce (*Picea abies* (L.) Karst.) trees to various foliage characteristics and found that crown density increased with increasing number of live branches per tree, needle retention, and shoot length. Schütt and Cowling (1985) found a direct relationship between crown density and tree vigor of white fir (*Abies concolor* (Gord. & Glend.)) and Norway spruce in Germany.

Crown dieback

Crown dieback (CDBK) is defined as percent recent mortality within the live crown outline of the terminal portion of branches that are less than 2.54 cm in diameter and in the upper, sun-exposed portion of the crown. The premise is that these branches have died from some stress other than competition and shading. Crown dieback is recorded in five-percent classes and coded as 0, 05, 10, . ., 100.

High crown dieback usually indicates defoliating agents and a general loss of vigor. Oak and Tainter (1988) used crown dieback to link loblolly pine tree symptoms to littleleaf disease. They found that trees with severe symptoms had smaller mean radial increments. Crown dieback has also been used to assess the status of sugar maples, particularly in the joint U.S.-Canadian Sugar Maple Decline Project (Millers et al. 1991, 1993, 1994). Others have used crown dieback to analyze the health of black ash (*Fruxinus nigra* Marsh.) in Maine (Trial and Devine 1994) and hardwoods in Vermont (Kelley et al. 1992). Larger regional surveys that used crown dieback have been reported by Bechtold et al. (1992) for the southeast and Gillespie et al. (I 993) for New England and the mid-Atlantic states.

Foliage transparency

Foliage transparency (FTRAN) is the amount of skylight on a percent basis that is visible through the live, normally foliated part of the crown. Foliage transparency differs from crown density because it emphasizes foliage and ignores holes in the crown that are due to missing branches. Dead branches, crown dieback, and missing branches are excluded from the estimate. For example, a tree with one branch of thick foliage would score well for foliage transparency but poorly for crown density. Foliage transparency is estimated in five-percent classes and coded as 0, 05, 10, ... 100.

High foliage transparency can be related to insect defoliation and subsequent growth loss and mortality (Kulman 1971). In a study of the effect of pear thrips (*Taeniothrips inconsequens*) on sugar maples, Korb et al. (1992) found that trees with heavy damage also had significantly greater foliage transparency (18–48%) over the next 2 years than trees with less damage.

Composite crown indicators

The absolute crown indicators described above are simple to obtain and relatively easy to interpret but limited because they do not individually reflect the multiple aspects of crown structure and defoliation. In particular, the individual absolute indicators are only one-dimensional and do not account for the three-dimensional attributes of a tree crown. Moreover, the absolute crown indicators form a set of variables that are multivariate in nature and, hence, the covariance structure of these variables should not be ignored.

Two multivariate crown attributes, crown volume and surface area, have been related to tree growth by several researchers. Hamilton (1969) reported that crown surface area and crown volume accounted for 88% and 80%, respectively, of the variation in volume increment of Sitka spruce (*Picea sitchensis* (Bong.) Carrière). He concluded that crown surface area appeared to be the most important factor in volume increment, which supports the hypothesis that carbon assimilation occurs basically in the outer sheath of the crown. Sprinz and Burkhart (1987) suggested the usefulness of crown surface area and crown volume but emphasized that these indirect measures of photosynthetic potential may be improved by weighting them by the distance that the photosynthate must translocate from the crown to the lower bole for DBH growth. The weighting factor may be height-to-crown diameter, which would reflect the theory that crowns closer to DBH have a greater potential to affect DBH

Table 2. Kandall's tau b correlation coefficients for the crown indicators based on 6167 trees.

Crown indicator	Crown length	Crown ratio	Crown diameter	Crown density	Crown dieback	Foliar transparency
Crown length	1.00	0.67	0.43	0.27	0.03	-0.14
Crown ratio	0.67	1.00	0.25	0.25	-0.01	-0.16
Crown diameter	0.43	0.25	1.00	0.21	0.14	-0.07
Crown density	0.27	0.25	0.21	1.00	-0.07	-0.21
Crown dieback	0.03	-0.01	0.14	-0.07	1.00	0.13
Foliar transparency	-0.14	-0.16	-0.07	-0.21	0.13	1.00
Composite crown volume	0.62	0.42	0.77	0.38	0.08	-0.13
Composite crown surface area	0.68	0.48	0.68	0.44	0.06	-0.15
Crown efficiency	-0.48	-0.28	-0.96	-0.22	-0.13	0.07

growth than those that begin a considerable distance up the bole. Van Laar (1969) analyzed the effect of crown surface area and crown volume on DBH growth of Monterey pine and found that their effects were not significant after accounting for crown length and DBH.

We therefore propose a set of composite indicators, which are calculated composites of tree height, live crown ratio, crown diameter, and crown density. The first two, composite crown volume (CCV) (cubic metres) and composite crown surface area (CCSA) (square metres), are measures of crown dimension and fullness. They are based on the assumption that the crown is approximated by a paraboloid and are defined as

$$\text{[1]}\qquad \mathrm{CCV} = 0.5\pi R^2\mathrm{CL} \times \mathrm{CD}$$

and

$$\text{[2]}\qquad \mathrm{CCSA} = \frac{4\pi\mathrm{CL}}{3R^2}\left[\left(R^2 + \frac{R^4}{4\mathrm{CL}^2}\right)^{1.5} - \left(\frac{R^4}{4\mathrm{CL}^2}\right)^{1.5}\right]\mathrm{CD}$$

where $\pi = 3.14159$, R = CDIA (metres)/2, H is total tree height (metres), CL = H(LCR)/100, and CD = CDEN/100. Although CD consists of only crown density, it may be possible to include other crown characteristics as multiplicative modifiers to develop composite crown indicators for other purposes. Except for the CD component, which adjusts for the fullness of the crown, the equations follow those of Larocque and Marshall (1994*a*). Note that both indicators increase as the crown diameters and (or) crown length and (or) CD index increases, which is biologically reasonable.

The ratio of crown surface area to crown volume has also been found to be a useful measure of crown production efficiency (CEFF) (Ford 198.5; Perry 198.5; Larocque and Marshall 1994*a*) and is defined as

$$\text{[3]}\qquad \mathrm{CEFF} = \frac{\mathrm{CCSA}}{\mathrm{CCV}}$$

Although large-crowned trees have the highest photosynthetic productivity, they are less efficient because of the greater maintenance respiration requirements for the roots, stems, and branches (Laracque and Marshall 1993). Thus, as a tree crown grows, there is less crown surface area per crown volume and the CEFF indicator becomes smaller. Larocque and Marshall (1994h) found that red pine (*Pinus resinosa* Ait.) DBH growth was negatively correlated with crown dimensions. Needle density and crown surface may have increased but the gain also resulted in greater internal shading, which subsequently decreased photosynthetic capacity. This effect indicates that a large crown does not necessarily represent an efficient crown structure. It appears that small trees are more efficient at low levels of competition but large trees are more efficient under severe competition (Larocque and Marshall 1994*a*).

The absolute and composite crown indicators are summarized in Table 1. Kandall's tau b correlation coefficient was used to determine the relationship between some of the absolute indicators and the composites (Table 2). Kendall's statistic is the nonparametric analog of the Pearson correlation coefficient and is used when the indicators are nonnormally distributed. CCV and CCSA are geometric measures of crown size and, thus, both are highly correlated with CL and CDIA (i.e., correlation coefficients ranging from 0.62 to 0.77). CDIA is also highly correlated with CEFF, where a correlation coefficient of -0.96 indicates a very strong negative relationship. CEFF is poorly correlated with CDEN, CDBK. and FTRAN.

Biological and statistical thresholds

Thresholds are key components in assessing forest health because they separate the sampled population into categories of good and poor. Ideally, thresholds should be developed on a biological basis. Biological thresholds, the point at which a tree becomes noticeably stressed and begins to decline, are difficult to pinpoint. This requires the establishment of correlations between crown indicators and other signs of tree stress such as current damage symptoms and reduced growth and prospective losses from future growth reduction and mortality. Of these, prospective losses are probably the most meaningful because current damage symptoms and reduced growth can be measured directly as indicators of forest health and, thus, there is no need to use a crown indicator as a surrogate for something that can be measured. Establishment of thresholds is further complicated because thresholds are species specific and the effect of normal stand dynamics and attrition must be partitioned from the analysis. Furthermore, reduced growth, damage, and mortality are not always abnormal and thresholds must first be established for these. The ultimate goal in establishing any threshold is to identify a signal that appears to be beyond the range of what is expected. Attempts at establishment of objective biological thresholds are currently underway.

Statistical thresholds are easier to establish by isolating observations at the tails of statistical distributions. This is risky because it is somewhat arbitrary and always results in a set of observations designated as poor, even in the absence of a problem. However, statistical distributions can be quite useful for detecting spatial patterns and measuring change over time. Statistical distributions of the absolute crown indicators have been included in a variety of recent forest health reports (Conkling et al. 2004; Rogers et al. 2001; Dale et al. 2000).

There are several problems associated with using statistical distributions of crown indicators to analyze forest health. Summarizations of raw values across species are difficult to interpret because statistical distributions can be expected to differ by species. The crown morphology of oaks is obviously different from that of pines. Most forest stands are composed of a mixture of species and, thus, comparing or combining stand level indicators across species may yield erroneous conclusions. Another difficulty is that raw values are confounded with the effects of normal stand dynamics. The remainder of this paper utilizes FHM data collected in Georgia, Alabama, and Virginia between 1997 and 1999 to demonstrate how composite crown indicators can be adjusted for species differences and stand structure.*

Standardized and residualized composite crown indicators

Standardized indicators

Crown indicators can be adjusted for different statistical distributions among species by standardizing them to a mean of 0 and a standard deviation of 1. Values are thus expressed in terms of standard deviation units from the mean for a given species, which results in a more meaningful interpretation when compared or combined across species. The standardization of an indicator is defined as

$$[4] \qquad I'_{ij} = \frac{I_{ij} - \bar{I}_j}{s_j}$$

where I'_{ij} is the standardized indicator for tree i within species j, I_{ij} is the nonstandardized indicator for tree i within species j, $\bar{I}_j$ is the average for the nonstandardized indicator for species j, and s_j is the standard deviation for the nonstandardized indicator for species j.

Residualized indicators

Another method to adjust the crown indicators before comparing or combining across species or within a species from several different plots is to define the indicator as its residual from a model based on tree and stand conditions. Each tree is adjusted for its specific natural competitive situation, resulting in an indicator more suitable for detecting abnormalities because the adjusted indicator identifies those crowns that do not conform to the model predictions. Specifically, let Y_{ij} be a specific composite indicator for tree i within species j and $\hat{Y}_{ij}$ be the predicted value of the indicator for tree i within species j based on the appropriate regression model. Then, the residualized indicator is defined as

$$[5] \qquad R_{ij} = Y_{ij} - \hat{Y}_{ij}$$

Standardized-residualized indicators

Like the raw indicator values, residualized indicators can be standardized for comparisons across species:

$$[6] \qquad R'_{ij} = \frac{R_{ij} - \bar{R}_j}{s_j}$$

where R'_{ij} is the standardized-residualized indicator for tree i within species j, R_{ij} is the residualized indicator for tree i within species j, $\bar{R}_j$ is the average for the residualized indicator for species j, and s_j is the standard deviation for the residualized indicator for species j. Note that $\bar{R}_j = 0$ for all species because the average residual from the regression model for species j is always zero.

Results

After expressing each of the three composite crown indicators in their raw and standardized-residualized forms, the distributional properties of the resulting six indicators were examined on a tree-level basis. Standardization of the indicators across species makes it feasible to produce stand-level indicators by averaging over all trees on each plot. Raw stand-level indicator values and their standardized residuals were likewise compared to determine how much the adjustment and standardization changes the results.

Tree-level composite crown indicators

Distributions of raw values

Raw composite crown indicators were computed for each tree and then grouped by species. Species with less than 30 observations (individual trees) were combined into “other hardwoods” or “other softwoods” categories. Mean values, by species, are presented in Table 3. Overall, there were 6167 trees distributed over 250 permanent plots located in Virginia, Georgia, and Alabama. Of all trees sampled, there were 29 different species with at least 30 observations, the most abundant of which was loblolly pine.

Mean composite crown indicators vary substantially by species, demonstrating the need to standardize across species. CCV ranges from 23.7 m^3 (slash pine (*Pinus elliottii* Engelm.)) to 215.6 m^3 (American beech (*Fagus grandifolia* Ehrh.)). The standard deviation for most species is usually larger than the mean, yielding coefficients of variation exceeding 100%. Similar results were observed for CCSA, with values ranging from 25.4 m^2 (slash pine) to 123.3 m^2 (American beech). However, the coefficients of variation for CCSA are generally smaller than those for CCV. As expected, CEFF increases with decreasing crown size, ranging from 0.71 (American beech) to 1.84 (bald-cypress (*Taxo-*

‘Tree heights were not measured by FHM field crews prior to 2000 but predicted from models obtained from FIA for this analysis.

Table 3. Descriptive statistics for the composite crown indicators by species.

Species	Plots (*n*)	Trees (*n*)	Trees per plot (mean)	Composite crown volume (m”) Mean	SD	Composite crown surface area (m^2) Mean	SD	Crown efficiency Mean	SD
Shortleaf pine	34	94	2.X	40.7	52.3	35.6	30.4	I.29	0.53
Slash pine	30	379	12.6	23.7	35.6	25.4	21.4	1.56	0.50
Longleaf pine	19	67	3.5	75.X	119.4	51.0	50.4	1.19	0.56
Eastern white pine	10	41	4.1	61.1	89.2	47.7	53.8	.48	0.96
Loblolly pine	107	1935	18.1	24.5	39.9	26.3	23.1	.53	0.52
Virginia pine	31	249	8.0	27.6	31.0	28.0	23.3	.35	0.52
Bald-cypress	5	30	6.0	33.6	36.0	37.0	32.3	.84	0.97
Red maple	93	367	3.9	66.6	67.9	53.6	35.0	.01	0.30
Other hickories	39	82	2.1	94.6	101.7	70.5	47.7	.oo	0.35
Pignut hickory	19	35	1.8	142.6	119.4	95.8	55.5	0.85	0.29
Mockernut hickory	26	64	2.5	101.1	148.5	71.0	62.6	1 .00	0.48
Flowering dogwood	23	43	1.9	33.6	25.4	30.0	16.3	1.13	0.65
American beech	14	35	2.5	215.6	223.1	123.3	78.0	0.71	0.19
Sweetgum	101	329	3.3	53.2	72.8	48.6	40.7	1.29	0.46
Yellow poplar	91	351	3.9	97.0	107.4	72.6	53.4	1.01	0.40
Sweetbay	20	65	3.2	36.7	41.6	35.0	24.9	1.21	0.35
Black tupelo	50	106	2.1	45.4	43.7	40.5	27.4	1.15	0.38
Swamp tupelo	11	88	X.0	43.9	46.1	37.6	24.3	1.17	0.52
Sourwood	29	7X	2.7	33.2	24.5	32.6	15.5	1.17	0.40
Black cherry	23	42	1.8	37.8	32.1	35.6	20.8	1.12	0.28
White oak	72	220	3.1	100.4	113.3	10.4	49.3	0.96	0.34
Scarlet oak	34	105	3.1	93.6	123.6	62.4	46.7	0.98	0.41
Southern red oak	42	89	2.1	87.3	149.9	5x.3	52.7	1.01	0.31
Laurel oak	10	32	3.2	76.5	86.9	57.3	45.8	1.02	0.29
Water oak	69	180	2.6	105.8	122.5	69.4	51.7	0.92	0.36
Chestnut oak	41	342	8.3	80.6	X6. I	60.3	40.8	1.01	0.37
Northern red oak	30	66	2.2	118.3	116.X	75.4	50.4	0.89	0.38
Post oak	25	45	1.X	54.9	98.1	43.1	45.5	1.10	0.33
Black oak	35	68	1.9	X2.3	9X.2	61.3	48.0	1.02	0.33
Other hardwoods	26	55	2.1	38.1	39.5	37.0	29.4	1.27	0.53
Other softwoods	127	4X5	3.8	84.2	111.8	59.8	47.6	1.04	0.52

Note: *n* is sample size. SD, standard deviation.

dium distichum (L.) L. Rich.)), with coefficients of variation notably smaller than CCV and CCSA.

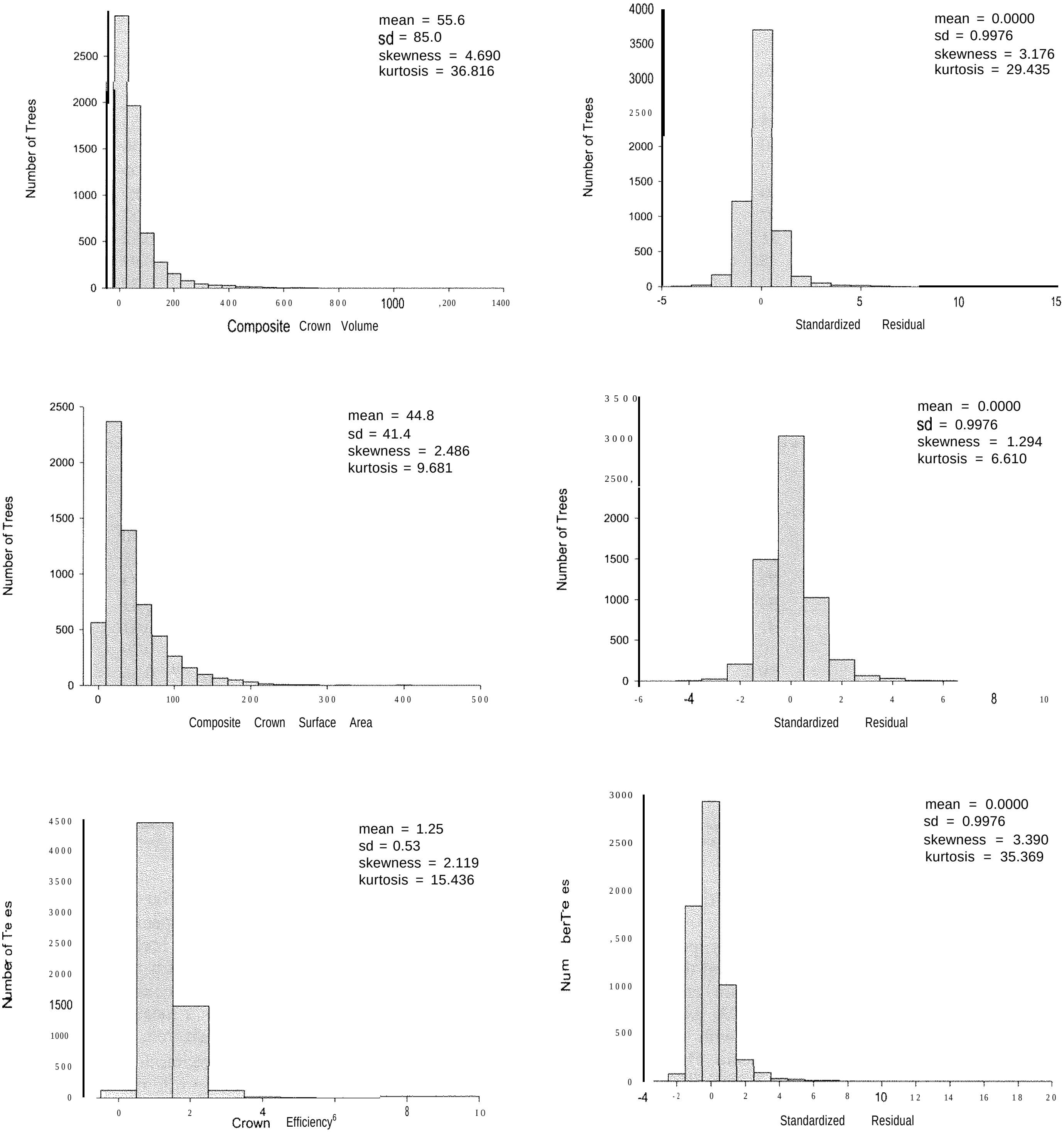
When the raw values are pooled across species, the resulting statistical distributions are skewed, and the high levels of variability observed within species are exaggerated even more (Fig. 2). Both CCV and CCSA exhibit extremely skewed exponential type distributions, with individual observations ranging IO-20 times the mean. This trend is less pronounced for CEFF, but the distribution of this indicator is still markedly skewed.

Residualization models

The development of residual indicators is contingent on the formulation of appropriate models for adjusting the composite crown indicators as functions of tree and stand conditions. Tree DBH, stand density, and stand age are known to be correlated with crown diameter and other crown parameters (Krajicek et al. 1961; Bonner 1964; Holdaway 1986; Sprinz and Burkhart 1987; Smith et al. 1992). DBH, stand age, and various measures of stand density were therefore used as candidate variables in stepwise linear regressions fit to the composite crown indicators by species. Measures of stand density used in the regressions included stems per hectare, basal area per hectare, quadratic mean DBH, and the Reineke stand density index (Reineke 1933). Crown light exposure was also included as a measure of competition in the immediate vicinity of each tree.

The results from the stepwise regression models were consistent for each of the three composite crown indicators. Tree DBH was highly significant in nearly every model, and at least one measure of stand density was significant in most models. When no measure of stand density was significant, it was usually because the species was shade tolerant, with crown parameters relatively unaffected by competition. Basal area per hectare had the broadest utility of all of the density variables; however, substitution of basal area along with other measures of density substantially improved the models for some species. When developing a model to adjust crown indicators, one might consider allowing the specification for stand density to change from species to species.

Fig. 2. Distribution of the composite crown indicators based on 6167 individual trees



For simplicity and consistency, DBH and basal area were selected as the best variables, yielding the general model for use across all species as

$$\text{CROWN} = b_0 + b_1(\text{DBH}) + b_2(\text{BA}) \tag{1}$$

where CROWN is the composite crown indicator of interest. DBH is tree diameter (centimetres) at breast height (trees 12.7 cm DBH and larger), BA is stand-level basal area per hectare (trees 2.54 cm DBH and larger), and b_i are regression parameters estimated from the data. Regression parameters for DBH are positive for all species for the CCV and CCSA models (Table 4) but negative for CEFF, which is biologically reasonable. The BA regression parameters oscillate between positive and negative, which is a reflection of the significance level of the BA variable in the regression model, the shade tolerance of the species, and the magnitude of the crown variable. The regression models are best for

Table 4. Regression parameters for the composite crown indicators.

	Composite crown volume (m^3)				Composite crown surface area (m’)				Crown efficiency			
Species code	b_0	b_1	b_2	R^2	b_0	b_1	b_2	R^2	b_0	b_1 (IO-‘)	b_2 (IO-‘)	R^2
Shortleaf pine	-80.4	4.34	0.352	0.57	-32.16	2.56	0.086	0.59	2.13	-3.73	5.23	0.42
Slash pine	-32.3	3.26	-0.538	0.58	-8.64	1.98	-0.330	0.59	2.37	-4.32	4.23	0.52
Longleaf pine	-8X.X	1.32	-2.165	0.63	-26.34	3.43	-1.006	0.78	2.09	-3.67	7.04	0.68
Eastern white pine	100.1	4.76	-5.228	0.50	x9.09	2.65	-3.497	0.46	0.48	-3.39	X7.43	0.43
Loblolly pine	-3X.2	4.13	-0.732	0.60	-2.63	2.36	-0.670	0.60	1.97	-4.23	14.80	0.40
Virginia pine	11.5	2.9X	-1.734	0.34	18.64	2.24	-1.405	0.36	1.95	-4.91	IS.80	0.27
Bald-cypress	12.7	2.2x	-0.680	0.59	22.79	1.98	-0.650	0.57	2.59	-6.37	16.56	0.61
Red maple	-42.0	5.19	-0.12X	0.37	-0.50	2.62	-0.096	0.35	1.46	-1.85	-1.67	0.23
Other hickories	-11.2	8.85	-1.673	0.53	-4.31	4.21	-0.986	0.54	1.61	-2.59	-0.94	0.37
Pignut hickory	30.4	X.07	-3.44s	0.56	47.80	3.26	-1.292	0.42	1.18	-1.91	5.80	0.54
Mockcrnut hickory	-194.0	10.99	1.050	0.52	-53.98	4.84	0.26X	0.56	1.58	-2.59	1.88	0.26
Flowering dogwood	-58.7	6.49	-0.385	0.28	-20.36	3.7x	-0.381	0.26	2.19	-6.52	-2.10	0.04
American beech	-23.4	14.88	-3.523	0.69	57.86	4.13	-1.417	0.59	0.87	-0.99	2.58	0.44
Sweetgum	-32.x	4.71	-0.758	0.41	8.02	2.58	-0.663	0.40	1.85	-2.59	0.89	0.32
Yellow poplar	-46.9	6.X2	-1.238	0.51	5.80	3.39	-0.793	0.51	1.39	-1.62	1.27	0.21
Sweetbay	9.3	2.70	-1.186	0.48	24.63	1.61	-0.928	0.52	1.28	-1.64	10.79	0.29
Black tupelo	-5.9	2.92	-0.310	0.25	13.14	1.69	-0.267	0.22	1.55	-2.27	2.32	0.20
Swamp tupelo	-31.9	2.26	0.470	0.51	-0.26	1.19	0.193	0.49	1.76	-1.91	-2.56	0.27
Sourwood	-6.6	2.66	-0.330	0.29	12.78	1.47	-0.269	0.24	1.59	-1.53	-6.20	0.04
Black cherry	-23.0	2.58	0.381	0.17	1.16	1.43	0.243	0.13	1.78	-2.15	-8.87	0.20
White oak	-114.3	8.55	0.470	0.64	-15.53	3.59	0.030	0.59	1.37	-2.12	3.32	0.43
Scarlet oak	-161.1	1.77	1.352	0.45	-36.09	2.97	0.551	0.46	1.68	-2.26	-2.55	0.34
Southern red oak	-151.7	11.18	-1.554	0.72	-16.41	4.10	-1.070	0.75	1.41	-2.10	4.94	0.51
Laurel oak	-107.9	8.52	0.269	0.86	-43.98	4.46	0.317	0.85	1.46	-2.41	2.21	0.62
Water oak	-3x.3	7.92	-1.762	0.49	20.02	3.21	-1.100	0.45	1.26	-1.94	5.20	0.34
Chestnut oak	-4X.6	5.19	-0.201	0.51	-1.42	2.40	-0.017	0.49	1.41	-1.85	2.92	0.35
Northern red oak	-89.1	6.X2	-0.216	0.67	-16.17	2.86	0.086	0.64	1.60	-1.92	-4.14	0.55
Post oak	-1II.6	x.21	-0.349	0.53	-31.X9	3.91	-0.416	0.56	1.63	-2.40	-0.X6	0.43
Black oak	-44.7	6.61	-1.349	0.54	6.80	3.16	-0.889	0.49	1.48	-1.58	-2.74	0.35
Other hardwoods	-17.9	2.40	-0.042	0.33	5.09	1.67	-0.322	0.29	2.21	-2.63	-13.13	0.24
Other softwoods	-7X.1	7.68	-0.371	0.46	-6.53	3.27	-0.267	0.46	1.39	-1.94	3.39	0.14

Note: CROWN = b_0 + b_1(DBH) + b_2(BA) where CROWN is the composite crown indicator of interest, DBH is tree diameter (cm) at breast height for trees 12.7 cm DBH and larger. and BA is stand-level basal area (m^2/ha) for trees 2.54 cm DBH and larger.

CCV **and** CCSA with R^2 ranging from 0.13 to 0.86 with an average of 0.50. The CEFF models have slightly smaller R^2, ranging from 0.04 to 0.68 and averaging 0.36.

Standardized residuals

The distributional properties of the standardized–residualized indicators for the three composite crown indicators for all trees pooled together are shown in Fig. 2. Standardization alone results in a mean of 0 and a standard deviation of I and has no effect on the skewness coefficient. However, residualization usually does. The standardized residuals associated with CCV **and** CCSA have substantially smaller skewness coefficients and are more normally distributed than their raw counterparts for most species. The reduction in skewness is an advantage when performing statistical tests based on assumptions of normality. In addition, reliance on transformations or nonparametric statistical methods is diminished.

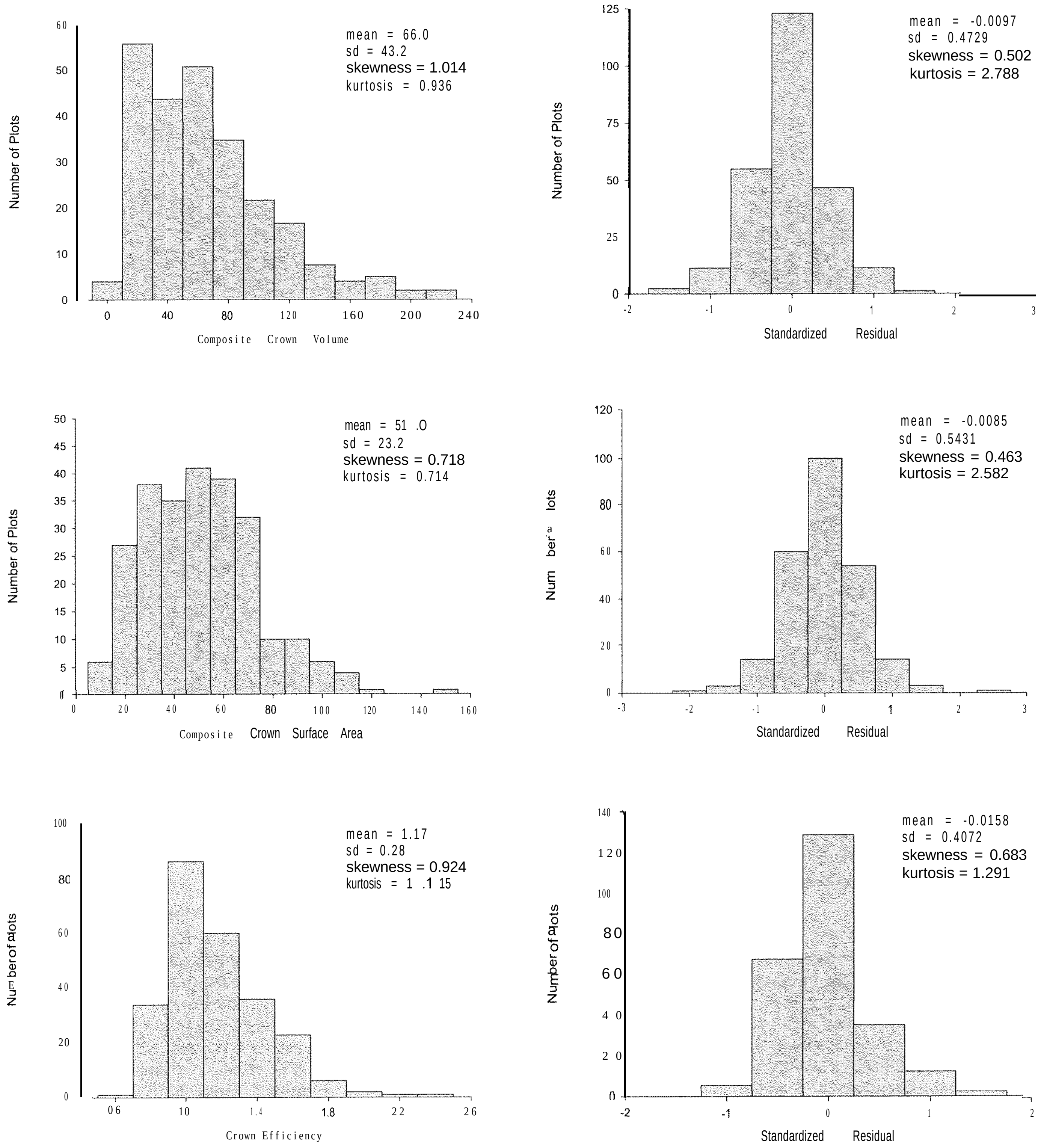
Unlike CCV and CCSA, CEFF skewness coefficients were larger than their raw counterparts for all but six species, raising the likelihood that a more complex model may be appropriate for this ratio estimator. The species with the largest CEFF skewness coefficients tended to be the species with the poorest model R^2 values.

Stand-level composite crown indicators

Plot averages across all species for both the raw and standardized-residualized indicators are shown in Fig. 3. Note that the standardized residuals do not have a mean of 0 and a standard deviation of I, as seen with the tree-level indicators. This is because standardization was performed at the individual tree and species level, and when plot-level indicators are computed, this property disappears because of differing species distributions across the plots. Standardization and residualization reduce the skewness coefficients of all stand-level indicators, resulting in more symmetric distributions for CCV, CCSA, and CEFF.

Further comparison of the raw stand-level indicators and their standardized residual counterparts was performed by classifying 250 plots into good and poor categories. For demonstration, the threshold for the poor class was set at the lower 5 percentile of the statistical distributions. Each pair of raw and standardized residual values was then plotted on a scatter diagram, with the threshold value indicated by ref-

Fig. 3. Distribution of the composite crown indicators based on 250 plot averages



erence lines (Figs. 4-6). Agreement between the raw composite crown indicator and its standardized residual is attained for all plots located in the upper right and lower left quadrants of each graph. The other two quadrants represent opposite classifications by the indicators.

The raw indicators and their standardized residual counterparts classify the same plots into the poor condition only two or three times, confirming that the raw and adjusted values are measuring different aspects of crown condition. Approximately 10 plots are classified as poor by the raw crown indicators but good by their standardized residual counterparts and vice versa. The scatter of the plots, with correlation coefficients of 0.51 or less, emphasizes this concept.

Fig. 4. Classification of the 250 plots based on the composite crown volume and standardized residual indicators.

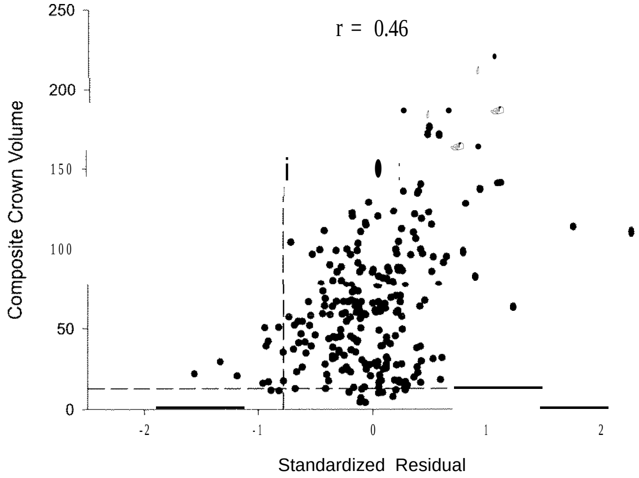


Fig. 5. Classification of the 250 plots based on the composite crown surface area and standardized residual indicators.

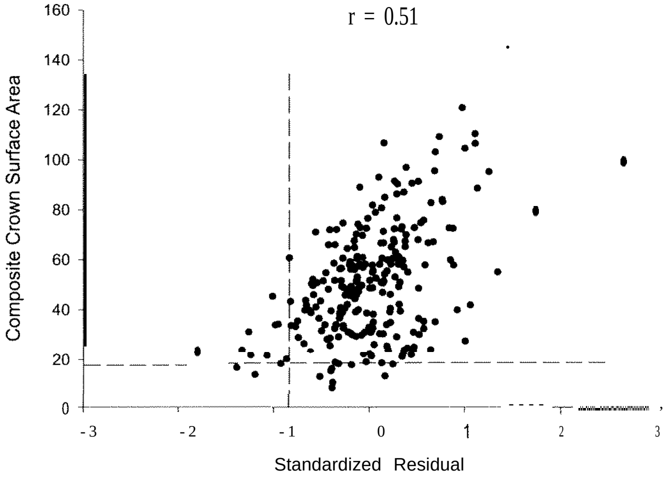
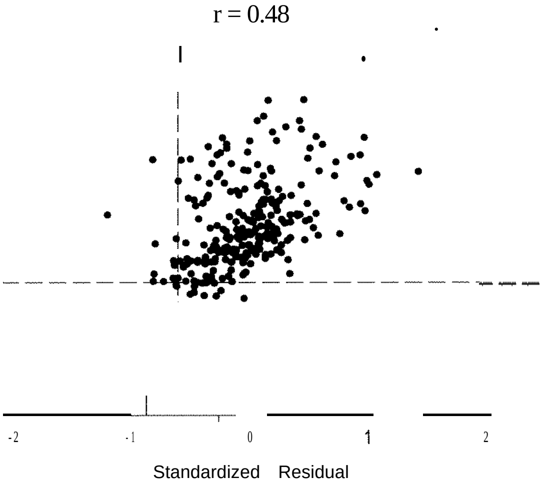


Fig. 6. Classification of the 250 plots based on the crown efficiency and standardized residual indicators.



The reason for differences in classification is based on the adjustment potential of the regression models and its effect on the creation of the standardized residual indicators. When using raw CCV and CCSA values, stands with high percentages of trees with small crowns are classified as poor, even if crowns are normally small for those particular species in those types of stands. However, when using the adjusted values, stands are classified as poor only if they have high percentages of trees at the lower end of their respective species statistical distributions after adjusting for tree and stand conditions. Of the 250 plots in this study, only two were classified as poor by both the raw and adjusted CCV indicators. The CCSA and its adjusted counterpart jointly classified only three as poor. For both indicators, these were low-density stands with minimal species diversity. Since the standardization process adjusts for species differences, adjustments will be minimal when applied to stands with low species diversity. This may be one reason why the raw and adjusted indicators both classified these stands as poor.

The CCV and CCSA indicators tended to classify the same plots as good or poor. However, plots designated poor by the CEFF indicator were different from those classified as such by CCV and CCSA. This is not unexpected, since CEFF is a ratio that measures an aspect of crown condition that is less directly related to overall crown size than the other two composites.

Discussion

The regression models

The regression models used to formulate the residualized crown indicators are simple linear models based on one tree and one stand attribute. The purpose of the modeling was not for prediction but for adjustment, and the precision is adequate for this purpose. All species were fit with the same variables for simplicity and consistency. More precise adjustments might be attained by relaxing this philosophy and tailoring the models for individual species. The use of nonlinear models may help quantify the more complex tree and stand interactions.

The effect of stand density is specified through the stand basal area variable, so every tree on a given plot is assigned the same estimate for stand density. An estimate of the competitive conditions more specific to the immediate vicinity of individual trees would likely improve the models. The crown light exposure variable showed promise in this regard for several species. Improved quantification of stand density and competition on individual trees might also be obtained from a distant-dependant crown competition index.

One of the objectives of the regression models and subsequent residualization and standardization was to transform the nonnormal composite crown variables into new indicators that were more normally distributed. It should be emphasized that the regression models do not have to assume normality of the dependent variable for valid parameter estimates under the theory of least syuares. It is only if one wants to perform tests on the parameters (intercept and slope) that normality of the residuals must be assumed. Thus, the dependent variable itself does not have to assume normality for tests of the parameters. For our situation, the composite crown variable may be highly skewed, but if the regression can model it as a function of tree and stand conditions, the resulting residuals may have a more normal distribution than the original dependent variable. Thus, a simple linear regression model can convert a skewed dependent variable to a more normally distributed residual variable that is more desirable for subsequent statistical hypotheses tests.

Standardized-residualized indicators

Although difficulties with the one-dimensionality of the absolute crown indicators are alleviated when they are combined into composite indicators, problems are apparent with high levels of within- and between-species variability. This results in large confidence intervals on parameter estimates as well as diminished statistical power to reject hypotheses. When the coefficient of variation is 100%, which is typical for CCV and CCSA, then 100 trees are required to ensure that the 95% confidence interval will be within 20% of the mean estimate. Generally, there was an average of only 25 trees (of all species) per plot, which yields 95% confidence intervals within 40% of the mean. This level of precision is too low to be useful in detecting forest health problems at the individual plot level.

Together, residualization and standardization of the raw indicators reduce the high level of variability and permit combining across species. The regression models adjust the composite crown indicators on a species basis for tree and stand differences. Combining across species is justified by standardizing the residuals to a mean of 0 and a standard deviation of 1. Indicators standardized in this manner reflect the deviation of all trees from their species mean (in terms of standard deviation units) and are invariant to the species distribution on the plot. This is important when species distributions consist of species with widely varying crown indicators, such as loblolly pine with CCV = 24.5 m^3 and southern red oak (*Quercus falcata* Michx.) with CCV = 87.3 m^3.

Both residualization and standardization have advantages over analyses involving raw values. If models are not available, analyses can proceed with indicators that have been standardized but not residualized. If it is not necessary to combine across species, then analyses can proceed with indicators that have been residualized but not standardized. Also, the techniques described herein are not restricted to the composite values — standardization and residualization can also be applied to the individual absolute crown indicators.

Application of indicators

The assortment of crown indicators presented in this paper may be useful as analytical tools for the identification and investigation of a variety of potential forest health issues. They have both biological and statistical utility. They can be correlated with other indicators such as growth, mortality, lichen diversity, or soil erosion to establish biological thresholds. They can be correlated with other plot-based data or spatial overlays such as elevation, forest type, or physiographic class to determine if there are any statistical differences between categories. They are particularly useful for spatial analyses designed to detect clusters or gradients of unusually good or poor tree crowns.

These proposed indicators can be examined at either the individual tree or the stand level. The individual-tree approach might be used to detect a forest health problem at initial onset, when only a few scattered individuals are affected. Stand-level values across all species are potentially useful for detecting broad problems such as air pollution or drought. If interest is on a specific insect or pathogen, then stand-level values based on an individual species or species groups might be appropriate

The classification of different plots into good/poor classes depending on whether an indicator is expressed as a raw value or its standardized-residualized counterpart indicates that these different expressions emphasize different aspects of tree crown health. Each has value in different situations. Standardized residuals may be more appropriate for detection of a problem in its early stages, particularly when many species are present or if a plot-level indicator is required. Since residualized indicators are adjusted for DBH and stand density, they would not be sensitive to widespread changes involving DBH or stand density and have the potential to mask simultaneous long-term reductions involving the model parameters upon which they are based. If this is suspected, residualization would not be warranted.

Conclusion

The absolute crown indicators have long been used as indicators of forest health, and the FHM Program has extended them to assess the forest health at regional and national scales. However, the absolute crown indicators do not account for the three-dimensional attributes of a tree crown, the multivariate nature of the crown variables, or differences among species.

The utility of absolute crown indicators can be extended with a geometric approach that yields composite estimates of crown volume, crown surface area, and crown production efficiency. Models can be used to produce residuals that are adjusted for the effect of tree size and stand dynamics. Absolute, composite, and residualized indicators can also be standardized to a mean of 0 and a standard deviation of 1, which enhances comparability among species. Combinations of these techniques result in a variety of analytical tools that can be tailored to address issues concerning forest health.

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