
Detection Monitoring of Crown Condition in South Carolina: A Case Study

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Abstract.—This article presents a case study of how indicators of forest health can be adjusted for natural factors, standardized to a common basis, and subjected to spatial analysis for the purpose of detecting potential problems related to forest health. Two of five Forest Inventory and Analysis inventory panels in South Carolina and surrounding States were completed in 2000 and 2001. The crown volume of each sampled live tree at least 5.0 inches in diameter was estimated from field measurements associated with the Phase 3 Crown Indicator. Regression models were then used to adjust each crown volume for differences in stem diameter by species. Model residuals were subsequently rescaled to a mean of 0 and standard deviation of 1, thereby enabling direct comparisons of deviations from expected crown volumes across species and tree sizes. The occurrence of trees below the 25th percentile on these adjusted statistical distributions was then examined for spatial cohesion. A statistically significant cluster of plots containing trees with below-threshold values was identified on the South Carolina-Georgia border. Additional spatial analyses in which thresholds were lowered to the 10th and 5th percentiles yielded similar results.

When the U.S. Department of Agriculture Forest Service Forest Inventory and Analysis (FIA) indicator advisors and analysts met in October 2002, the decision was made to showcase Phase 3 forest health indicators in the upcoming Maine and South Carolina analytical reports. The analyses included in this article began as a demonstration for the South Carolina report (Conner *et al.* 2004) to show how data for the crown indicator could be used in detection monitoring to check for unusual trends in tree crown health. Detection monitoring is the first of three analytical

processes applied by the Forest Health Monitoring (FHM) program to evaluate forest health (Riitters and Tkacz 2004). When a potential problem surfaces through detection monitoring, an evaluation monitoring project is initiated to increase the signal-to-noise ratio. If evaluation monitoring fails to yield a satisfactory explanation, and the potential problem is not a false signal, intensive site monitoring may then be used to more fully understand the situation.

With only the 2000 and 2001 data panels available for analysis, we were surprised to discover the demonstration in detection monitoring leading to significant results. This article describes the current status of the South Carolina crown analyses and discusses followup studies planned for evaluation monitoring.

Methods

Composite Crown Indicator

Field crews record the following tree-level variables as part of the crown indicator on all FIA Phase 3 plots: uncompact live crown ratio, crown density, crown dieback, foliage transparency, crown light exposure, and crown position. Complete descriptions of these variables are available in the FIA Phase 3 field guide (USDA Forest Service 2001). The crown variables can be analyzed singly or be combined to formulate composite indicators of crown condition. We decided that crown volume, a composite approximation of crown size that combines estimates of crown length, width, and density into a single value, was the most appropriate variable of interest for the purpose of detection monitoring. Net primary production originates at the tree crown; therefore, it logically follows that trees with small or sparsely foliated crowns might indicate a state of decline.

Field measurements of uncompact crown ratio, crown density, and tree length were thus combined with modeled crown diameter to estimate a composite crown volume (CCV) for each sampled tree:

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$$CCV' = 0.5(\pi R^2(CL)(DEN)) \quad (1)$$

where:

$$R = CD / 2,$$

$$CL = H (UCR) = \text{crown length (ft)},$$

$$UCR = \text{uncompacted crown ratio (percent)},$$

$$H = \text{total tree length (ft)},$$

$$DEN = \text{crown density (percent)}, \text{ and}$$

$$CD = \text{crown diameter (ft)}, \text{ which was estimated from the model:}$$

$$\hat{CD} = b_0 + b_1(D) + b_2(D^2) + b_3(UCR) \quad (2)$$

where:

$$D = \text{d.b.h. (in)}, \text{ and}$$

$$b_0 \dots b_3 = \text{regression coefficients unique to each species.}$$

The crown-diameter models were derived from trees on 1,740 FHM plots measured in 24 Eastern States between 1991 and 1999 (Bechtold 2003). Note that crown diameter had to be modeled because of the decision to drop the direct measurement of crown diameter when the FIA and FHM programs were integrated in 2000.

Standardized-Residualized Indicator

The next step was to adjust the computed crown volumes for natural factors known to influence crown size. Two of the most obvious and easily available factors in the data set were species and diameter at breast height (d.b.h.). Adjustments for species and d.b.h. were accomplished by solving the linear model specified in equation (3) for each species. Note that the model could have taken any form or been expanded to include any tree, stand, plot, or exogenous attributes for which adjustment is wanted.

$$CCV' = b_0 + b_1(D) \quad (3)$$

The residuals from the least-squares solution of equation (3) serve to quantify deviations of individual trees from their expected crown volumes for a given species and tree size:

$$R_{ts} = CCV'_{ts} - \hat{CCV}'_{ts} \quad (4)$$

where:

$$R_{ts} = \text{the residualized indicator for tree } t \text{ of species } s.$$

Because the model residuals are scaled differently by species, one additional adjustment was made to standardize the residuals across species. The residualized indicators (R_{ts}) from equation (4) were rescaled to a standard deviation of 1 by dividing the model residuals by the standard deviation of the residuals for each species:

$$R'_{ts} = \frac{R_{ts}}{d_s} \quad (5)$$

where:

$$R'_{ts} = \text{the standardized-residual indicator for tree } t \text{ of species } s, \text{ and}$$

$$d_s = \text{the standard deviation of the model residuals for species } s.$$

At this point, we have a tree-level indicator of CCV (R'_{ts}) that has been adjusted for d.b.h. and standardized (by species) to a mean of 0 (i.e., the mean of the model residuals is 0) and a standard deviation of 1. Standardization in this manner allows trees to be combined across species for analysis. Trees can thus be averaged or otherwise grouped for comparison by tree-level attributes (e.g., overstory versus understory trees), condition-level attributes (e.g., public versus private ownership), or plot-level attributes (piedmont versus coastal plain). More details on standardization and residualization techniques are provided by Zarnoch *et al.* (2004).

Note that a regression model is not required to standardize indicators by species. Had the adjustment for d.b.h. not been wanted, a standardized indicator could have been produced by replacing the predicted (CCV') in equation (4) with the mean (\bar{CCV}') from the data. Using the mean of the indicator allows standardization to proceed when adjustment is not necessary or possible.

Spatial Analysis

The spatial scan statistic developed by Kulldorff (1997) was used to search for potential clusters of plots with below-average crown conditions. This statistic was developed to test for randomness of disease occurrence in the spatial and spatiotemporal domains and has been applied to indicators of forest health by Coulston and Riitters (2003). The scanning proceeds by visiting every location (i.e., plot) in the study area. A series of circular windows of increasing size (up to 50 percent of the study area) is then superimposed over each location. The test statistic, Ψ_w , is then

calculated using the total number of “events” inside and outside each window. Ψ_w is the likelihood ratio, based on the Bernoulli distribution, that the occurrence of events is the same everywhere after adjusting for differences in the total number of observations (events and nonevents) inside and outside the window:

$$\Psi_w = \left(\frac{E_c}{N_c} \right)^{E_c} \left(1 - \frac{E_c}{N_c} \right)^{N_c - E_c} \left(\frac{E_{c'}}{N_{c'}} \right)^{E_{c'}} \left(1 - \frac{E_{c'}}{N_{c'}} \right)^{N_{c'} - E_{c'}} (I) \quad (6)$$

where:

E_c = the number of events within the window,

N_c = the number of nonevents within the window,

$E_{c'}$ = the number of events outside the window,

$N_{c'}$ = the number of nonevents outside the window, and

$I = 1$ if $E_c/N_c > E_{c'}/N_{c'}$, or 0 otherwise.

The indicator function (I) in equation (6) sets up a one-sided test of the null hypothesis ($H_0: E_c/N_c = E_{c'}/N_{c'}$) against the alternative that the rate of events is higher inside the window.

The distribution of (Ψ) across the study area and p -values associated with (Ψ_w) were obtained by a Monte Carlo simulation that repeated the analysis for 9,999 random replications of the full data set under the null hypothesis of complete spatial randomness. The significance test for the cluster of observations within the window compared (Ψ_w) for the window to the distribution of (Ψ) from the Monte Carlo simulation. If the value of (Ψ_w) exceeded 95 percent of the values from the Monte Carlo simulation, the cluster was considered significant at the 5-percent level.

We defined an event (E) as a plot with a mean adjusted crown volume (\bar{R}_p') below the 25th percentile of the frequency distribution of all plot-level means in the study area and non-events (N) as the complement:

$$E = 1 \text{ if } (\bar{R}_p') \leq T_p, \text{ or } 0 \text{ otherwise} \quad (7)$$

$$N = 1 \text{ if } (\bar{R}_p') > T_p, \text{ or } 0 \text{ otherwise} \quad (8)$$

where:

$$(\bar{R}_p') = \frac{\sum_{p=1}^{n_p} (R_{ps}')}{n_p},$$

n_p = the number of trees on plot p , and

T_p = the 25th percentile of the distribution of (\bar{R}_p') across all plots in the study area.

Plots up to 40 miles outside South Carolina were included in the spatial analysis to avoid any edge effect caused by truncating the analysis at the border. A total of 43 systematically distributed forest plots were available for analysis within the State, with an additional 33 plots contained in the band of border plots.

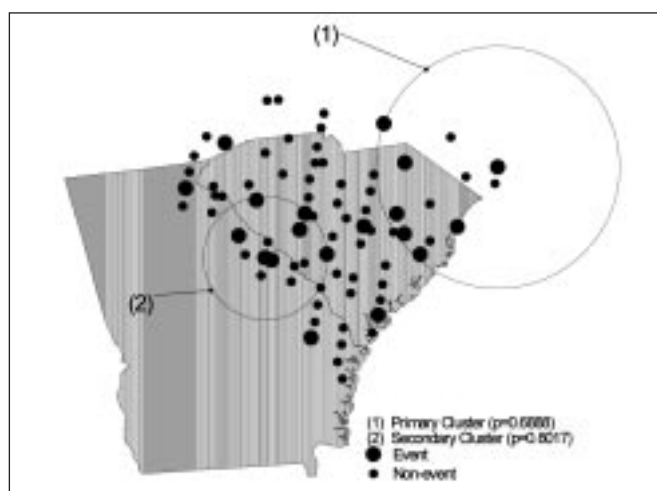
Results and Discussion

Detection Monitoring Analyses

Figure 1 shows the spatial distribution of forest plots in the study area classified as events and nonevents based on the 25th percentile of the (\bar{R}_p') frequency distribution. Two spatial clusters of plots with relatively small mean crown volumes (\bar{R}_p') were detected, but neither was statistically significant, and the observed clustering could have occurred by random chance.

The analysis was subsequently refined to increase the signal-to-noise ratio. Because the spatial clusters identified by the circles in figure 1 extended beyond the South Carolina border, the buffer area was expanded from 40 to 80 miles. This expansion increased the number of plots in the buffer from 33 to 80, yielding a total of 143 plots in the study area. We also revised the definition of an event. Recall that an event was previously defined as a plot in the lower 25th percentile of the distribution of (\bar{R}_p') across plots; thus, the number of events assigned to

Figure 1.—The distribution of FIA plots measured within 40 miles of South Carolina (2000–01), showing two clusters with a relatively high rate of events (mean plot-level standardized-residualized crown volumes below the 25th percentile). Neither cluster is statistically significant.



each plot location was either 0 or 1. In our refined analysis, *trees* in the lower 25th percentile of the distribution of the residuals for their species (R'_{ts}) were identified as events, and the number of tree-level events and nonevents was then summed for each plot (equations 9 and 10) before calculating the test statistic (equation 6).

$$E = E_p = \sum_{t=1}^{n_p} E_{tp} \quad (9)$$

where:

E_p = the sum of events on plot p ,

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

T_s = the 25th percentile of the distribution of the residuals for species s (R'_{ts}) across the study area.

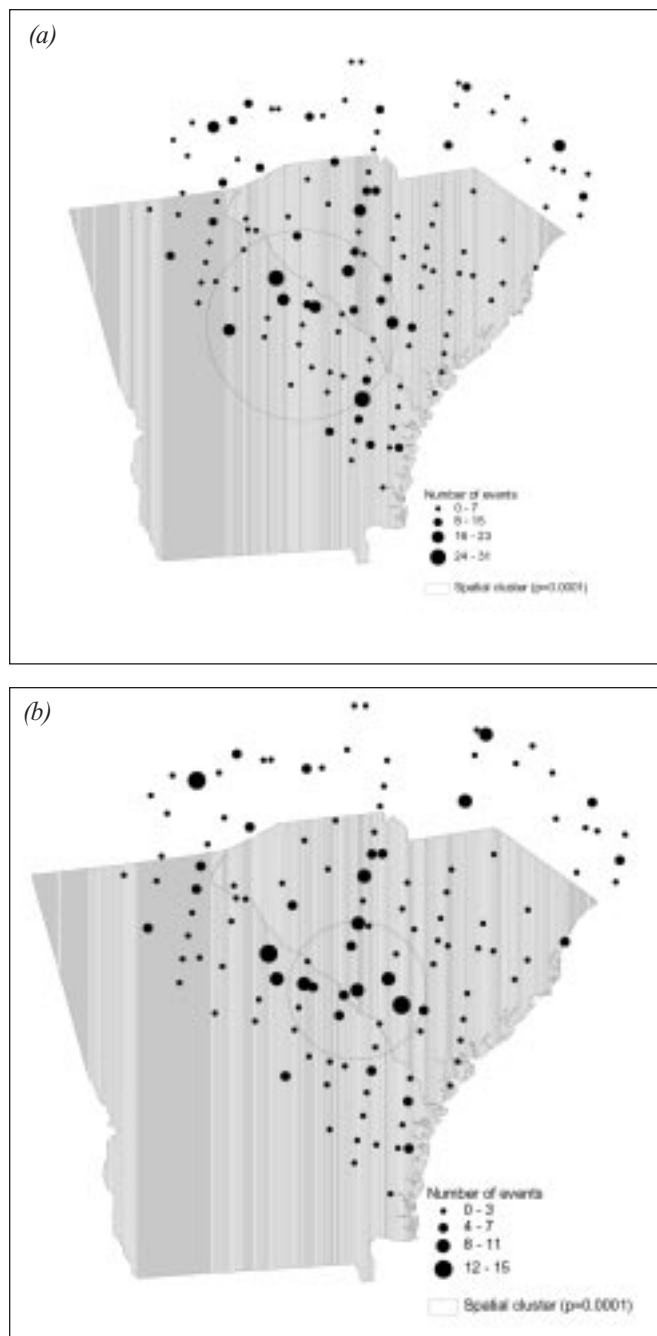
The number of nonevents on each plot (N) was then

$$N = N_p = n_p - E_p \quad (10)$$

Each plot was thus characterized by the number of events and nonevents observed, as opposed to the binary 0-1 classification used in the initial analysis. This adaptation was more consistent with Kulldorff's (1997) original technique and gave more precision and power to the analysis.

The revised analysis again detected a cluster of plots with small crowns (fig. 2a) in the same approximate location as the secondary cluster from the initial analysis (fig. 1), but this time the spatial cluster was statistically significant ($p = 0.0001$). In the cluster, 288 events were recorded when the expected number was 221. The threshold used to define an event was then progressively reduced to check the sensitivity of the cluster to the somewhat arbitrary threshold. Similar results were obtained when the threshold was lowered to the 10th percentile (fig. 2b). Again, the cluster was statistically significant ($p = 0.0001$), and 87 events were recorded when the expected number was 49. Although the 10th-percentile cluster was smaller and shifted slightly to the east, the cluster was mostly contained within the larger cluster associated with the 25th-percentile threshold. Further reducing the event threshold to the 5th percentile resulted in a significant spatial cluster ($p = 0.0002$) contained by the cluster from the 25th percentile, with 41 events recorded when only 18 were expected (fig. 2c). Substantial overlap was observed in the location of the spatial cluster across thresholds (fig. 2d).

Figure 2.—The distribution of FIA plots measured within 80 miles of South Carolina (2000–01), showing significant ($p < 0.01$) spatial clusters of FIA plots containing sample trees with standardized-residualized crown volumes below the (a) 25th, (b) 10th, (c) 5th percentile, and (d) overlay of significant spatial clusters.



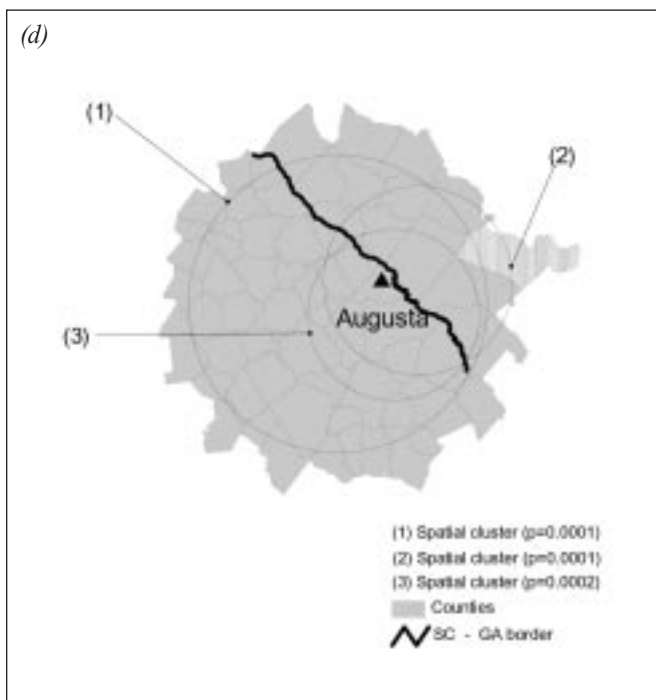
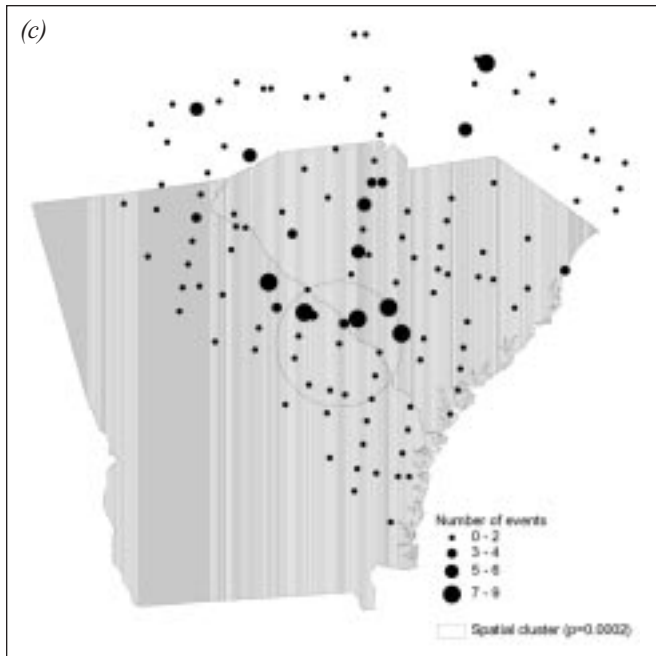
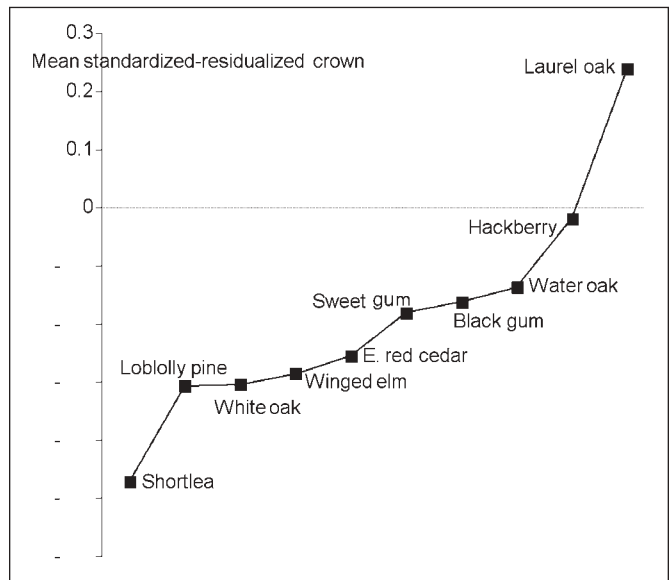


Figure 3 lists the 10 most common species encountered in the 25th-percentile cluster. By species, the mean standardized residuals of trees inside this cluster (\bar{R}'_{sc}) were below zero for all species except laurel oak, indicating that the spatial anomaly seems to cross species boundaries. (\bar{R}'_{sc}) was calculated as follows:

Figure 3.—Mean standardized-residualized crown volumes of FIA sample trees within a significant ($p < 0.01$) spatial cluster of trees below the 25th percentile on the South Carolina-Georgia border (2000–01), by species.



$$(\bar{R}'_{sc}) = \frac{\sum_{i=1}^{n_{sc}} (R'_{ts})i}{n_{sc}} \quad (11)$$

where:

n_{sc} = the number of trees of species s in cluster c , and
 i = 1 if tree t is located in the cluster c and of species s , or 0 otherwise.

At -0.47 , shortleaf pine had the lowest (\bar{R}'_{sc}) of all species in the cluster. Loblolly pine, with a mean standardized residual of -0.30 , did not fare much better. Loblolly is by far the most common species in the region, accounting for 60 percent of the trees sampled within the cluster.

Evaluation Monitoring Proposal

Given these results, we conclude that the applied detection monitoring techniques have exposed a cluster of below-average crown volumes worthy of further investigation under evaluation monitoring. We have consequently proposed an evaluation monitoring study designed to probe deeper into the unusual cluster of trees with small crowns straddling the South Carolina/Georgia border. The objectives of the proposed study are as follows:

1. To examine the influence of specific crown dimensions and tree species on the location and significance of the cluster. This will be accomplished by using the standardization procedures and spatial scan statistics described above on the individual crown components (transparency, dieback, density, crown length, and crown width) and species separately. Pursuing this objective is important because the presence of a single crown dimension or tree species responsible for the geographic cluster will guide the selection of potential explanatory variables.
2. To run the analysis again separately on individual panels and add a third panel with 2002 data (when available) to determine if a particular panel is driving the results, which may indicate a training issue.
3. To validate the data. Field plots inside and outside the cluster will be visited to check the field measurements. Crown diameters will also be measured and checked against the crown diameters estimated with regression models.
4. To identify potential explanatory variables. A tree pathologist will be included on the revisit team to examine tree and stand characteristics that might explain the cluster.
5. To develop cause-effect hypotheses and test with statistical models. We will use multivariate statistical techniques to test potential explanatory variables for differences between plots inside and outside the cluster. Explanatory variables will include potential causal agents identified during the field visits, as well as environmental differences available from other data sets such as drought occurrence, ozone exposure, insect and pathogen activity, and soil characteristics. Based on results from the multivariate analysis, we intend to build models to evaluate and test cause-effect relationships.

Conclusions

Besides the potential problem with crown condition, some additional observations during the detection monitoring exercise are worthy of note.

Analysis of the crown indicator was severely handicapped by the absence of crown-diameter data. Because crown diameters had to be estimated using regression models, we essentially had to guess at one of the three variables needed to estimate the CCVs featured in the detection monitoring exercise, and are now faced with obtaining the missing data in the evaluation phase. We also had to delete species for which crown-diameter models were not available, such as palmetto and hawthorn. FIA should reconsider the decision to drop crown-diameter measurements. If not measured, crown diameters should at least be estimated in the field, which only requires 15–20 seconds per tree (Bechtold *et al.* 2002). We also experienced difficulty with the way uncompact crown ratios are measured on leaning and down trees, ultimately resulting in their deletion from the analysis. We have recently submitted a change proposal to correct that problem.

The detection monitoring techniques applied to the crown indicator can be used as a template for almost any indicator. One major advantage of the standardization approach is that it does not require biological thresholds, which involve difficult and time-consuming, process-level research, usually on a species-by-species basis. Statistical thresholds are quite useful and available for immediate use. In addition, the standardization approach easily lends itself to adjustment for the influence of natural factors through modeling. The spatial scan statistic also can be easily applied to other indicators, and it seems very efficient at identifying nonrandom spatial patterns with relatively few observations.

Finally, the spatial clustering detected in this analysis was surprisingly persistent (fig. 2d). Adjustments were made in the way crown volumes were computed for down trees and trees with broken tops, and the event thresholds were changed—all with essentially the same result. Whether a real problem exists in this area remains to be seen. Evaluation monitoring certainly is appropriate given the information at hand. Even if evaluation monitoring discovers a problem with the data or the applied analytical techniques, valuable experience will be gained in the effort to monitor forest health.

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