Spatial Continuity of Tree Attributes in Bottomland Hardwood Forests in the Southeastern United States

Luben D. Dimov, Jim L. Chambers, Brian Roy Lockhart

Abstract: Sustainable forest management and conservation require understanding of underlying basic structural and competitive relationships. To gain insight into these relationships, we analyzed spatial continuity of tree basal area (BA) and crown projection area (CPA) on twelve 0.64-ha plots in four mixed bottomland hardwood stands in Louisiana, Arkansas, and Mississippi. Variogram range indicated that BA spatial continuity of trees with dbh $>$ 10.0 cm extended an average 4.5 m. This distance equaled the quadratic mean crown radius (QMCR) of the overstory trees. Overall, 95% of the variability in BA was accounted for by the spatially structured variance and could be modeled as spatial dependence. Removal of suppressed trees from the analyses reduced the variability in BA at small separation distances and increased the variogram range. The average spatial continuity of unsuppressed trees averaged 18.2 m and was 17.6, 18.5, and 18.5 m based on the BA variograms, CPA variograms, and cross-variograms, respectively. This distance corresponded to four times the QMCR of the overstory trees and extended far enough to encompass the first- and second-order neighbors. The results suggest an existence of complex competitive influences and confirm findings in nonwoody vegetation that competitive effects can propagate beyond the direct neighbors. FOR. SCI. 51(6):532–540.

Key Words: Spatial dependence, geostatistics, variogram, cross-variogram.

MANY BIOLOGICAL PHENOMENA have properties that cannot be analyzed with statistical techniques that are designed to take into account only nonspatial relationships. One such property is the spatial dependence of the values of examined samples. Spatial dependence can be thought of as the similarity of sample values as a function of the spatial separation between them. Their similarity can be a result of underlying spatially continuous processes. Examination of spatial dependence can aid in determining some features of the biology and ecology of a species and in revealing important spatial characteristics that cannot be found if the data are described only by standard statistical analysis based on measures of central tendency and dispersion (Rossi et al. 1992). A set of statistical tools often used for spatial analysis is geostatistics. Geostatistics is the branch of applied statistics that is concerned with the detection, modeling, and estimation of spatial dependence, or continuity (Isaaks and Srivastava 1989, Rossi et al. 1992), that may commonly underlie many biological and environmental phenomena. Geostatistics is therefore intended for use with spatially continuous variables. It is also used to provide unbiased estimation of values at unsampled locations distributed among the sampled locations. Although spatial distribution of trees in a particular stand represents a point pattern of discrete objects (Dale 2000), the spatial distribution of tree attributes (e.g., basal area, area of the projected crown, height, volume) can be considered spatially continuous (Chen et al. 2004).

Spatial continuity of tree attributes is an expression of spatially continuous factors, which may include soil characteristics, competition, and seed dispersal. Soil characteristics (e.g., fertility, moisture, depth) may vary continuously with factors such as elevation, distance from stream, and parent material (Bringmark 1989, Bekele 2001), while competition likely decreases with the increase of intertree separation distance. Continuity in seed dispersal might result in higher concentrations of regeneration in close proximity to the parent tree, especially for heavy-seeded species, possibly resulting in higher genetic similarity of adjacent trees (Nanos et al. 2004). By not assuming independence among the samples, geostatistical analysis methods strengthen the

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more traditional studies of competition and may be particularly suited for forestry research.

Forestry research has indeed recently been taking more extensive advantage of advances in geostatistics (e.g., Meko et al. 1993, Hyppanen 1996, Grushecky and Fajvan 1999). A number of issues are yet to be explored, however, including questions related to potential presence and extent of spatial continuity in data from relatively undisturbed natural forest stands. An intriguing aspect of exploring stands that have been developing with little or no human interference since harvest is the possibility of detecting spatial relationships reflecting their relatively undisturbed development. Once trees have become established on a particular site and in the absence of major disturbances, their survival, relative dimensions, and spatial distribution are largely consequences of two main counteracting processes: growth and competition. Growing trees occupy portions of the soil and aboveground space, from which they extract resources necessary for their own and their neighbors' growth and survival. Unequal sharing of the limited resources, or competition, acts in conjunction with growth processes and, in part, results in specific tree spatial distributions. Geostatistical analysis methods can provide a unique insight and perspective of the spatial distribution of tree attributes that resulted from the action of the two opposing forces, growth and competition, over the life of the stand. Additionally, some geostatistical methods, like variogram analysis, add a new and crucial aspect to the studies of tree competition. Although traditional methods for studying tree competition account for the influence of a competitor or competitors on the growth and development of an individual tree, they are not expressive of the competitive pressure of individual trees back onto their competitors. Variogram analysis, however, may shed new light on tree competitive relationships by pairing each tree with all of its neighbors in a systematic manner.

In this study, we used variogram analysis techniques to (1) determine the distances within which the tree attributes basal area (BA) and crown projection area (CPA) are spatially dependent; (2) quantify the proportion of variability in tree size, and therefore tree growth, that can be attributed to tree spatial distribution; and (3) contrast the extent of spatial dependence of tree BA and CPA. Both of the variables of interest in the current study, BA and CPA, have particular importance in forestry research. Because CPA is related to leaf area (Kuuluvainen 1991, Bartelink 1997), CPA is indicative of tree growth potential. The BA represents the realization of this growth potential.

Materials and Methods

Study Areas and Collected Data

We used geostatistical analysis for data from four stands in natural bottomland hardwood forests on major and minor stream bottoms in Louisiana, Arkansas, and Mississippi. The selected stands (Table 1) experienced little or no silvicultural disturbance since stand initiation and had a large proportion of species from subgenus *Erythrobalanus* (from here on referred to as red oak species or red oaks), genus *Quercus*. One of the stands is on a major stream bottom, as defined by Hodges (1997), in central Louisiana's St. Landry Parish within the Mississippi River floodplain. The site is no longer hydrologically connected with the river. The last silvicultural operation in the stand was carried out over 25 years earlier. The remaining three stands are located on minor stream bottoms (Hodges 1997). The stand in northern Louisiana is in Jackson Parish on the Cypress Creek floodplain and was subjected to removal of the small number of available pine (*Pinus* sp) trees 12 years earlier. The Arkansas site is located in Drew County on Hungerrun Creek and has remained uncut since establishment. The Mississippi stand is in Oktibbeha County on the Noxubee River floodplain and was undisturbed by silvicultural activity since establishment. All sites had either clay loam or silt loam soils (Table 1), the stands were established over 40 years

Table 1. General study site characteristics

State	Lat/Long	Parish or County	Stream type[a]	River or stream name	Plot number	Age[b] (yr)	Time since most recent thinning (yr)	Soils
Central Louisiana	30°40′/91°59′	St. Landry Parish	Major	Mississippi River	1	83	25	Clay loam (fine montmorillonitic, thermic Vertic Epiaqualfs)
					2	75		
					3	75		
Northern Louisiana	32°22′/92°41′	Jackson Parish	Minor	Cypress Creek	1	71	12	Silt loam (fine-silty, siliceous, thermic Typic Glossaqualfs)
					2	61		
					3	72		
Arkansas	33°41′/91°52′	Drew County	Minor	Hungerrun Creek	1	76	Not cut	Silt loam (fine-silty, siliceous, thermic Fluventic Dystrochrepts)
					2	67		
					3	75		
Mississippi	33°17′/88°54′	Oktibbeha County	Minor	Noxubee River	1	46	Not cut	Clay loam (fine, montmorillonitic, thermic Vertic Halpudalfs)
					2	61		
					3	74		

[a] Stream type classified as major and minor. Major stream bottoms are defined as large streams with deep and minerally diverse alluvium brought from large distances, while minor stream bottoms are floodplains and terraces with small streams and somewhat shallower alluvium with local origin (Hodges and Switzel 1979, Hodges 1997).

[b] Age on the plots estimated from annual ring count of basal tree sections of up to three overstory red oak trees from genus *Quercus* and subgenus *Erythrobalanus*.

ago, and were well stocked with proportions of basal area in red oaks of between 13% and 73% (Table 2).

We established three plots at each of the four stands for a total of 12 plots. Initial reconnaissance was used in each stand to identify potential plots where cherrybark oak (*Quercus pagoda* Raf.) was present and the visually estimated red oak component was at least 10% by basal area. Geographic positioning system (GPS) coordinates were recorded for the plot center of each potential plot. Three plots were then randomly selected from among the 12 or more potential plots at each site. The square plots were 80 m per side. Sides of the plots were orientated in the cardinal directions.

Only trees with dbh (1.37 m aboveground) greater than 10.0 cm were measured. For each tree, the dbh, species, location on a local plot coordinate system, and crown class were recorded. The crown classification used was developed by Kraft (1884, as cited by Assmann 1970), and modified to its current form by Smith et al. (1997). Additional data recorded included the total height and the radius of the vertical crown projection in the four cardinal directions. Height and crown radii were not measured on suppressed trees.

Diameter tapes were used for the dbh measurements, and a laser hypsometer-rangefinder and a digital angle encoder were used to map tree locations within plots. Mapping entailed measuring the horizontal distance and angle from North to each tree from locations within the plot. These measured distances and angles were later transformed to Cartesian coordinates. To ensure vertical viewing in determining the edges of the vertical crown projections, we used a densitometer, unless severe crown overlapping occurred. The distance from the center of the bole to the projected crown edge was measured with the laser hypsometer-rangefinder or a measuring tape. Diameters were measured to the nearest 1 mm, horizontal angles to the nearest 0.01°, and distances to the nearest 1 cm.

Geostatistical Analysis

A basic principle in geostatistics is that samples located closer in space are more related and therefore more similar than distant ones, i.e., their attributes are more continuous (Isaaks and Srivastava 1989, Cressie 1993, Goovaerts 1997). The semivariogram (also referred to as variogram), a statistical model of structural spatial dependence, is the most common tool in geostatistics for characterizing spatial continuity (Isaaks and Srivastava 1989). The variogram indicates the degree of similarity among the values of a variable when the samples are at sequential distance increments (called lags or lag distances) away from each other and in a specified direction from each other. The semivariance function is thus estimated for each lag distance and direction by the formula

$$\hat{\gamma}(h) = \frac{1}{2n(h)} \sum_{s_i - s_j = h} (y_i - y_j)^2, \tag{1}$$

where $\hat{\gamma}(h)$ is the semivariance estimator, h is the separation vector (lag distance); $n(h)$ is the number of pairs separated by vector h, s_i and s_j are the locations of points i and j, and y_i and y_j are the values of variable y at these locations. Normally, a certain amount of tolerance for the separation distance and direction is required because there will rarely be another sample located at the exact separation distance. As the distance between the samples increases, so usually

Table 2. Summary of stand and plot characteristics at the four study locations

Location and Plot number	Density (trees/ha)	Proportion in red oak trees[a] (%)	BA[b] (m^2/ha)	Red oaks BA (%)	Stocking[c] (%)
Central Louisiana					
1	309	32	28.59	66	104
2	378	27	32.39	46	119
3	347	29	32.81	60	119
Mean	345	29	31.26	57	114
Northern Louisiana					
1	519	13	33.44	35	127
2	578	21	31.03	47	120
3	594	9	31.59	23	122
Mean	564	14	32.02	35	123
Arkansas					
1	434	33	32.02	55	119
2	405	27	24.75	46	94
3	394	43	29.06	73	108
Mean	411	35	28.61	59	107
Mississippi					
1	614	13	29.72	21	116
2	595	5	36.50	13	139
3	545	6	32.41	19	124
Mean	585	8	32.88	17	126

[a] Genus *Quercus* and subgenus *Erythrobalanus*.

[b] Basal area of all tree stems larger than 10.0 cm in diameter at breast height (1.37 m above ground).

[c] Stocking calculated by the formula in Goelz (1995) and modified here for metric units: $S = 0.033927\ \text{TPH} + 0.060254\ (\text{TPH})(\text{QMD}) + 0.023725\ (\text{TPH})(\text{QMD})^2$, where S = stocking (%), TPH = trees per hectare, QMD = quadratic mean diameter (in cm).

does the difference between the sample values, which results in a larger semivariance. The trend in the semivariance values can be approximated by a model variogram calculated using the least-squares method or other methods as a fit criterion. The semivariance tends to increase up to some particular distance and then to level off. By convention, the model variogram is considered to level off when it reaches 95% of the distance from the abscissa axis to the asymptote. The ordinate at which the model variogram levels off is referred to as the *sill*. The abscissa at which the sill is reached is referred to as the *range*. The sill represents the variance of the random variable as well as the average maximum variogram value achieved at large separation distances, whereas the range represents the distance within which the samples are spatially dependent. The intercept of the model variogram on the ordinate axis is referred to as the *nugget effect* or *nugget variance* and represents the random component of the spatial structure. The nugget effect can also be due to the presence of spatial variability below the minimum lag distance and due to measurement errors. The difference between the sill and the nugget variance is the *structural variance*, and the ratio between the structural variance and the sill represents the amount of variance that can be modeled as spatial dependence (Rossi et al. 1992). A variogram can be (1) isotropic (omnidirectional) when the spatial dependence is a function of the distance between the samples only, and (2) anisotropic (directional) when the spatial dependence is also a function of the direction.

The notion of the variogram, where the pairing is between values of the same variable y at different locations, can be extended to pairing the values of two different variables y and z at different locations to find how they co-vary spatially. This is done through the cross-variogram estimated by the function,

$$\hat{\gamma}_{yz}(h) = \frac{1}{2n(h)} \sum_{s_i - s_j = h} (y_i - y_j)(z_i - z_j), \qquad (2)$$

where $\hat{\gamma}_{yz}(h)$ is the cross-variance estimator of the two variables y and z.

In the current study, initial analysis involved visually examining tree spatial distribution by crown class and by basal area. This is a simple, but important initial step in spatial analysis, because some of the most effective tools for spatial description of data are visual ones (Isaaks and Srivastava 1989). Spatial continuity was examined by constructing isotropic variograms and isotropic cross-variograms for each plot. The models considered in fitting the variogram were linear, linear to sill, spherical, exponential, and Gaussian (Journel and Huijbregts 1978, Cressie 1993). The selection criterion used was the minimal residual sum of squares. The recommendations of Journel and Huijbregts (1978) were followed regarding the lag distance and search distance (the distance between the most distant pairs of samples). The lag distances used were 4 m, which allowed for a sufficient number of pairs (about 30 or more) for each lag distance. The maximum search distance used corresponded to half the plot width (Liebhold et al. 1993), which was 40 m. The coefficient of determination, r^2, was examined to determine how the model variograms fitted the sample variogram (i.e., the observed semivariance values for the different lag distances). However, r^2 is inherently not very useful when a large part of the regression line is horizontal, which is exactly the case for variograms with short range. The software package used for geostatistical analysis was GS$^+$ version 5.3b (Gamma Design Software, LLC, Plainwell, MI).

Results

Because the anisotropic variograms did not appear to have any structure, i.e., no directional dependence was observed, only isotropic variograms were used in the analysis. Trees of different basal area size classes appeared regularly dispersed on most of the study plots (e.g., plot 3 in central Louisiana, Figure 1). There were, however, some exceptions. On plot 1 in Mississippi, the larger trees were concentrated mostly in the western part of the plot (Figure 2), whereas on plot 2 in the same stand (Figure 3), the larger trees were concentrated in the southeastern quadrant. The smaller trees occupying the denser portions of these two plots were mostly sweetgum. The observed spatial separation in these two plots was in contrast to tree distributions found on the remaining plots. Construction of separate variograms for the different portions of plots 1 and 2 in Mississippi was considered, but resulted in too few tree pairs for most of the lag distances. Therefore, comparisons were kept at the whole plot level.

The range of the BA variograms for all plot trees, regardless of relative tree size or position in the canopy, averaged 4.5 m (Table 3). Plots 1 and 2 in the central Louisiana stand were not included in this average because they were characterized by pure nugget-effect variograms,

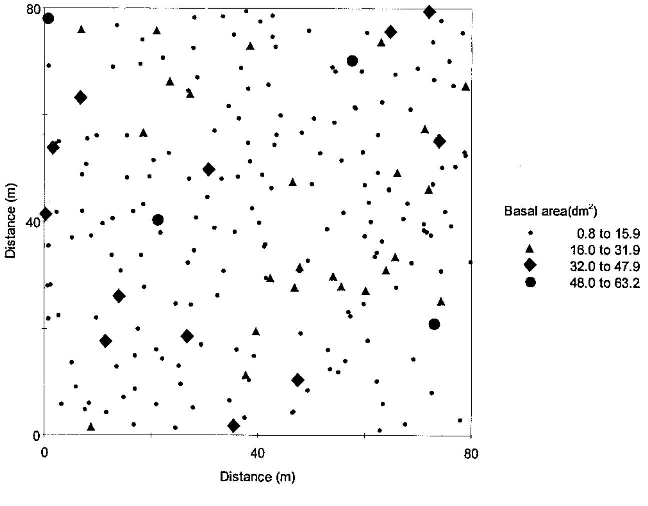

Figure 1. Typical tree distribution plot map (plot 3 in central Louisiana) illustrating relatively regular size distribution across a sample plot with trees represented as different symbols according to their basal area category.

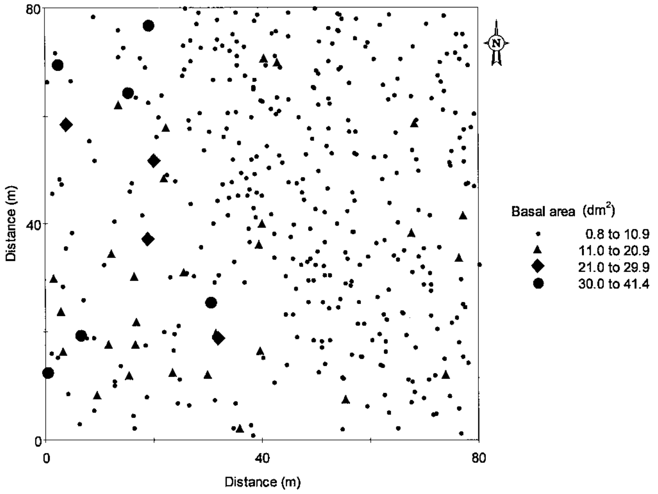

Figure 2. Tree distribution on plot 1 in the state of Mississippi. Trees are represented as different symbols according to their basal area category. Nearly all of the larger trees are in the western portion of the plot.

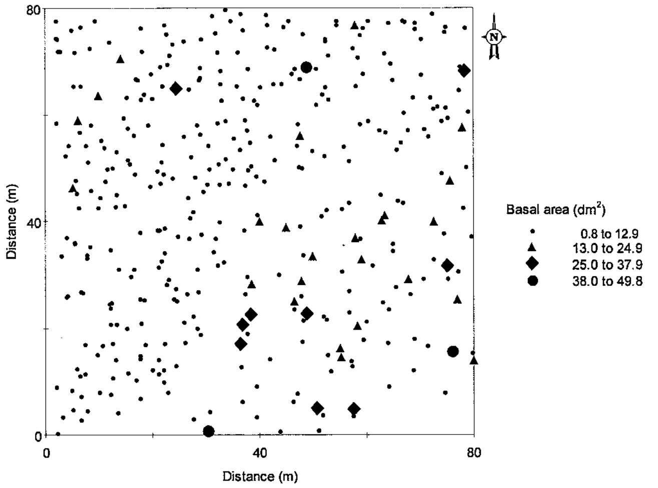

Figure 3. Tree distribution on plot 2 in the state of Mississippi. Trees are represented as different symbols according to their basal area category. Most of the larger trees are in the southeastern quadrant.

which are variograms that lack spatial structure, i.e., constant value of the semivariance over all distances (Liebhold et al. 1993). Two additional plots were excluded because the variogram range extended beyond the studied search distance of 40 m (plot 3 in northern Louisiana with variogram range of 128.5 m and plot 1 in Mississippi with 117.7 m). A variogram range extending beyond the search distance is not reliable, because it is constructed using assumptions regarding the spatial distribution of the trees and their size over distances that are not examined. On the average, 95% of the variability in tree basal area could be explained by the spatially structured variance and can be modeled as spatial dependence (the mean $C_1/(C_0 + C_1)$ in Table 3). If judged by the coefficient of determination (average r^2 of 0.34), the model variograms fitted the sample variogram relatively poorly. However, as indicated earlier, this is because the coefficient of determination is not very useful for cases where a large portion of the regression line is horizontal, as in our variograms with short range.

Table 3. Spatial dependence of basal area in 12 hardwood study plots from variograms for all plot trees larger than 10.0 cm in diameter

Location and Plot number	Variogram range[a] (m)	$C_1/(C_0 + C_1)$[b]	r^2[c]
Central Louisiana			
1		Pure nugget effect[d]	
2		Pure nugget effect	
3	2.6	1.00	0.00
Northern Louisiana			
1	4.2	0.95	0.17
2	6.4	0.97	0.57
3	N/M[e]	N/M	N/M
Arkansas			
1	3.6	0.91	0.28
2	6.7	0.85	0.36
3	4.7	0.92	0.90
Mississippi			
1	N/M	N/M	N/M
2	2.2	1.00	0.00
3	5.3	1.00	0.45
Mean	4.5	0.95	0.34

[a] Variogram range is the distance after which spatial dependence is no longer observed.

[b] $C_1/(C_0 + C_1)$ represents the proportion of variance that can be modeled as spatial dependence, where C_0 is nugget variance, C_1 is structural variance, and $(C_0 + C_1)$ is the sill or the value of the semivariance at which the variogram levels off.

[c] Coefficient of determination of the variogram.

[d] Pure nugget effect is observed when there is no spatial dependence found at the studied scale.

[e] Not meaningful. These plots were excluded because the variogram range extended beyond the search distance of 40.0 m.

Excluding the suppressed trees from the analysis reduced the variability in basal area at small separation distances and resulted in a BA variogram range that extended to greater distances (Table 4), i.e., the BA of the unsuppressed trees was more continuous than the BA of the trees of all crown classes (Figure 4). The CPA variogram range and the BA-CPA cross-variogram range were commensurate with the BA variogram range of the unsuppressed trees (Table 4). As indicated by the ranked BA variogram range (Figure 5a), the spatial dependence on the first nine plots extended between 11.0 and 20.4 m. The spatial dependence on plot 3 in the north Louisiana site, however, extended further to 30.4 m. The average range of these first 10 plots was 17.6 m (Table 4). On the remaining two plots (Mississippi plots 1 and 2) the range extended well beyond the 40.0 m search distance and was therefore an unreliable measure of spatial dependence at the studied scale.

The CPA variogram range indicated that the spatial continuity was between 11.4 and 31.0 m and averaged 18.5 m (Figure 5b, Table 4), excluding three plots whose variogram range extended beyond the 40-m search distance (plot 3 in northern Louisiana and plots 1 and 2 in the Mississippi stand; Figure 5). The extent of spatial dependence determined through the cross-variograms of the BA and CPA was commensurate with the spatial dependence indicated by the BA and CPA variograms (Table 4, Figure 5c), although BA and CPA were not perfectly correlated (r^2 from 0.43 to

Table 4. Parameters of plot basal area (BA) variograms, crown projection area (CPA) variograms, and the cross-variograms for the unsuppressed trees on the 12 plots used in this study

Location and plot number	QMCR[a] (m)	BA variograms			CPA variograms			Cross-variograms		
		Range (m)	r^2[b]	$C_1/(C_0 + C_1)$[c]	Range (m)	r^2	$C_1/(C_0 + C_1)$	Range (m)	r^2	$C_1/(C_0 + C_1)$
Central Louisiana										
1	4.6	14.1	0.74	0.80	17.3	0.67	0.50	14.0	0.78	0.87
2	5.1	15.7	0.59	1.00	12.4	0.64	1.00	20.6	0.68	0.69
3	5.6	18.2	0.51	0.58	11.5	0.55	1.00	11.7	0.64	1.00
Northern Louisiana										
1	4.7	16.5	0.79	0.96	11.4	0.90	0.94	15.1	0.87	1.00
2	4.6	17.3	0.93	0.94	27.4	0.92	0.93	27.2	0.92	0.99
3	3.9	30.4	0.91	0.67	N/M[d]	N/M	N/M	N/M	N/M	N/M
Arkansas										
1	4.9	15.1	0.86	0.98	11.8	0.73	0.79	11.2	0.70	0.77
2	4.9	20.4	0.86	0.73	23.2	0.80	0.64	27.2	0.81	0.60
3	4.6	11.0	0.85	0.98	20.8	0.86	0.90	77.6	0.61	0.51
Mississippi										
1	3.6	N/M	N/M	N/M	N/M	N/M	N/M	N/M	N/M	N/M
2	3.5	N/M	N/M	N/M	N/M	N/M	N/M	N/M	N/M	N/M
3	4.4	16.9	0.88	0.91	31.0	0.90	0.78	20.7	0.90	0.98
Mean	4.5	17.6	0.79	0.86	18.5	0.77	0.83	18.5	0.77	0.82

[a] Quadratic mean crown radius of the unsuppressed trees.

[b] Coefficient of determination for the variogram model.

[c] $C_1/(C_0 + C_1)$ is the amount of variance that can be modeled as spatial dependence, where C_0 is nugget variance, C_1 is structural variance, and $(C_0 + C_1)$ is the sill, which is the value of the semivariance at which the variogram levels off.

[d] Not meaningful. These plots were excluded because the variogram range extended beyond the search distance of 40.0 m.

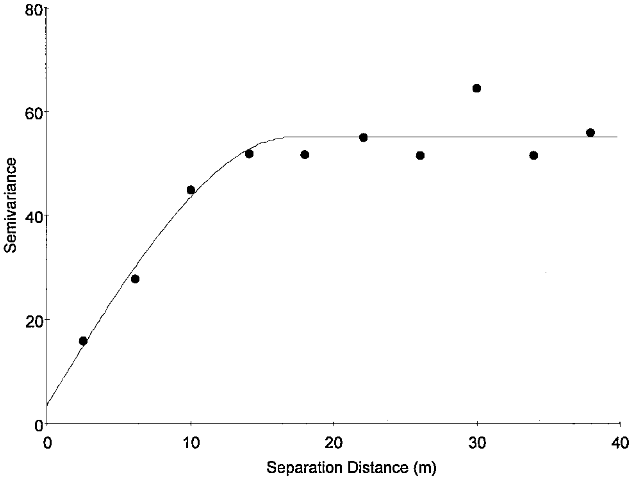

Figure 4. A representative isotropic variogram of the basal area of the unsuppressed trees (plot 2 in northern Louisiana). The variogram range on this plot was 17.3 m.

0.80). The spatial dependence indicated by the cross-variogram range was from 11.2 to 27.2 m and averaged 18.5 m. The cross-variogram range exceeded the search distance of 40 m on four plots (plots 1 and 2 in the Mississippi stand, plot 3 in Arkansas, and plot 3 in northern Louisiana).

For the unsuppressed trees, the proportion of variance that could be modeled as spatial dependence averaged 0.86 for the BA variograms, 0.83 for the CPA variograms, and

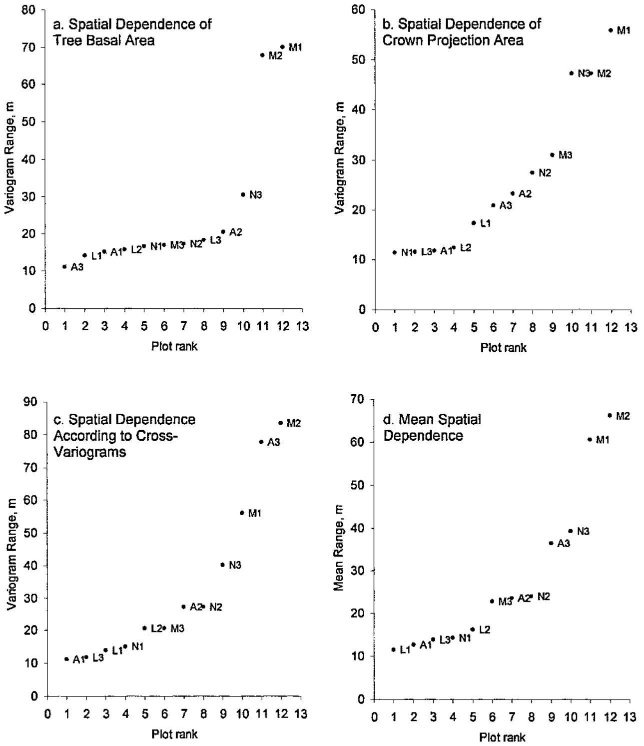

Figure 5. Plot rank according to spatial dependence based on variogram range values of the unsuppressed trees' basal area (a), crown projection area (b), on the cross-variogram range (c), and the average range of the three (d). The stands are in Arkansas (A), central Louisiana (L), northern Louisiana (N), and Mississippi (M), and are followed by plot number.

0.82 for the cross-variograms. The average r^2 values were 0.79, 0.77, and 0.77, respectively.

Discussion

Spatial Continuity of the Basal Area of Trees from All Crown Classes

The average extent of spatial dependence of the BA of all trees (including the suppressed) of 4.5 m, as determined by the variogram range, was equal to the quadratic mean crown radius (QMCR) of the unsuppressed trees. However, the spatial dependence varied greatly on the different plots. On the plot with the most continuous basal area (i.e., longest variogram range), the spatial dependence extended three times as far as on the plot with the least continuous basal area. Expressed as mean crown radii, the variogram range on eight of the plots was from 0.5 to 1.4 times the QMCR of the unsuppressed trees.

The observed short variogram range (e.g., Mississippi plot 2) and pure nugget effect variograms (e.g., central Louisiana plots 1 and 2) resulted from pairing of trees that are located close to each other, but are very dissimilar in size. However, the presence of mostly similarly sized trees (e.g., on about half of Mississippi plot 1) resulted in spatial continuity that extended well beyond the maximum search distance (e.g., Mississippi plot 1 and northern Louisiana plot 3).

The average extent of tree basal area spatial continuity (of the trees from all crown classes) of 4.5 m might be a result of similar growth conditions at this scale. It might also be a result of simultaneous tree establishment within canopy gaps, similar competitive abilities among trees (if trees are genetically similar), or simply an adequate resource base. If it is assumed that competitive effects are greatest near the crown center and extend outward to the edge of the crown or even farther, then stands should consist of dissimilarly sized neighboring trees. Contrary to this assumption, however, trees at distances less than the mean overstory tree crown radius had similar basal areas. This suggests that they may be relatively equally competitive and that competition is symmetrical. When resources are limited, one tree can become dominant over time and may eventually eliminate other trees in its sphere of influence. In contrast, when resources are not limited, which may be the case for most plots in this study, trees in the sphere of influence may be able to coexist at close proximity.

Spatial Continuity of the Basal Area and Crown Projection Area of the Unsuppressed Trees

Compared to the BA variogram range when all trees were included, the variogram range of the intermediate, codominant, and dominant trees was longer. The spatial continuity, as indicated by the average variogram range for the two tree attributes (BA and CPA) and the cross-variograms, extended to distances that corresponded to 3.9 to 4.1 times the QMCR (Figure 6). This would be far enough to encircle the first- and second-order upper canopy neighbors (i.e., the direct and the indirect neighbors), assuming their crown size is average (Figure 7). The spatial dependence on the plots where it extended beyond the maximum search radius of 40.0 m (Table 4) was not used in determining average variogram range.

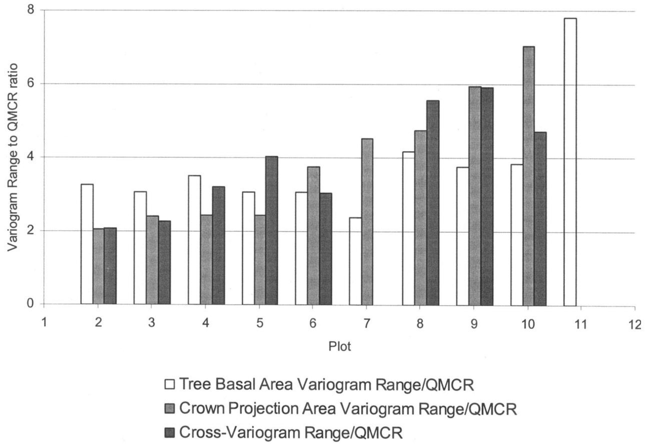

Figure 6. Ratio of tree basal area variogram range to the quadratic mean crown radius (QMCR), crown projection area variogram range to QMCR, and cross-variogram range to QMCR for the unsuppressed trees. The plots are ordered consecutively from small to large crown projection area variogram range. The ratio expresses the spatial dependence in QMCR units. Plots on which the variogram range extended beyond the search distance (the maximum distance at which trees are pared) are excluded.

For comparison, a study in Appalachian hardwood stands (Grushecky and Fajvan 1999), where either diameter-limit harvests or shelterwood seed cuts were applied, found that spatial dependence of the residual canopy trees extends

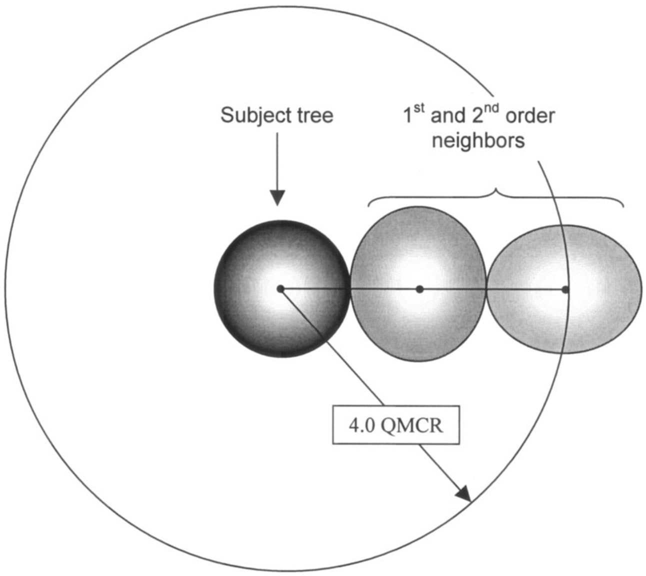

Figure 7. Representation of the zone of spatial dependence. According to the average range of the variograms of the basal area, crown projection area, and the cross-variograms, spatial dependence was present up to a distance of 4.0 times the quadratic mean crown radius (QMCR) of the unsuppressed trees. This distance is represented as a circle surrounding a subject tree and its first- and second-order neighbors in one direction. The trees are assumed to be unsuppressed and to have a crown radius equal to the QMCR.

between 7.5 and 11.5 m. This distance corresponded to twice the average crown radius in the stand they studied. The 7.5-m variogram range value was interpreted by Grushecky and Fajvan as average crown diameter, or "intratree dependence," whereas the larger range was interpreted as the "mean width of crown groups" and was termed "intertree dependence." Similar findings were reported by Cohen et al. (1990), who found spatial dependence to extend to twice the mean crown radius in Douglas-fir (*Pseudotsuga menziesii* [Mirbel] Franco) forest stands in the Pacific Northwest region of the United States. Biondi et al. (1994), however, found spatial dependence, indicated by variograms of the basal area, stem diameter, and 10-year periodic basal area increment, in an old-growth stand of ponderosa pine (*Pinus ponderosa* Dougl. Ex Laws. Var. *scopulorum*) to be a constant 30 m. This was equal to the average diameter of the groups (clump) of pine that were present on the study area.

Kint et al. (2003) speculated that spatial dependence of tree attributes may represent any of the following factors: competition, soil attributes, topography, and soil parent material, depending on the scale. Indeed, several studies do report spatial continuity in important soil factors at distances that may affect tree growth at scales observed in the current study (Bringmark 1989, Lechowicz and Bell 1991, Bekele 2001).

The extension of spatial dependence as far as the second-order neighbors in the current study presents the challenging question of whether any of the factors identified in previous studies describe the processes responsible for spatial dependence in our stands. If spatial continuity is influenced by genetic similarity as a result of poor seed dispersal, root sprouting, or other factors, then the individual species would tend to be aggregated. This could be tested by spatial point pattern analysis techniques (e.g., Ripley's K function and the neighborhood density function). Competition may be another possible factor, because propagation of competitive effects beyond the first-order neighbors has been reported for some plant species. Yoda et al. (1957, cited by Harper 1977) detected negative correlation between the biomass of individual maize (*Zea mais* L.) plants and their first-, third-, and fifth-order neighbors, but positive correlation with the second- and fourth-order neighbors. If such competitive effects existed in the stands from the current study, the trees that are currently in the overstory may have already outcompeted their first-order neighbors at earlier stages of stand development. If their current first- and second-order overstory neighbors have also overtopped their own first-order neighbors, then the trees left in the upper canopy would be those that were previously second-, fourth-, etc., order neighbors in the earlier stages of stand development. In other words, in the forest stand conditions studied, it may be that, on average, former first- and third-order neighbors were eliminated and only the presently more similar-in-size second- and fourth-order neighbors remain in the overstory. Oliver (1978a, b, 1980) and Hibbs (1981, 1983) indicated that some oak species tend to be outgrown by competitors with fast initial growth, but the oaks can eventually overtop them. Thus, rapid initial height growth does not necessarily guarantee the tree an interspecific competitive advantage over the long term. The stand development pattern indicated by Oliver (1978a, b, 1980) and Hibbs (1981, 1983) would be consistent with the one discussed in this study, where trees that in the past were first-order neighbors are eventually eliminated from the overstory.

Management Implications

Growth differences and indicators of tree vigor within tree groups may help managers to decide when trees in close proximity should be left and when the trees should be removed. Removing noncompetitors within a group (i.e., trees that, despite their close proximity to neighbors, have equal dominance and do not exhibit signs of suppression) may only serve to reduce stand volume without much positive effect on the residual trees. Trees within a group with similar basal areas possibly act as "trainer" trees (a tree that, by its shading and abrasive action, accelerates the natural pruning of an adjacent tree), rather than as competitors.

Despite the impression that thinning or release is needed in many young mixed stands in which oaks appear to be in the process of being suppressed, such silvicultural activity may actually not always be necessary. It is likely that, if resources were limited, oaks would eventually outcompete their first-order neighbors and would eventually dominate the stand at later stages of stand development. Avoiding unnecessary silvicultural operations would reduce expenses and decrease the probability of residual tree damage and reduce the probability of proliferation of epicormic branches on low-vigor residual trees and trees from susceptible species (Meadows and Goelz 1998, 2002). Depending on the vigor and degree of crowding around trees that will be retained for the entire rotation, thinning operations for silvicultural reasons may not necessarily be needed until the stand is mature.

The results of the geospatial analysis in this study indicated that some complex intertree interactions may exist in these bottomland hardwood stands. Further geospatial analysis of stands at different development stages and ages would provide additional insight into the spatial distribution and spatial dependence that may be present and might influence the direction of stand development. Future research in this direction would certainly contribute to a clearer understanding of the spatial aspect of stand development and its management implications and should eventually be tied to an economic analysis for decision-making.

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