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Spatial cross-correlation of undisturbed, natural shortleaf pine stands in northern Georgia

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In this study a cross-correlation statistic is used to analyse the spatial relationship among stand characteristics of natural, undisturbed shortleaf pine stands sampled during 1961–72 and 1972–82 in northern Georgia. Stand characteristics included stand age, site index, tree density, hardwood competition, and mortality. In each time period, the spatial cross-correlation statistic was used to construct cross-correlograms and cumulative cross-correlograms for all significant pairwise combination of stand characteristics. Both the cross-correlograms and cumulative cross-correlograms identified small-scale clustering and weak directional gradients for different stand characteristics in each time period. The cumulative cross-correlograms, which are based on inverse distance weighting were more sensitive in detecting small-scale clustering than the cross-correlograms based on a 0–1 weighting. Further analysis suggested that the significant cross-correlation observed among basal area growth and other stand characteristics were due, in a large part, on a subset of sample plots located in the northern part of the state, rather than regional or broad-scale variation as first thought. The ability to analyse the spatial relationship between two or more response surfaces should provide valuable insight in the development of ecosystem level models and assist decision makers in formulating pertinent policy on intelligent multiresource management.

Keywords: cross-correlogram, Moran's *I*, spatial anomaly

1. Introduction

Spatial autocorrelation characterizes the organization or pattern of some phenomenon at fixed localities. In testing for spatial autocorrelation, one is generally interested in discovering whether the phenomenon is randomly distributed, or whether there is some spatial order to their arrangement (Upton and Fingleton, 1985, pp. 151–213). The null hypothesis is that the samples are independent of one another in space.

In a recent article Czaplewski *et al.* (1994) observed a significant positive spatial autocorrelation in the net growth of shortleaf pine (*P. echinata* Mill.) in northern Georgia during 1972–82.

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However, there was no significant spatial autocorrelation among residuals from a regression model that uses stand structure to predict net basal area growth. Czaplewski *et al.* (1994) hypothesized that spatial patterns in stand structure accounts for the spatial variability observed in net basal area growth. The test of this hypothesis requires a procedure capable of analysing the spatial relationship between two or more variables.

In an attempt to address this question, researchers have frequently resorted to various methods of reducing the dimensionality of the data (Orloci, 1978, pp. 42–101), and then employing one of several tests for spatial autocorrelation such as Moran's I statistic (Moran, 1948), spectral analysis (Ripley, 1981, pp. 78–87) or the Mantel test (Mantel, 1967). Unfortunately this approach does not address the question of whether or not two or more response variables are spatially correlated with one another.

Using a variation of Mantel's (1967) one-sample test statistic, Klauber (1975) developed the expected value and variance of a multivariate cross-product statistic, which tests for clustering in more than two samples. More recently, Wartenberg (1985) developed a multivariate spatial correlation statistic based on the Mantel-type coefficient used by Klauber (1975) for quantifying the spatial relations among a set of univariate data. The diagonal elements of Wartenberg's (1985) multivariate spatial correlation matrix are themselves Moran's I statistic, while the off-diagonal elements are bivariate cross-correlation coefficients, which Czaplewski and Reich (1993) refer to as Moran's bivariate I_{YZ} statistic. Because of difficulties in describing the 'distributional properties of these coefficients' Wartenberg (1985) relied on principal component transformation for detecting spatial patterns. These techniques are also related to the cross-variograms that geostatisticians use for describing the cross-continuity between two or more variables (Isaaks and Srivastava 1989, pp. 60–64, 93–106). It is also possible to obtain bivariate cross-spectra for identifying spatially displaced relationships which is similar to their major use in finding leads or lags in time series analysis.

In this paper, the cross-correlation statistic I_{YZ} is used to characterize the spatial structure of undisturbed, natural shortleaf pine stands in northern Georgia.

2. Data

The data used in this study is a subset of data from the USDA Forest Service, Forest Inventory and Analysis Program (FIA), for natural, undisturbed shortleaf pine stands in northern Georgia. The data were originally used by Bechtold *et al.* (1991) to detect a growth decline between 1961–72 and 1972–82. Because of high rates of disturbances (from timber cutting, insect and disease infestations, and fire) the number of sample plots used to estimate basal area growth for undisturbed shortleaf pine stands varied in each time period (Bechtold *et al.* 1991); 127 plots for the 1961–72 period and 40 plots for the 1972–82 period. In spite of the presence of a few paired plots, the two data sets were assumed to be independent. The location of the FIA sample plots for the two time periods are depicted in Fig. 1.

The data included the natural logarithm of gross annual pine basal area growth, m^2/ha (G); site index m (S), which is a measure of stand productivity based on the height of dominant-codominant trees at 50 years of age; natural logarithm of stand age (A) which is the midpoint of 10-year classes; natural logarithm of the number of trees per ha (N); ratio of pine basal area to basal area of all species (P), which is an index of hardwood competition; and natural logarithm of annual basal area mortality, m^2/ha (M) (Appendix B). To be consistent with previous studies, it was decided to use the transformed data instead of the original data. In their study Bechtold *et al.* (1991) used a logarithmic transformation in modeling basal area growth as function of selected stand

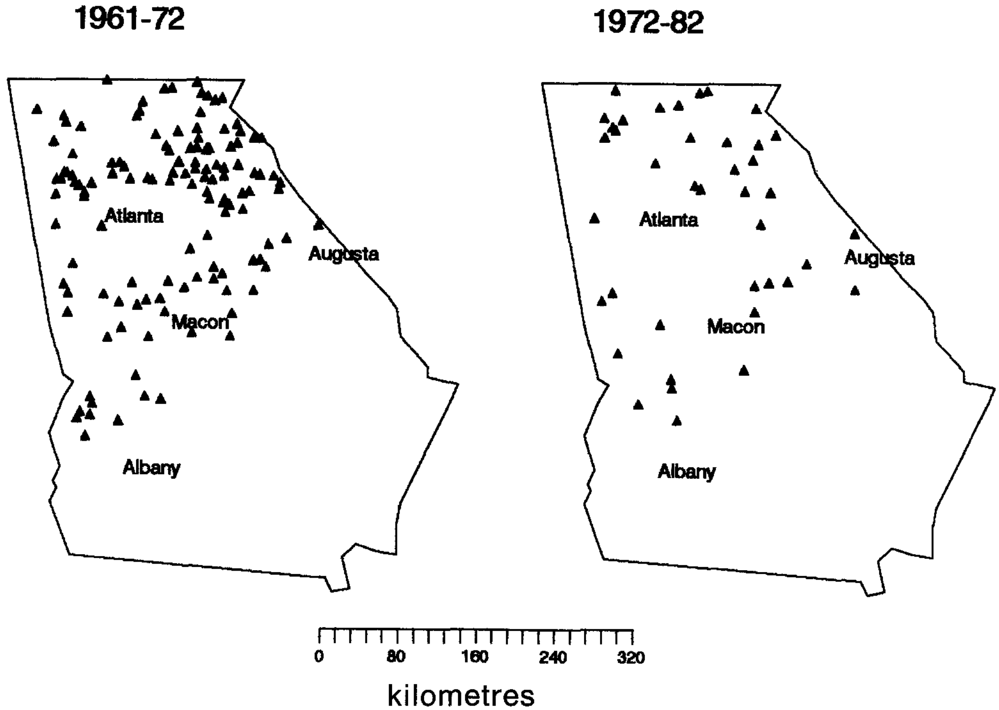

Figure 1. Location of natural, undisturbed shortleaf pine plots sampled in northern Georgia during 1961–72 and 1972–82.

characteristics while Czaplewski *et al.* (1994) noted that a logarithmic transformation increased the power of Moran's I to detect spatial autocorrelation among slow growing plots. For a more detailed description of the data, see Bechtold *et al.* (1991).

3. Methods

3.1 *Cross-correlation coefficient* I_{YZ}

Given two response variables, say y_i and z_i observed at n locations, an index expressing the spatial cross-correlation between two response variables can be expressed as follows (Wartenberg, 1985):

$$I_{YZ} = \frac{\sum_{i=1}^{n} \sum_{\substack{j=1 \\ i \neq j}}^{n} w_{ij} y_i z_i}{W\sqrt{\mathrm{Var}(y)\,\mathrm{Var}(z)}} \tag{1}$$

where w_{ij} is a scalar that quantifies the degree of spatial association or proximity between locations i and j (e.g. inverse distance between locations i and j, or a 0–1 variable indicating that locations i and j are within some distance range of each other); y_i is the observed value of variable y for plot i ($i = 1, 2, \ldots, n$), transformed to have a mean of zero; z_j is the observed value of variable z for plot j ($j = 1, 2, \ldots, n$), transformed to have a mean of zero; W is the sum of all n^2 values of w_{ij}; $\mathrm{Var}(y)$ is the sample variance of y_i; and $\mathrm{Var}(z)$ is the sample variance of z_i. The expected value and variance of the cross-correlation statistic I_{YZ} is provided in Appendix A.

The denominator in Equation (1) makes I_{YZ} a dimensionless statistic that can be interpreted as a Pearson product moment correlation between variables y_i and z_j. Thus, one would expect I_{YZ} to range over the interval of -1 to 1, although it can exceed these limits for an irregular pattern of weights, w_{ij}, or if extreme values are heavily weighted (Cliff and Ord, 1981, p 21).

The cross-correlation statistic was calculated for each pairwise combination of the six stand characteristics in each time period. In calculating I_{YZ}, inverse distance between sample plots was used as a weighting factor (w_{ij}) to give more weight to the closest sample plots and less to those that are farthest away. The null hypothesis of no spatial autocorrelation was rejected when the p-value associated with the test statistic was less than 0.05. Moran's I was used to estimate the spatial autocorrelation associated with each of the six stand characteristics.

3.2 *Cross-correlogram*

A natural counterpart to testing the significance of the overall pattern is to see how this spatial autocorrelation changes with distance. The cross-correlation coefficient I_{YZ} was used to construct correlograms for all significant pairwise combinations of the six stand characteristics. Distance categories (h) used in constructing the correlograms ranged from 0–10 km to 181–190 km, in increments of 10 km. The null hypothesis of no spatial autocorrelation within a given distance category was rejected when the p-value associated with the test statistic was less than $0.05/19 = 0.0026$. In testing this hypothesis binary weights (i.e. $w_{ij} = 0$ or 1) were used to designate whether the distance between a given pair of sample plots occurs in one of the 19 discrete distance classes.

3.3 *Cumulative cross-correlogram*

Regardless of whether a mosaic pattern exhibits any spatial autocorrelation or not, one may wish to have an objective measure of the spatial scale of the pattern under investigation. One method of calculating this scale is to use the cross-correlation statistic I_{YZ}, to estimate the cumulative cross-correlation as one radiates outward from a given sample point. This is similar to Greig-Smith's (1952) method of pattern analysis based on the use of contiguous quadrats for measuring aggregation. The parameter h in this case can be thought of as the radius associated with an area surrounding each sample point. If one graphs the change in the cross-correlation statistic I_{YZ} versus the parameter h, one should be able identify which distance category yields the strongest evidence of a spatial autocorrelation. As h increases so will the spatial autocorrelation until the imaginary area is close to that of the mean area of the pattern under investigation. If h is increased further, the cumulative correlogram reaches an asymptote if the patches are random or aggregated. The cumulative correlogram will decrease if the clusters are regularly distributed (Greig-Smith, 1952). Finally, if the pattern is randomly distributed, the cumulative correlogram should remain constant with increasing distance (Greig-Smith, 1952). A cumulative cross-correlogram was calculated for all significant pairwise combinations of stand characteristics. The null hypothesis of no spatial autocorrelation within a given distance category was rejected when the p-value associated with the test statistic was less than 0.0026.

3.4 *Point cross-correlation coefficient*

In doing any type of spatial analysis, researchers need to be aware of any potential problems due to outliers, extreme data or local anomalies (Haslett *et al.*, 1991). In such cases, inferences based on spatial autocorrelation analysis may be misleading. One way of identifying this type of variation is to use a method suggested by Czaplewski *et al.*, (1994), which decomposes the cross-correlation statistic I_{YZ} to obtain the relative contribution each sample point has to the overall statistic. The point cross-correlation statistic, given by

$$I_{YZi} = \frac{\sum_{j=1}^{n} w_{ij} y_i z_j}{W\sqrt{\mathrm{Var}(y)\,\mathrm{Var}(z)}}, \tag{2}$$

represents the contribution of the *i*th element to the overall statistic. Summing across all samples plots ($1 \le i \le n$) will yield the sample cross-correlation statistic I_{YZ}.

The location of each sample point is then plotted along with its corresponding point cross-correlation coefficient. Areas with a large (positive or negative) point cross-correlation statistics surrounded by an area with small statistics indicates a local anomaly, or possible outlier. A flat plane of point-correlation statistics that differ from zero would suggest the presence of a gradient, while a plane near zero indicates no spatial autocorrelation.

4. Results

Basic statistics for the data in the two time periods are given in Table 1. The Anderson-Darling (Stephens, 1974) test statistic confirmed that all stand characteristics except tree density and net basal area growth departed significantly from normality ($\alpha = 0.01$) (Table 1). Tests for equality of variances (F-test) indicated less variability in site index in the first time period compared to the second time period, while the opposite was true for stand age and tree density. Sample plots in 1961–72 were also significantly younger than sample plots in 1972–82 (t-test). The results of a two-sample empirical goodness-of-fit coverage test (Mielke and Yao, 1990) suggested that the distribution of all stand characteristics, except basal area growth, differed significantly in the two time periods.

Estimates of the spatial autocorrelation and cross-correlation statistics for the six stand characteristics are summarized in Tables 2 and 3, respectively. In the following discussion only variables showing significant spatial autocorrelation are discussed.

4.1 *1961–1972*

In the 1961–72 data, only site index and stand age exhibited a significant spatial autocorrelation (Table 2). However, the correlograms for the two variables were non-significant for all distance classes (Fig. 2a). In contrast, the cumulative correlograms for site index and stand age indicated a significant spatial autocorrelation with increasing distance. The cumulative correlogram for stand age increased until it reached a maximum at approximately 40 km and then decreased thereafter. Such a pattern is characteristic of patches regularly distributed throughout a landscape (Greig-Smith, 1952). This small-scale clustering is apparent if one looks at the spatial distribution of age classes associated with individual sample plots (Fig. 3).

The cumulative correlogram for site index increased steadily until it reached a maximum at 120 km and then decreased slightly (Fig. 2b). Such a trend is characteristic of a directional gradient. The correlogram for site index exhibited a decreasing trend from a positive to a negative autocorrelation with increasing distance which is an indicator of a gradient, but this trend was not significant (Fig. 2a).

The cross-correlation statistic showed a significant positive spatial correlation between site

Table 1. Stand summary statistics of natural, undisturbed shortleaf pine stands sampled in northern Georgia during 1961–72 ($n = 127$) and 1972–82 ($n = 40$).

Stand parameter[1]	*Mean*	*Median*	*Min*	*Max*	*Variance*	*Anderson-Darling test of normality*
			1961–72			
S	19.43	12.00	18.00	27.00	9.75	5.17*
A	2.83	2.71	1.61	4.07	0.50	7.00*
N	6.63	6.69	3.80	8.85	1.24	0.50
P	0.83	0.88	0.50	1.00	0.03	7.38*
M	0.09	0.00	0.00	0.77	0.02	15.85*
G	−0.42	−0.38	−2.46	0.85	0.42	0.33
			1972–82			
S	20.78	21.00	12.00	30.00	18.18	1.63*
A	3.10	3.22	1.61	4.01	0.30	3.23*
N	6.86	6.84	4.95	8.01	0.54	0.33
P	0.76	0.74	0.51	1.00	0.02	0.95*
M	0.13	0.10	0.00	0.58	0.02	2.13*
G	−0.70	−0.71	−2.55	0.68	0.55	0.48

The sample size of the 1972–82 data in this paper is slightly smaller than that used by Bechtold *et al.* (1991). These plots were dropped because they contained a tree with a terminal d.b.h. that was estimated because of an abnormality (such as fusiform rust). Dropping these plots did not alter the results of Bechtold *et al.*, but it was decided to drop them here to eliminate a source of potential measurement error.
[1] See text for a description of stand characteristics.
* Significant at the 0.05 level.

index and stand age (Table 3). Because of the spatial autocorrelation associated with stand age and site index, the significance of this outcome is uncertain in terms of the Type I error. The null hypothesis in the permutation test used in deriving the expected value and variance assumes that each observation is equally likely at each location. Therefore, the permutation procedure not only tests the hypothesis that there is no spatial cross-correlation between two variables, it simultaneously tests the hypothesis that neither of the two variables are spatially correlated. If the null hypothesis is rejected, as in this case, either of these two types of spatial correlation may exist. Taking this into consideration, if we examine the cross-correlogram for site index and stand age a significant negative spatial autocorrelation is observed at approximately 20 km (Fig. 2c) and was equal to zero around 40 km. The point at which the correlogram intercepts the x-axis is an indication of patch size (Sokal

Table 2. Spatial autocorrelation of natural, undisturbed shortleaf pine stand characteristics sampled in northern Georgia during 1961–72 and 1972–82.

Stand parameter	*1961–72* I	p-*value*	*1972–82* I	p-*value*
G	−0.0125	0.38272	0.1365	0.00033
S	0.0592	5.47×10^{-6}	0.0853	0.00994
A	0.0242	0.01784	−0.0200	0.45117
N	−0.0264	0.11404	0.0433	0.07388
P	−0.0021	0.35185	0.2721	0.13720
M	−0.0195	0.22338	−0.1102	0.03886

Table 3. Spatial cross-correlation of stand characteristics of natural, undisturbed shortleaf pine stands sampled in northern Georgia during 1961–72 and 1972–82.

Stand parameters	*1961–72*		*1972–82*	
	I_{YZ}	p-*value*	I_{YZ}	p-*value*
G–S	−0.0020	0.49860	0.1070	0.00078
G–A	0.0086	0.31272	−0.0659	0.02264
G–N	−0.0126	0.26496	0.1173	0.00047
G–P	0.0030	0.29318	0.1285	8.4×10^{-5}
G–M	0.0048	0.35036	0.0160	0.32923
S–A	0.0487	4.1×10^{-6}	−0.0577	0.05203
S–N	−0.0099	0.20431	0.0531	0.08560
S–P	0.0125	0.09891	0.0383	0.09955
S–M	−0.0021	0.41104	−0.0164	0.38213
A–N	0.0079	0.26513	−0.0501	0.07491
A–P	0.0158	0.08949	−0.0581	0.06634
A–M	0.0133	0.09198	−0.0180	0.31694
N–P	−0.0009	0.43896	0.0805	0.00770
N–M	−0.0183	0.11541	−0.0531	0.11554
P–M	0.0103	0.15609	−0.0227	0.29870

and Jacquez 1991). In contrast, the cumulative cross-correlogram reached a significant peak around 30 km (Fig. 2d) and then leveled off, again suggesting the presence of patches. Such a pattern could occur by chance when two surfaces with different spatial scales are overlaid to create a mixture of heterogeneous patches (Sokal and Jacques, 1991).

4.2 *1972–1982*

In the second time period the natural logarithm of net basal area growth and site index had a significant positive spatial correlation (Table 2). There was also a significant negative autocorrelation associated with tree mortality. The correlogram for basal area growth indicated a significant positive spatial autocorrelation at 50 km (Fig. 4A). The cumulative correlogram for basal area growth reached its first significant peak at 20 km and then levelled off after 50 km. Both the correlograms and cumulative correlograms for tree density (Fig. 4a and 4c) and mortality (not shown) were not significant indicating that both tree density and mortality were independent of neighbouring plots. Site index had a significant negative spatial autocorrelation at 160 km but its importance is somewhat questionable because of the few pairs of sample plots used in the calculation. It is possible, however, for populations with a gradient to exhibit long-distance negative spatial autocorrelations (Sokal, 1979). This would be consistent with the pattern observed for site index in the first time period.

The cross-correlation statistic showed a significant positive correlation of basal area growth and site index, tree density and hardwood competition (Table 3); basal area growth had a negative correlation with stand age. There was also a significant positive correlation between tree density and hardwood competition (Table 3). The cross-correlogram for basal area growth and tree density (Fig. 4c) had a significant short distance positive correlation at 20 km. A similar pattern was observed in the correlogram for basal area growth and hardwood competition, again indicating the presence of small scale patches.

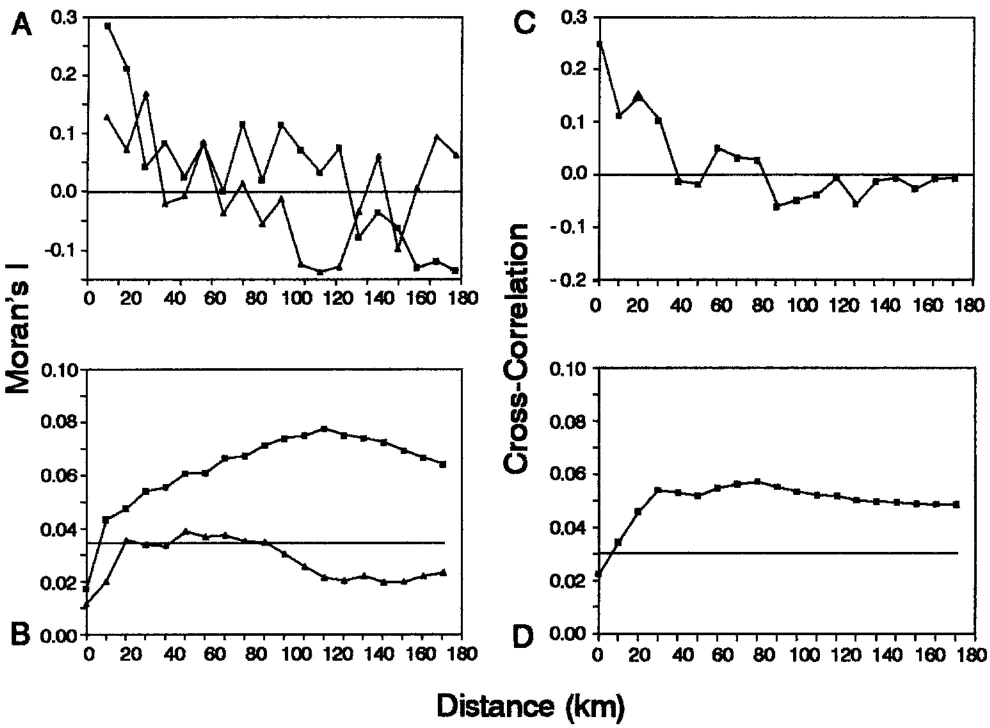

Figure 2. Spatial autocorrelation among site index and natural logarithm of stand age during 1961–72; (A) univariate correlogram of site index (square) and natural logarithm of stand age (triangle); (B) cumulative correlogram for site index (square) and stand age (triangle); (C) cross-correlogram among site index and stand age; (D) cumulative cross-correlogram among site index and stand age. The large solid triangle in (C) represents a significant positive spatial autocorrelation at the $0.05/19 = 0.0026$ level of significance while the upper solid line in (B) and (D) represents the upper $1 - 0.05/19 = 0.9974$ confidence band.

The cumulative cross-correlogram for site index and basal area growth increased steadily until it reached a maximum at 160 km. This peak corresponds to the long distance autocorrelation observed in the correlogram, both of which suggest the presence of a weak directional gradient between site index and basal area growth. A similar pattern was observed for the cumulative cross-correlogram of basal area growth and tree density (Fig. 3d). The cumulative cross-correlogram for tree density and hardwood competition showed a significant positive spatial autocorrelation between 40 and 90 km, with a maximum at 70 km. All of these correlograms indicate some type of patchiness, or the presence of a weak directional gradient.

4.3 *Local anomalies*

To help identify the presence of local anomalies or outliers, orthographic displays depicting the point cross-correlation coefficients were generated for stand characteristics having a significant cross-correlation statistic. For example, Fig. 5 depicts an orthographic view of the point cross-correlation coefficient for basal area growth and site index for the two time periods. In 1961–72 the point cross-correlation statistic did not vary across the study area. However, in 1972–82 a large point cross-correlation was observed among basal area growth and site index on six

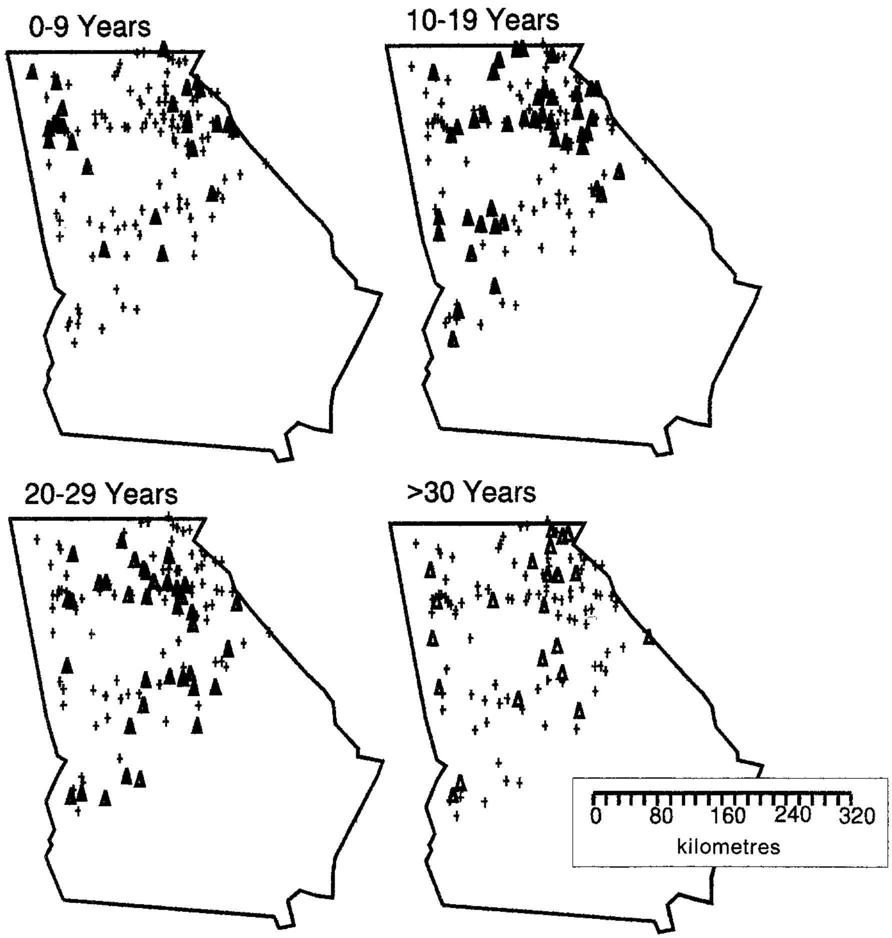

Figure 3. Spatial distribution of stand ages of undisturbed, natural shortleaf pine stands in northern Georgia during 1961–72.

sample plots located in northwestern Georgia. It is this clustering of sample plots with similar characteristics that we are detecting in the cross-correlograms.

Similar patterns were observed in the point cross-correlation coefficient for site index and stand age in 1961–72 and basal area growth and tree density in 1972–82, though the former trend is not as strong as the latter (Fig. 6). This suggests that the significant cross-correlation observed among basal area growth and other stand characteristics are due to a subset of sample plots located in the northern part of the state and not as a result of a regional or broad scale variation as first thought. These results stress the importance of not relying on any one technique in interpreting spatial patterns, but suggests that a variety of techniques should be used to get a better understanding of the pattern under investigation.

5. Discussion

This paper discusses the use of a cross-correlation statistic to highlight the spatial structure common

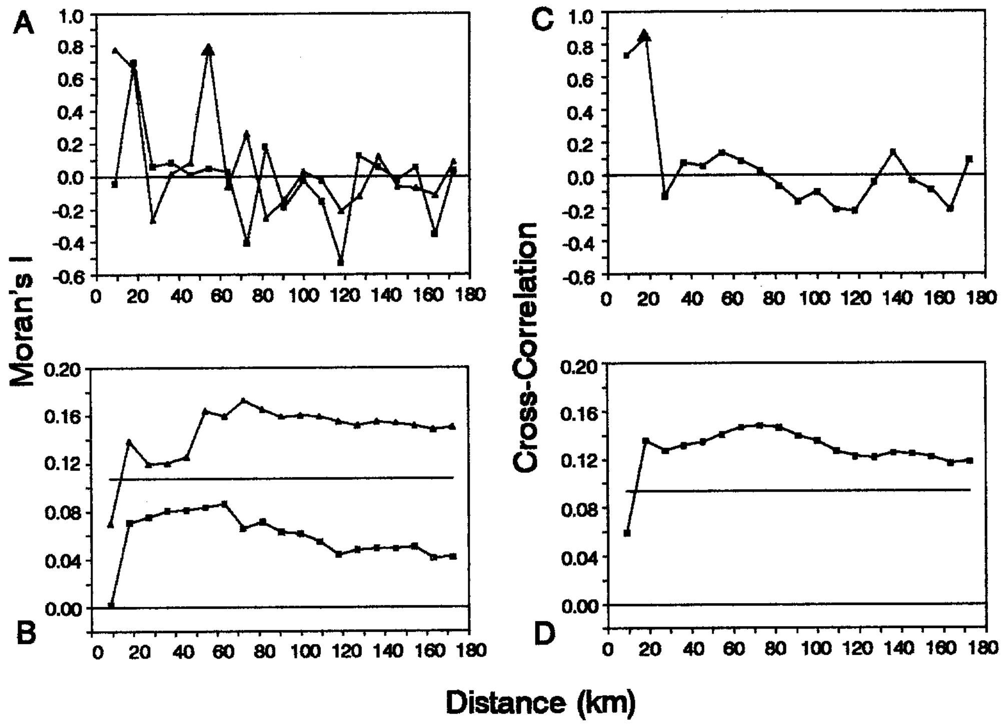

Figure 4. Spatial autocorrelation of natural logarithm of net basal area growth and natural logarithm of tree density during 1972–82; (A) correlogram of natural logarithm of basal area growth (triangle) and natural logarithm of tree density (square); (B) cumulative correlogram of basal area growth (triangle) and tree density (square); (C) cross-correlogram of basal area growth and tree density; (D) cumulative cross-correlogram of basal area growth and tree density. The large solid triangle in (C) represents a significant positive spatial autocorrelation at the $0.05/19 = 0.0026$ level of significance while the horizontal solid line in (B) and (D) represents the upper $1 - 0.05/19 = 0.9974$ confidence bound.

to a set of response surfaces. The technique is demonstrated by analysing the spatial relationship of stand characteristics of natural undisturbed shortleaf pine stands in northern Georgia. Results of the spatial analysis identified small scale clustering and weak directional gradients for several stand characteristics in each time period. While there is no direct evidence to suggest the presence of a true gradient, Bocquet-Appel and Sokal (1989) point out that the weak directional gradients such as the ones observed in this study may be due to a simple autocorrelated processes at the local level. In this study, the significant long distance negative spatial correlation of basal area growth and site index was due to a cluster of slow growing plots in northern part of the state. Such patterns seem reasonable considering the forest landscape is ever-changing as land-use patterns change, and individual stands are subjected to disturbances of varying types, intensities, and frequencies.

The ability of the cross-correlation statistic to detect small scale clustering varied depending on the weights used. The cumulative correlograms, which were based on inverse distance weighting, were more sensitive in detecting small scale clustering. These small-scale patterns went undetected in the correlograms using a 0–1 weighting. This is not to say that inverse distance weighting is necessarily better than some other weighting scheme.

Since the researcher does not know *a priori* the underlying spatial structure of the data, in most

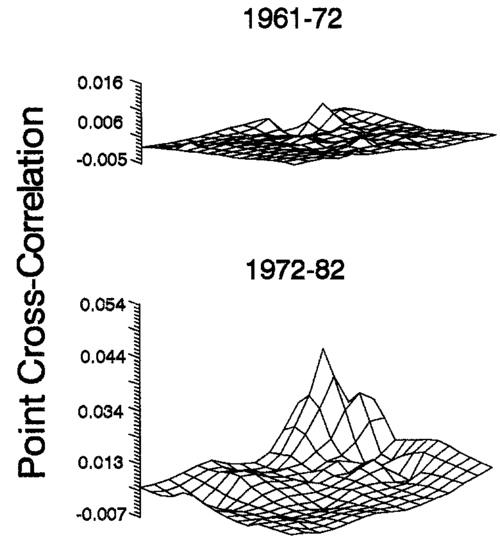

Figure 5. Orthographic view (looking northwest) of the point cross-correlation coefficient of natural logarithm of basal area growth and site index on sample plots separated by a distance of 151–160 km in 1961–72 (top) and 1972–82 (bottom).

cases, there is a danger of interpreting the results in terms of the existence of distinct clusters even when this is not the case. In fact, the small scale clustering observed in this study may be due, in part, to the natural clustering of sample plots in the forest landscape which we were not able to take into consideration when using inverse distance weighting.

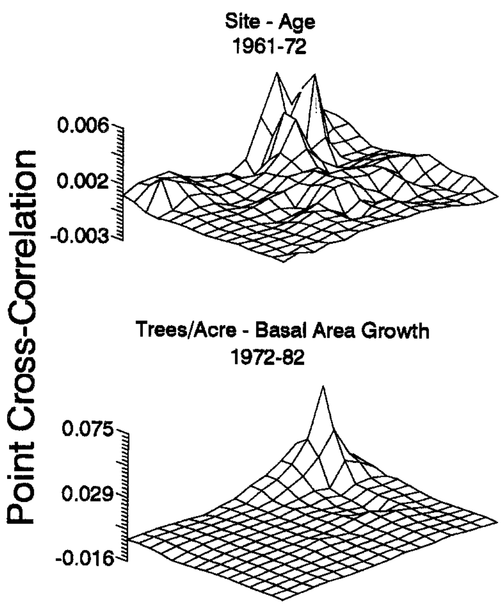

Figure 6. Orthographic view (looking northwest) of the point cross-correlation coefficient of site index and natural logarithm of stand age on sample plots separated by a distance of 129–130 km in 1961–72 (top) and of natural logarithm of net basal area growth and natural logarithm of tree density on sample plots separated by a distance of 61–70 km in 1972–82 (bottom).

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Biographies

Robin M. Reich is an Associate Professor of Forest Biometrics in the Department of Forest Sciences, Colorado State University. Robin received his B.S in forestry, and his M.S. and Ph.D. in forest biometrics from the University of Florida. Current research interests include the application of spatial statistics in studying the spread and intensification of forest diseases, environmental risk assessment, and natural resource sampling.

Raymond L. Czaplewski has been a mathematical statistician with the USDA Forest Service since 1982, working with regional- and continental-scale forest monitoring data. Current research interests include spatial analysis of forest health and broad-scale landscape changes, and assessment of earth-observing satellite data for resource monitoring and management. Ray designed the sampling methods for the 1990 Global Tropical Forest Resource Assessment by the Food and Agricultural Organization of the United Nations. Ray earned his B.A. in biology, his M.S. in systems ecology and his Ph.D. in quantitative rangeland science.

William A. Bechtold has been a member of the Forest Inventory and Analysis Work Unit of the U.S. Forest Service since 1977. He has served as a resource analyst for most of his career, working with state and regional forest inventory data. His current research interests focus on the use of continuous inventory data to analyse changes in productivity and other indicators of forest health at the regional scale. Bill has designed much of the mensuration system utilized by the national Forest Health Monitoring Program, and is now supervising its implementation. He holds a B.S. in forestry from Purdue University, and an M.S. in forestry from Duke University.

Appendix A

Given a set of n! equally likely random permutations of sample data, the expected value and variance of the cross-correlation statistic I_{YZ} under the null hypothesis of no spatial correlation between two response variable, say y_i and z_i, is given by:

$$E[I_{YZ}] = \frac{-\mathrm{Cov}(yz)}{(n-1)\sqrt{\mathrm{Var}(y)\,\mathrm{Var}(z)}} = \frac{-\rho_{YZ}}{n-1} \tag{A.1}$$

$$\mathrm{Var}(I_{YZ}) = \frac{\left(\begin{aligned} &\left(\frac{m_{YZ}^2 n}{m_{Y^2} m_{Z^2}}\right)\left[2(W^2 - S_2 + S_1) + \left(\frac{S_1 - S_2}{2}\right)(n-3) + \frac{S_1}{2}(n-2)(n-3)\right] \\ &+ \left(\frac{-m_{Y^2Z^2}}{m_{Y^2} m_{Z^2}}\right)[6(W^2 - S_2 + S_1) + (4S_1 - 2S_2)(n-3) + S_1(n-2)(n-3)] \\ &+ n\left[(W^2 - S_2 + S_1) + \left(\frac{S_1 - S_2}{2}\right)(n-3) + \frac{S_1}{2}(n-2)(n-3)\right] \end{aligned}\right)}{(n-1)(n-2)(n-3)W^2} - \left(\frac{-\rho_{YZ}}{n-1}\right) \tag{A.2}$$

where $m_{Y^2} = \mathrm{Var}(y)$, $m_{Z^2} = \mathrm{Var}(z)$, $m_{YZ} = \mathrm{Cov}(yz)$, $m_{Y^2Z^2} = \sum_{i=1}^{n} y_i^2 z_i^2 / n$, $S_1 = \sum_{i=1}^{n} \sum_{j=1}^{n} w_{ij}^2$, $S_2 = \sum_{i=1}^{n} \sum_{j=1}^{n} \sum_{i'=1}^{n} w_{ij} w_{ji'}$, and ρ_{YZ} is the linear correlation between y_i and z_i.

The detailed derivation of these results is given in Czaplewski and Reich (1993). The authors also recommend for moderate sample sizes ($n > 40$) it is sufficient to take $T = (I_{YZ} - E[I_{YZ}])/V(I_{YZ})^{1/2}$ as a standard normal variate, where I_{YZ} is the observed cross-correlation statistic defined in Equation (1). The null hypothesis of no spatial autocorrelation between two response variables is rejected when $|T| > z_{\alpha/2}$. A value of I_{YZ} significantly different from $E[I_{YZ}]$ would indicate a positive, or negative spatial autocorrelation depending on the sign of the estimated linear correlation coefficient $\hat{\rho}_{YZ}$.

Appendix B

Table B1. Stand characteristics of undisturbed, natural shortleaf pine stands sampled in northern Georgia during 1961–72 ($n = 127$) and 1972–82 ($n = 40$).

Stand characteristics[1]						*Coordinates (km)*	
S	*A*	*N*	*P*	*M*	*G*	*X*	*Y*
			1961–72				
18	1.61	3.80	0.70	0.00	−2.06	70	459
18	1.61	8.43	0.95	0.06	0.64	83	414
12	1.61	4.84	0.50	0.00	−1.16	71	436
24	1.61	6.34	1.00	0.02	0.13	257	347
21	1.61	7.19	0.72	0.00	−0.15	195	269
18	1.61	7.06	0.96	0.00	−0.25	65	439
21	1.61	8.85	0.91	0.20	0.49	232	406
18	1.61	8.70	1.00	0.46	0.50	208	465
21	1.61	5.53	0.59	0.00	−0.33	278	438
18	1.61	7.95	1.00	0.00	0.85	53	417
18	1.61	8.13	0.76	0.15	0.28	227	437
18	1.61	7.93	1.00	0.00	−0.18	54	433
24	1.61	6.61	1.00	0.00	0.21	243	484
15	1.61	7.30	0.97	0.00	0.30	62	440
21	1.61	5.87	0.54	0.00	−1.55	284	431
12	1.61	4.84	0.54	0.00	−1.34	34	507
15	1.61	6.75	0.86	0.00	−0.28	226	487
21	1.61	8.21	1.00	0.02	0.35	102	383
18	1.61	6.71	1.00	0.00	−0.21	240	492
18	1.61	4.97	1.00	0.00	−0.55	227	445
15	1.61	6.88	0.80	0.00	−0.06	64	493
24	1.61	4.84	1.00	0.00	0.37	186	317
15	1.61	7.58	0.88	0.05	0.16	264	439
18	1.61	5.94	0.96	0.20	−1.33	122	274
27	1.61	7.51	0.92	0.00	0.73	198	537
21	2.71	6.34	1.00	0.00	0.35	209	467
18	2.71	7.83	1.00	0.01	−0.28	192	467
21	2.71	8.58	1.00	0.77	0.22	112	439
21	2.71	6.80	0.54	0.00	−0.02	207	435
18	2.71	4.84	0.52	0.00	−0.46	143	516
21	2.71	6.34	1.00	0.00	0.33	67	311
21	2.71	6.90	0.98	0.02	−0.57	270	340
21	2.71	5.12	0.67	0.00	−1.04	85	152
18	2.71	6.64	0.63	0.05	−0.69	257	478
21	2.71	6.87	0.70	0.00	0.02	246	419
18	2.71	8.04	0.88	0.47	−0.31	258	440
21	2.71	7.99	1.00	0.03	0.41	103	310
21	2.71	8.55	0.87	0.11	0.35	292	371
21	2.71	7.44	0.69	0.00	0.41	137	221
21	2.71	4.95	0.93	0.00	0.39	136	501
21	2.71	6.75	1.00	0.00	−0.11	241	449
15	2.71	6.80	0.59	0.00	−0.02	83	419

Continued

Table B1. Continued

Stand characteristics[1]						*Coordinates (km)*	
S	*A*	*N*	*P*	*M*	*G*	*X*	*Y*
21	2.71	7.61	0.98	0.00	0.38	91	189
18	2.71	7.30	0.80	0.00	0.21	153	433
18	2.71	5.65	0.81	0.00	−0.59	124	446
24	2.71	7.79	1.00	0.21	−0.38	174	440
15	2.71	4.84	1.00	0.00	−0.68	226	409
21	2.71	8.14	1.00	0.10	−0.45	172	531
24	2.71	6.75	1.00	0.00	−0.27	187	439
21	2.71	6.80	1.00	0.00	−0.07	147	304
18	2.71	8.38	0.73	0.30	−0.61	209	522
24	2.71	6.69	0.94	0.00	−0.13	253	421
15	2.71	7.24	0.53	0.06	−0.55	90	429
18	2.71	4.27	0.58	0.00	−0.84	133	323
24	2.71	7.37	0.80	0.04	−0.63	246	402
21	2.71	7.77	0.78	0.04	0.68	264	348
24	2.71	7.13	0.97	0.68	−0.46	107	264
18	2.71	5.87	0.69	0.00	−0.35	265	478
18	2.71	6.04	0.62	0.00	−1.16	61	500
24	2.71	5.53	0.76	0.00	−0.57	164	529
21	2.71	4.95	0.61	0.00	−0.96	119	302
18	2.71	5.65	1.00	0.00	−1.16	67	290
21	2.71	8.23	0.91	0.19	0.22	200	477
27	2.71	5.67	0.53	0.19	−1.25	240	472
21	2.71	6.75	1.00	0.00	0.47	197	444
15	2.71	6.75	1.00	0.00	0.29	212	412
18	2.71	7.73	0.64	0.03	0.17	138	298
18	3.22	6.80	1.00	0.00	0.04	146	197
24	3.22	6.28	1.00	0.00	−0.34	219	448
15	3.22	6.64	0.68	0.00	−0.33	156	481
18	3.22	7.26	1.00	0.17	−0.44	228	398
18	3.22	4.91	1.00	0.00	−0.80	119	169
15	3.22	5.97	0.81	0.22	−1.11	73	429
21	3.22	4.95	0.51	0.00	−0.88	230	314
18	3.22	7.44	0.86	0.44	−0.35	140	506
21	3.22	5.89	0.79	0.00	−0.29	150	265
18	3.22	6.68	1.00	0.04	−0.98	120	451
18	3.22	5.87	0.68	0.25	−0.83	234	265
15	3.22	8.43	1.00	0.42	0.19	77	426
21	3.22	7.47	0.78	0.06	−0.26	197	451
18	3.22	6.29	0.55	0.18	−0.87	166	291
18	3.22	6.42	1.00	0.25	−1.34	170	464
24	3.22	8.66	0.90	0.37	0.14	89	176
24	3.22	6.94	0.88	0.00	−0.70	199	487
18	3.22	8.08	1.00	0.10	−0.22	257	315
21	3.22	5.92	0.52	0.00	−0.53	162	194
24	3.22	7.64	0.85	0.08	0.61	167	469
18	3.22	7.26	0.99	0.09	−0.10	79	489
18	3.22	6.51	0.59	0.22	−0.70	209	420

Continued

Table B1. Continued

Stand characteristics[1]						*Coordinates (km)*	
S	*A*	*N*	*P*	*M*	*G*	*X*	*Y*
21	3.22	6.41	0.72	0.02	−0.70	111	450
18	3.22	8.42	0.91	0.41	0.16	71	343
18	3.22	4.84	1.00	0.00	−0.87	273	365
21	3.22	5.29	1.00	0.00	−0.55	148	435
21	3.22	6.06	1.00	0.00	−0.85	216	326
24	3.22	6.22	0.73	0.00	0.01	208	444
21	3.22	6.22	0.86	0.15	−0.77	225	332
24	3.22	6.92	0.88	0.11	−0.95	180	452
15	3.22	6.88	0.55	0.00	−0.54	171	432
24	3.22	6.75	1.00	0.02	−0.18	199	328
18	3.22	6.75	1.00	0.00	0.74	170	324
24	3.22	5.69	0.88	0.00	−0.44	227	412
18	3.22	6.44	0.50	0.00	−0.37	283	424
21	3.22	8.07	0.78	0.10	0.03	215	433
24	3.22	6.08	0.72	0.00	−0.38	76	172
18	3.56	5.94	0.56	0.00	−0.91	59	433
18	3.56	6.40	0.62	0.33	−1.38	217	518
15	3.56	4.52	0.58	0.00	−1.41	235	290
15	3.56	7.40	0.91	0.40	−1.05	179	485
24	3.56	5.68	0.97	0.00	−1.51	324	385
18	3.56	7.59	0.58	0.18	−1.02	89	196
18	3.56	6.12	0.51	0.21	−2.06	192	359
18	3.56	4.91	1.00	0.00	−0.95	193	428
21	3.56	6.92	0.80	0.08	−0.06	161	306
15	3.56	6.54	1.00	0.26	−0.89	211	466
18	3.81	5.75	0.52	0.00	−0.76	62	320
12	3.81	6.33	0.51	0.25	−1.75	105	539
15	3.81	6.39	0.67	0.00	−0.72	51	473
21	3.81	6.25	1.00	0.13	−1.34	130	434
18	3.81	6.11	0.75	0.00	−1.19	224	520
21	3.81	4.84	1.00	0.00	−0.85	210	373
15	3.81	5.45	0.64	0.00	−0.90	199	468
18	3.81	5.87	0.56	0.26	−2.46	54	384
24	3.81	8.34	0.99	0.36	−0.13	216	340
18	4.01	6.43	1.00	0.00	−0.10	203	525
21	4.01	6.15	0.91	0.00	−0.62	79	179
18	4.01	7.73	1.00	0.28	−0.66	233	468
18	4.01	5.12	0.58	0.00	−1.59	202	504
			1972–82				
21	1.61	6.20	0.69	0.01	−0.52	103	192
18	1.61	7.64	0.61	0.19	0.46	212	424
27	1.61	6.62	0.74	0.34	−0.57	325	380
21	2.71	6.71	0.95	0.07	−0.79	243	484
18	2.71	4.95	0.62	0.00	−2.18	68	481
27	2.71	7.00	0.62	0.00	−0.19	65	306
18	2.71	6.44	0.73	0.00	−0.72	223	295

Continued

Table B1. Continued

Stand characteristics[1]						*Coordinates (km)*	
S	*A*	*N*	*P*	*M*	*G*	*X*	*Y*
18	2.71	8.01	0.68	0.16	0.24	126	281
12	2.71	6.84	0.62	0.14	−2.55	124	513
18	2.71	7.07	0.62	0.24	−1.42	78	531
18	2.71	6.77	0.89	0.00	−0.71	276	347
21	3.22	7.83	0.80	0.04	0.03	325	319
21	3.22	5.95	1.00	0.00	−1.44	201	448
30	3.22	6.03	0.94	0.25	−0.86	256	328
21	3.22	7.76	0.84	0.06	0.68	143	174
18	3.22	7.05	0.67	0.00	−0.28	220	458
18	3.22	7.34	0.96	0.00	−0.14	155	482
21	3.22	7.46	0.95	0.24	0.18	58	395
18	3.22	7.16	0.81	0.26	−0.71	143	516
27	3.22	6.56	1.00	0.00	−0.28	211	231
24	3.22	7.20	0.89	0.24	−1.09	172	531
24	3.22	6.52	0.82	0.00	−0.47	164	529
21	3.22	7.03	0.57	0.25	−0.84	120	454
15	3.22	6.22	0.58	0.00	0.04	67	502
24	3.22	7.02	0.63	0.04	−1.05	137	221
18	3.22	8.00	1.00	0.18	−0.40	166	427
15	3.22	6.69	0.58	0.00	−1.24	86	499
21	3.22	5.72	0.51	0.25	−1.12	222	323
21	3.22	8.00	0.74	0.32	−0.21	82	249
21	3.22	7.90	0.99	0.58	−0.09	229	389
18	3.22	7.70	0.72	0.04	0.28	225	475
27	3.56	6.43	0.84	0.28	−0.85	138	210
21	3.56	5.46	0.58	0.00	−1.64	75	491
21	3.56	7.46	0.63	0.15	−0.39	193	477
27	3.56	5.59	0.74	0.00	−0.74	76	315
30	3.56	6.84	0.87	0.24	−0.47	238	423
12	3.81	6.78	0.63	0.01	−2.03	223	512
18	3.81	6.70	0.72	0.12	−0.83	160	430
21	3.81	6.70	0.76	0.52	−2.25	79	489
21	4.01	7.14	0.95	0.17	−0.97	237	327