Mapping Synecological Coordinates: A Spatial Analysis of Environmental Indices in a Forested Landscape

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Abstract.—The Method of Synecological Coordinates was used to compute environmental indices (synecological coordinates) for moisture and nutrients based on plant species presence. Plots were sampled in a 65.6-ha area in St. Louis County, Minnesota, dominated by quaking aspen. A four-level, nested sampling design quantified spatial variability over a wide range of distances. Semivariances at the four distances suggested a 45-m equidistant grid of plots would be appropriate for mapping synecological coordinates. Variograms of moisture and nutrients coordinates showed ranges of 350 m or greater, indicating that spatial dependence continues well beyond the limits normally found with most soil studies. Nutrients coordinate showed greater spatial dependence than moisture coordinate, which showed more random variation. The nutrients coordinate map proved useful in defining areas of differing quaking aspen site index. Thus, the efficient mapping of site synecological coordinates has helped capture the pattern of environmental variation.

INTRODUCTION

Our ability to appropriately manage a forest community can be improved if we can accurately map environmental conditions. We propose a general method that maps environmental indices (plant-based indicators). The intent of this paper is to investigate whether environmental indices can be accurately mapped, and if so, whether the maps identify areas of contrasting site productivity.

Environmental indices are produced by the Method of Synecological Coordinates (MSC) (Bakuzis 1959, Bakuzis and Kurmis 1978, Brand 1985, and Gutiérrez-Espeleta 1991). MSC uses plant presence as an indicator of the environment. It is based on the notion that floristic composition of a site indicates the nature of the environment there. MSC is an easily applied approach that computes semi-quantitative values for four environmental factors—moisture (M), nutrients (N), heat (H), and light (L). M and N represent the edaphic conditions and H and L represent the climatic conditions at the site. Each plant species has its own set of synecological coordinate values on a relative scale of from 1 to 5, representing on average, the species "need" for that factor. An arithmetic mean of the coordinates for those species occurring together is called the site synecological coordinate.

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coordinate for that factor. For this paper we will concentrate on edaphic environmental conditions as represented by M and N.

Synecological coordinates, which use the integrative nature of plants and prior knowledge of their environmental “requirements,” may provide a practical means to determine the spatial variability and distribution of environmental factors. Spatial variability is analyzed using geostatistical techniques. Geostatistical theory is based on the simple notion that measurements made closer together in space are more alike than those made farther apart. The spatial variability or structure can be modeled via a mathematical function known as the variogram. Once the variogram is modeled, kriging uses information in the variogram to spatially interpolate unknown data points.

The spatial variation in soil properties has been extensively analyzed with geostatistical techniques (Oliver and Webster 1991, Burgess and Webster 1980, and Webster and Burgess 1983). Because soil is such an important determinant of the environmental conditions of a site, describing the spatial distribution of soil properties should spatially describe important aspects of the environment. However, the chemical and physical composition of soils is complex and extremely variable over short distances (Lechowicz and Bell 1991, Jackson and Caldwell 1993, Oliver and Webster 1991). Therefore, synecological coordinates may provide a more effective means to integrate soil variability and complexity into maps of edaphic conditions.

The choice of sampling distance to use in any study depends on the range over which the phenomena are spatially correlated. Complex multi-step designs are especially suited for exploring the full spatial structure when there is no previous knowledge of the spatial nature of the data. Designs containing several sampling scales, such as a systematic-cluster design (Fortin et al. 1989) or a nested design (Oliver and Webster 1986) are ideally suited for such investigations. Sampling is performed in two stages. In the initial stage, a complex sampling scheme is carried out over a wide range of distances to ascertain the range of the process. This information then helps establish the sampling grid in the second stage, where points are sampled on an equal-spaced grid at a scale well within the spatial range.

We are investigating synecological coordinates and geostatistics as methods to represent the local edaphic environment in an aspen-dominated forest. By representing the edaphic environment, the medium of forest growth, we expect to make inferences about overstory site productivity. Our purpose here is: (1) to analyze the spatial structure and scale of spatial variability of site synecological coordinates for moisture and nutrients using geostatistical techniques, (2) to assess the accuracy of site coordinates mapped by kriging, and (3) to examine what the mapped site coordinates indicate about site productivity.

METHODS

The stage 1 study site (larger square in figure 1) covers 65.6 ha in St. Louis County, 30 km north of Duluth, Minnesota. A timber inventory (based on limited field sampling) delineated stand boundaries and measured site index (SI), the traditional measure of site quality in forest management. Quaking aspen is the primary overstory species. The topography is gently rolling with elevations ranging from about 1440 feet to slightly more than 1490 feet with no obvious directional trends in the topography.
A nested sampling design was selected to provide variability data for a wide range of distances. In stage 1 of the sampling design, we determined the variability at coarse (135 m), moderate (45 m), fine (15 m) and very fine (5 m) distances. The sampling distances needed to be simultaneously small enough to estimate the nugget variance (unexplained or random variance that occurs at very small sampling distances) and large enough to identify the spatial range.

In stage 1, the primary or coarsest grid of points (level 1) had separation distances of 135 m. The axes of the sampling grid were oriented in a north-south, east-west direction with the starting grid point randomly located. A geometric progression of decreasing distances between sample points was used. Therefore, the distances for the second-level points were 45 m. Two second-level points were located 45 m to the south and west of each first-level point (see figure 2a). Each primary and secondary point included third- and fourth-level points (figure 2b). The two third-level points were located 15 m to the south and west of every primary and secondary point; the two fourth-level points were located 5 m to the north and east of every primary and secondary point.

Collecting plant lists at each point in a complete four-level sampling design would have been too intensive for the time and money available. Therefore, alternating primary rows and columns were dropped from the study for second-level points (figure 2a) and the number of third- and fourth-level points were reduced by randomly selecting half of the level 1 and level 2 points for sampling at levels 3 and 4. At each point, plant species occurring within a square plot of 5x5 m were recorded and synecological coordinates were computed using a data recorder and program (Nimerfro and Brand 1993). Species synecological coordinates developed for Minnesota forests were used in the computations (Bakuzis and Kurmis 1978).

Obvious outliers were removed from the data at each stage. A plot was removed if its value for either factor was judged an outlier by the box plot. The stage 1 semivariance based on sampling at four lag distances (5, 15, 45, and 135 m)
Figure 2.—Final sampling design: (a) coarse and moderate distances, (b) fine and very fine distances.

m) was plotted against distance. Ranges were estimated, and an appropriate sampling distance was chosen from among the four lag distances for stage 2 plot spacing.

In stage 2, the experimental unidirectional variograms were calculated. Cross validation was performed to check the validity of the final models. Differences between kriged estimated and observed values were analyzed using these cross validation statistics: mean error, median absolute error, and MSE.

VARIOGRAM MODELING AND CROSS VALIDATION

Site synecological coordinates were computed from 254 plots at stage 1 grid points. At an additional 13 plots, plant lists could not be collected due to environmental conditions detrimental to terrestrial vegetation (road, permanent standing water, etc.) or site coordinates were outliers. The semivariances at the four lag distances for stage 1 data (black dots on figure 3) show increasing spatial variability at 135 m for N. However, this distance may be too large when kriging M, so we chose 45 m as the grid sampling distance for the stage 2 analysis.

Stage 2 plots (smaller square in figure 1) were located on a 11x11 grid centered within the stage 1 area. Nine plots out of 121 were located on the road or in permanently wet areas and were ignored. An additional five plots were removed because their site synecological coordinates were outliers. A summary of site coordinates for the remaining 107 plots shows similar means for M and N of just under 2.5 with values ranging roughly from 2.0 to 3.0. Nutrients had slightly greater range and standard deviation than moisture.

Isotropic variograms were calculated, using a minimum distance of 45 m and a maximum of 500 m (75% of the largest distance.) Models were fit to the experimental variograms (figure 3). Model and parameters were estimated visually and provided excellent fits with $R^2$ of .943 for M and .985 for N. The linear model was fit to M, the spherical model to N. The experimental variogram
values for stage 2 N data progressively increased with distance and then showed a systematic decrease, known as a hole effect, beyond the range of spatial dependence. Since variograms were plotted beyond half the maximum separation distance, the apparent hole effect is likely an edge effect. The models are fitted for values up to the range. In addition, anisotropy was examined. However, there were not enough data to accurately estimate apparently mild directional influences.

Figure 3.—Experimental and fitted variograms for site synecological coordinates: (a) Moisture and (b) Nutrients.

The supplemental information about the spatial variability at close distances confirms that there is at most a moderate nugget effect (i.e., random variation or spatial dependence at less than 5 m) in the experimental variograms, which ranges from 52% (for M) to 22% (for N) of the total sample variability. That signifies that 48 to 78% of the total variability is spatially dependent. If we assume small measurement errors, the large relative nugget for M appears to be the result of very closely spaced variation. N's range is 350 m and M's range is 525 m, indicating that our choice to resample on a 45-m grid was appropriate. Results of the cross validation are summarized (table 1). Ordinary kriging was performed on the grid points using the 16 nearest neighbors within a radius of 130 m. Cross validation statistics for median absolute error indicate that 50% of the observations will be within .113 units (for M) and .111 units (for N) of the true value.

Table 1.—Stage 2 cross validation statistics for Moisture (M) and Nutrients (N).

<table>
<thead>
<tr>
<th>Factor</th>
<th>Mean Error</th>
<th>Median Abs Error</th>
<th>MSE</th>
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<tbody>
<tr>
<td>M</td>
<td>.001</td>
<td>.113</td>
<td>.018</td>
</tr>
<tr>
<td>N</td>
<td>.000</td>
<td>.111</td>
<td>.024</td>
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SITE SYNECOLOGICAL COORDINATE MAPPING

We used the cross-validated variogram models to estimate values for M and N by applying ordinary block kriging. Using the previous search procedure, we produced contour maps (figure 4). Maps of the synecological coordinates were compared with topographic relief in the study area. No obvious relations with elevation were found. The nutrients contour map shows the presence of a large, homogeneous region to the southeast. Moisture seems more influenced by random or micro-relief variation, thus producing more irregular contours than nutrients.

![Contour maps of kriged estimates of site synecological coordinates for stage 2 data: (a) Moisture and (b) Nutrients.](image)

We looked for similarities between the spatial distribution of each coordinate and the inventoried SI. The spatial patterns of kriged N appear to yield the best relationship to the three SI classes (figure 5a). By plotting contours at 2.35 and 2.55 for N, we delineated three areas with A < 2.35 < B < 2.55 < C (figure 5b), which correspond roughly to areas with SI = 50, 70, and 80 ft (figure 5a). Estimated N coordinates in these upland aspen stands separated by .20 units may account for SI changes of 10 to 20 ft. Comparing figure 5a with 5b gives us reason to support the belief that vegetative-based nutrient estimates may be useful in depicting areas of differing site quality.

DISCUSSION

Spatial dependence is clearly evident, which allows for mapping site synecological coordinates. The N coordinate showed greater spatial dependence than the M coordinate, which showed a relative nugget effect of roughly 50%. Viewed from another perspective, the variogram for M reveals two very different
and yet equally strong aspects to the variability: 50% is due to measurement error and very short-distance variability (less than 5 m), and 50% is due to long-range spatial dependence. For the N coordinate, the relative magnitude of the variability due to the long-range spatial dependence has increased and the magnitude of the micro-site variability has decreased.

Both coordinates showed ranges of at least 350 m, which is far greater than the usual limits of spatial dependence in soil studies. Spatial ranges for various soil properties range from 1 to 2 m (Lechowicz and Bell 1991, Jackson and Caldwell 1993) up to 15 to 40 m (Oliver and Webster 1991, Palmer 1990). The variation of soils is almost always more noisy or random than other environmental variables such as landform, climate, or geology, where long-range effects often dominate (Burrough 1983). The high proportion of short-range sources of variation in soil is caused by very localized biological activity, weathering, and small differences in relief due to glacial action, erosion, and deposition (Burrough 1983). Because of its large relative nugget, M appears more influenced by localized sources of variation than N. The large ranges and the large-scale patterns evident in figure 4 suggest that broader trends are operating for both factors. Synecological coordinates have reduced the complexity of the spatial variation so that micro-site variation in soil properties no longer dominates, but rather broader trends are revealed, such as the relationship of N coordinates to overstory productivity.

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REFERENCES


BIOGRAPHICAL SKETCH

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