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Multivariate Analysis of the Ecoregion Delineation for Aquatic Systems

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ABSTRACT / The ecoregion concept is a popular method of understanding the spatial distribution of the environment', however, it has yet to be adequately demonstrated that the environment is distributed in accordance with these bounded units. In this paper, we generated a testable hypothesis based on the current usage of ecoregions: the ecoregion classification will allow for discrimination between lakes of different water quality. The ecoregion classification should also be more effective better than a comparably scaled classification based on political boundaries, land-use class, or random grouping. To test this hypothesis we used the Environmental Monitoring and Assessment Program (EMAP) lake water chemistry data from the northeast United States. The water chemistry data were reduced to four components using principal component analysis. For comparison to an optimal grouping of these data we used K-means cluster analysis to define the extent at which these lakes could be segregated into distinct classes. Jackknifed discriminant analysis was used to determine the classification rate of ecoregions, the three alternative spatial classification methods, and the clustering algorithm. The classification based on ecoregions was successful for 35% of the lakes included in this study, in comparison to the clustered groups accuracy of 98%. These results suggest that the large scale spatial distribution of ecosystem types is more complicated than that suggested by the present ecoregion boundaries. Further tests of ecoregion delineations are needed and alternative large-scale management strategies should be investigated.

Recent interest in water quality management has begun addressing the spatially heterogeneous nature of the environment and, in particular its effect on water quality (Omernik 1987, Urban and others 1987, Omernik and others 1991, Bryce and Clarke 1996, Lovejoy and others 1997). It has long been recognized that terrestrial processes have a large influence on the state of a recipient body of water (Peterjohn and Correll 1984, Summer and others 1990). It has also been recognized that the environmental variables affecting water quality are not uniformly distributed across the landscape and do not necessarily change at watershed boundaries (Omernik and Griffith 1991). Particular variables such as physiography, soil characteristics, and human land use have been found to be important in determining water quality (Geleta and others 1994, Shirmohammadi and others 1997). These variables are often distributed in patches of various sizes and configurations or as gradients across the landscape. Not only do the spatial patterns of the driving variables not conform to watershed boundaries, they often occur at scales different than watersheds. Understanding how these patterns are distributed and the effect of this distribution on local water quality have become a focus of aquatic ecology and water quality management.

A recently developed technique for solving this problem has been the delineation of "relatively homogeneous" ecological regions (e.g., Bailey 1983, Omernik 1987, Omernik and Bailey 1997). A popular scheme being explored by the United States Environmental Protection Agency (US EPA) is the Conterminous Ecoregions of the United States as developed by Omernik (1987, see also Omernik and Griffith 1991, US EPA 1991). This approach is also being considered as a framework for a national water quality monitoring effort (Intergovernmental Task Force on Monitoring Water Quality 1995). Originally this delineation divided the conterminous United States into 76 distinct ecological regions considered to be relatively homogeneous in

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environmental characteristics and applicable to both terrestrial and aquatic systems (Omernik 1987). These delineations were based on the perceived patterns in the overlay of four thematic maps: potential natural vegetation, physiography, soils, and land use/land cover. While being decidedly subjective, it was suggested that the process is repeatable by properly trained geographers. Differences, however, do exist between Omernik's (1987) delineation and that of other ecological regionalization methods (e.g., Bailey 1983, Omernik and Bailey 1997).

Recently, hierarchical extensions of the ecoregion model have been developed. Within the United States, a hierarchical ecoregion approach has been developed based on the previously delineated ecoregions of the conterminous United States (Bryce and Clarke 1996). Currently, many projects have begun to develop subecoregion boundaries in an attempt to maximize the environmental homogeneity within the region (Clarke and others 1991, Thiele and others 1992, Thiele and Omernik 1993, Griffith and others 1994, Bryce and Clarke 1996, Smith and Carpenter 1996, Bernert and others 1997). Outside of the United States this type of ecological mapping has been developed in Canada, the Netherlands, and New Zealand (Marshall and others 1987, Wickware and Rubec 1989, Warry and Hanau 1993, Klijn and others 1995).

In addition to extending the mapping procedure through these hierarchical delineations, applications of these regionalizations have also been developed (US EPA 1991). Reference sites, which describe the most natural site within an ecoregion, have been described for a variety of ecological regions (Hughes and others 1986, Warry and Hanau 1993, Reynoldson and others 1997). Management directives have also been generated based on these ecological regions through the identification of the restoration potential of an ecoregion (Omernik and Griffith 1991, US EPA 1991). This restoration potential has been derived from an estimate of the attainable water quality within the particular ecoregion (Heiskary and others 1987, Fulmer and Cooke 1990, Schonter and Novotny 1993).

Much of this work—developing extensions and applications of the model—has been conducted without adequately testing the general principles of the ecoregion concept. Two distinct problems are likely responsible for this lack of adequate testing. One problem is generating a testable hypothesis from the ecoregion concept. Reducing the subjective and intuitive ecoregion concept to a testable hypothesis is not a trivial exercise. A formal test will only be able to address a subset of the notions that are incorporated in the concept. The open nature of the definitions used for ecoregions suggests that these ideas are still in a developmental stage. The nonspecific environmental characteristics to which this regionalization refers make rigorous testing of the delineation difficult. While the spatial pattern of any particular variable might not correspond to ecoregional differences, the general environmental pattern should (Intergovernmental Task Force on Monitoring Water Quality 1995, Omernik and Bailey 1997). Another poorly defined concept is the relative homogeneity of ecoregions. Different ecoregions will vary in their degree of homogeneity and the change at the borders between differing ecoregions might fluctuate in a manner specific to the locality. Previous interpretations have suggested that these ecological maps are often more hypotheses than descriptions (Bailey 1983, 1984). In reality, the ecoregion concept has achieved paradigmatic status; it provides a framework for understanding the natural world, which includes an appropriate set of questions that can be asked through the procedure. Working within the paradigm will not allow for an evaluation of the paradigm. Primarily this paradigm describes how spatial heterogeneity is distributed across a region. Recent tests that proposed to examine the appropriateness of the ecoregion concept for describing water quality variability have contrasted ecoregions with a model of no spatial heterogeneity (e.g., Fulmer and Cooke 1990). An appropriate test of ecoregions will evaluate the potential for the spatial pattern of water quality to be distributed into relatively homogeneous discrete units in contrast to other spatial frameworks. Without such a test of ecoregions we do not known what reference sites refer to or the meaning of regional restoration potential.

The second problem, the lack of a comprehensive large scale data set, has prevented any specific hypotheses derived from being tested. Recently, the Environmental Monitoring and Assessment Program (EMAP), as part of the US EPA, conducted a multivariate lake water chemistry survey for the northeast United States (Larsen and others 1994). The data provided by this survey allow some tests of the ecoregion concept to be conducted. While it will not be possible to infer the appropriateness of ecoregions to other areas, the spatial pattern of water quality in this area alone is important to characterize.

In this study we tested the applicability of the ecoregion concept for describing the large scale spatial pattern of lake water quality variation. One specific hypothesis generated from the ecoregion concept is that ecoregion membership should describe a unique set of lakes, defined by a large suite of water chemistry variables, which can be differentiated from lakes in different ecoregions (sensu Omernik and Bailey 1997). In

Table 1. Varimax rotated PCA loadings matrix

Variable (unit)	Component 1 loading—ionic strength	Component 2 loading—trophic state	Component 3 loading—organic material
HCO_3 (μeq/liter)[a]	0.958	0.109	0.046
Acid neutralizing capacity (μeq/l)[a]	0.958	0.112	0.084
Calcium (μeq/l)[b]	0.941	0.238	0.006
Alkalinity (μeq/l)[a]	0.940	0.111	0.062
H^+ (μeq/l)[a]	−0.898	0.058	0.090
Conductance (μs/cm)[a]	0.797	0.273	−0.098
Total dissolved aluminum (μg/l)[b]	−0.627	−0.051	0.447
Chlorophyll *a* (μg/l)[a]	0.191	0.871	0.149
Total phosphorus (μg/l)[b]	0.185	0.866	0.177
Total suspended solids (mg/l)[a]	0.148	0.857	0.186
Secchi depth (m)[a]	0.028	−0.826	−0.435
Color (PCU)[b]	−0.115	0.437	0.825
Dissolved organic carbon (mg/l)[a]	−0.075	0.482	0.807
Organic anion content (μeq/l)[a]	0.046	0.477	0.795
Silica (mg/l)[b]	0.403	−0.260	0.415

[a]Variables base 10 log transformed.

[b]Variables are natural log transformed.

this paper, the level at which ecoregions segregate lakes into distinct sets defined by surface water variables will be examined. This segregation level will then be compared to the level of discrimination that can be generated from a random grouping and alternative spatial grouping methods—state boundaries and land-use classes. The level of discrimination achieved by the ecoregion grouping will be evaluated in comparison to the level of discrimination reported in a similar ecological study that examined the effectiveness of a watershed classification scheme (Momen and Zehr 1998). Additionally, the potential for any grouping of these lakes will be examined through a clustering analysis based on the surface water variables. The potential grouping effectiveness and the random groupings will suggest an upper and lower bound on the expected level at which ecoregions could segregate the spatial patterns of lake surface water chemistry. We will also map the distributions of cluster membership to examine the possibility of finding a homogeneous unit delineation. This test will examine the empirical basis of the concept, as well as the performance of the concept in relation to alternative grouping methods.

Methodology

The EMAP conducted an intensive study of the environmental resources of the northeast United States in the early 1990s. Lakes for analysis were chosen based on a modified stratified random sampling protocol that was designed to allow statistical inferences into the entire population of lakes in the northeast United States. Thirty-six different variables were measured in each lake. For lakes sampled more than once, we used the median value of variables to eliminate redundancy.

Principal component analysis (PCA) was used to compress the variance in the data matrix. PCA greatly reduces the dimensionality of the variable space by identifying correlational structure within the data matrix. This technique identifies orthogonal vectors describing a significant portion of the variance within the original data matrix. The resulting components can be treated as traditional variables for further statistical analysis. The benefits of PCA include the reduction of many variables into a few components, the inclusion of all original variables in each component so that further analysis is not based on only a single variable but all variables of the data matrix, and generation of orthogonal, nonintercorrelated, components.

Normally distributed variables are required for PCA; to satisfy this restriction each variable was tested using the Kolmogorov-Smirnov (K-S) one-sample test (Masley 1951). The K-S one-sample test is similar to the K-S two-sample test; the variable is tested against a generated variable defined as having a normal distribution; if the K-S test was statistically significant ($P < 0.01$), we rejected the hypothesis that the data followed a normal distribution. Variables rejected by this test were logarithmically, base 10 and natural, and square root transformed and again tested; variables that failed the normality test were excluded from the analysis. This resulted in the final matrix of 15 water quality variables entered into the PCA (Table 1). Of the original 370 lakes sampled, only 89 were free of missing data points. As any case with missing data is excluded from the PCA, this was problematic. The large reduction in sample

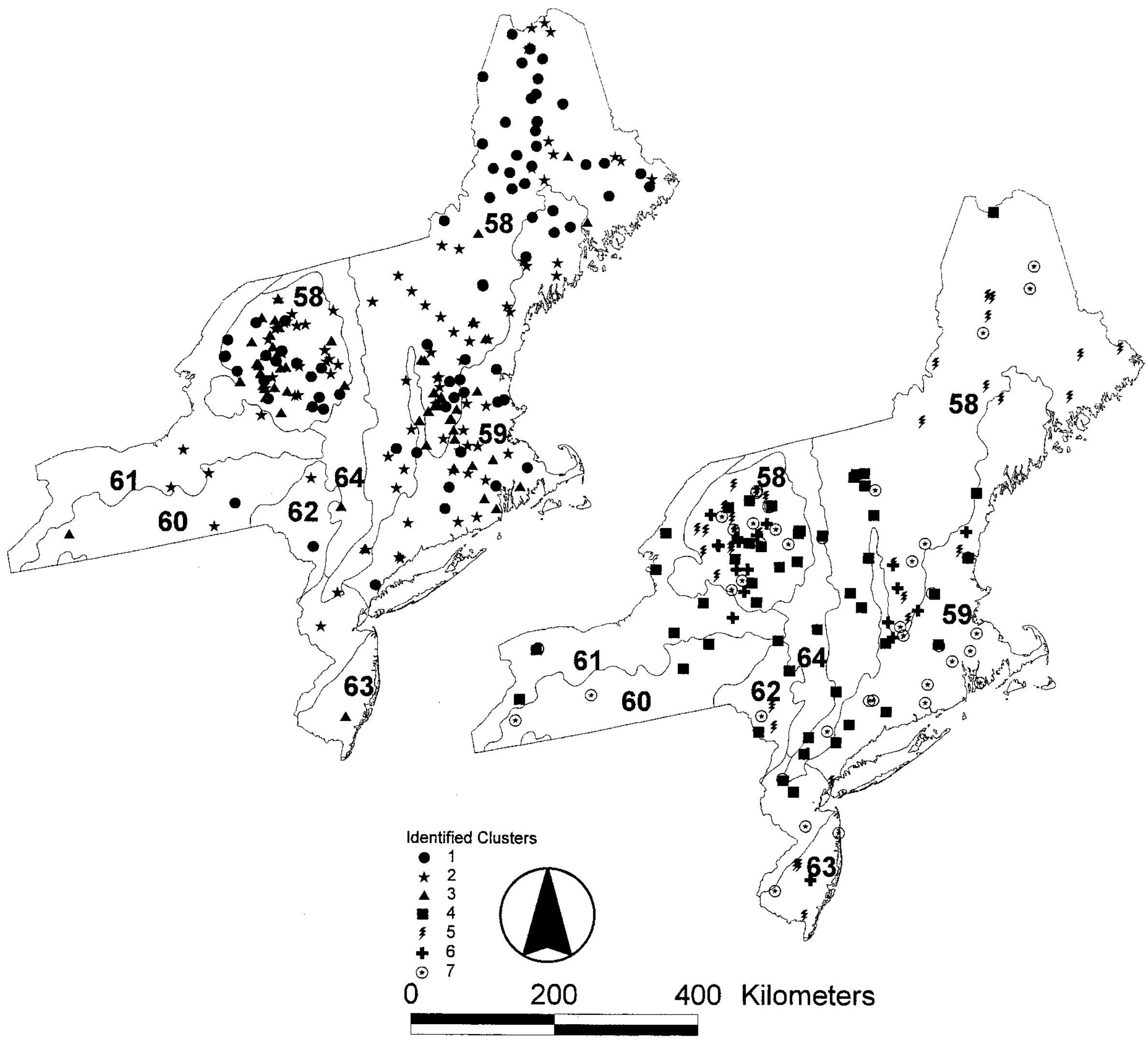

Figure 1. Spatial distribution of the groupings identified by K-means clustering analysis. Seven clusters were specified, corresponding to the number of ecoregions in this region.

size could potentially bias our results and reduce the power of our statistical analyses. To correct for this, we used regression substitution to estimate missing data points. Because of the high degree of intercorrelation within the original data, as identified through the correlation matrix as well as preliminary PCA, we have high confidence in the technique. This method is much preferred over a common alternative, the use of the variable mean for each missing case. This technique estimated values for 344 missing data points, 5% of the entire data matrix. Using this, our final number of cases was 365, four cases were excluded due to a gross lack of data—less than 40% of the variables were present or there was an obvious locational error.

Individual lakes were georeferenced to the appropriate ecoregion using a geographic information system (GIS) based on thematic maps obtained from the United States Geologic Service (USGS) (Figure 1). A similar analysis was also conducted utilizing state boundaries and land-use classes, also obtained from the USGS A random assignment of groupings with the same frequency distribution of cases as ecoregions was also generated. This segregated the lakes into groups having similar numbers of members as the ecoregion delineation but was random. In contrast to this random grouping, a K-means clustering analysis was used to identify the extent to which the lakes could be partitioned into identifiable groups. K-means clustering begins with all the cases in a single cluster; the cluster is split by choosing a second cluster centered on the case farthest in parameter space from the center of the original cluster. This is followed by a reassignment of cluster memberships into the closest cluster center. This continues until the specified clusters are generated and reassignment of cases can no longer reduce the within-group sum of squared deviation. For comparison with the ecoregion delineation, we chose to generate seven clusters.

To test the effectiveness of a classification method to partition the lakes into different categories, the discriminant analysis technique was chosen. Discriminant analysis is a technique that generates a function similar to multiple regression; however, instead of attempting to predict a particular value, the technique predicts the relaxed criteria of group membership. This method can be used to determine the effectiveness of a given classification scheme. An estimation of classification effectiveness can be generated from the rate at which the original cases are placed into the groups specified. In this study the classification rate is an estimate of the effectiveness of the grouping method, such as ecoregion membership, to identify different classes of lakes. The higher the classification rate, the better the grouping method (e.g., ecoregion or land-use class) is performing.

An improved method for obtaining an estimate of the classification rate is generated through the use of a jackknifing procedure. This technique involves leaving out each case in turn, calculating the function based on the remaining $n - 1$ cases and then classifying the left out case. Since the case being classified is not used in the calculation of the classification function, the observed classification rate is a less biased estimate of the true one. A previous study that used this method to test a classification scheme for watersheds found classification rates of 87% and 75% (Momen and Zehr 1998).

Results

Three components were identified from the original data matrix (based on a Scree test and a cutoff at an eigenvalue of 1.0). These three components explained 81.1% of the variance in the original data matrix. These components were rotated using varimax rotation, a technique that maximizes the simple structure of the components. Simple structure occurs when a component is represented by high loadings (a description of the correlation of a variable and a component) on only a few variables; this allows for the variables that dominate a component to be identified. All three components separated the original variables into distinct categories easily identified as an ionic strength component, a trophic state component, and an organic matter component (Table 1). The component scores do not seem to be distributed in accordance with ecoregion delineations (Figure 2).

The K-means clustering algorithm identified seven clusters of lakes. The total sum of squared deviations within each of the groups was 308.7, while the sum of squared deviations between groups was 781.3. This distinction suggests that each cluster is well defined by the algorithm; there is less than half the variance within the groups than among them. The spatial distribution of the clustered lakes also is not suggestive of any spatial framework we tested or the potential for any delineation into homogeneous units (Figure 1).

Based on the jackknifed classification function, the clustering algorithm provided the best groupings of lakes. In contrast, the randomized grouping method performed poorest. Of the examined spatial grouping methods, the land-use classification method performed best, followed by ecoregions and then state boundaries (Figure 3). All these spatial methods were much closer to the classification effectiveness of randomized groups rather than the clustered groups. Scaling the ecoregion score by the lower and upper bounds provided by the random and clustered groupings via equation 1 suggests that ecoregions are performing at only an 18% effectiveness.

$$\textit{Scaled classification score} = (\textit{classification score} - \textit{lower bound})/(\textit{upper bound} - \textit{lower bound}) \quad (1)$$

Discussion

Ecological region mapping has been characterized as describing the general environmental characteristic and has been applied extensively for the management of aquatic systems. The EMAP lake database was well suited to testing the ecoregion concept because it utilized a randomized sampling regime and surveyed a large suite of water chemistry variables (Larsen and others 1994). PCA compressed the data to three components describing a substantial amount of the variance in the original data matrix while still being ecologically interpretable. The potential for grouping lakes based on surface water chemistry at the scale of ecoregions, a partitioning into seven distinct groups, was high, as suggested by the effectiveness of the clustering algorithm; the variance of the data was partitioned into relatively low variability groups. The effectiveness was also shown by the high classification accuracy obtained through the discriminant analysis.

Discriminant analysis based on the component

Figure 2. Distribution of the three different component scores for the lakes included in this study. The numbered regions are the ecoregion classification regions of Omernik (1987).

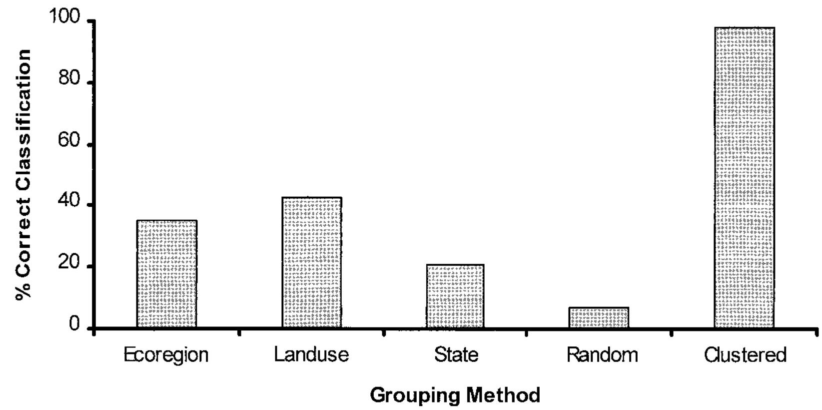

Figure 3. The percent correct classification based on jackknifed discriminant analysis for each grouping scheme.

scores and georeferenced groupings provided a test of the ecoregion concept. The difference in the resulting classification rates based on ecoregion groupings and a random grouping suggests the importance of an explicit consideration of spatial characteristics in an examination of lake water quality. The relatively low rate of ecoregion classification, much below a level found in a similar study examining the effectiveness of a watershed classification scheme (Momen and Zehr 1998), suggests that ecoregions are not effectively partitioning the environment into distinct limnological units. The failure of ecoregion-based groupings to significantly out-perform the land-use-based grouping also suggests that the ecoregion delineation is an inadequate spatial framework.

These results are highlighted by the spatial pattern of clustered lake groups. The noncontiguous and overlapping distributions of all groups suggests that no spatially homogeneous region approach could be successful. While seven distinct groups are at a sufficient scale to generate a grouping method, it does not seem possible to perform such a classification in a spatial context. The patterns of lake water quality in the northeast United States are not distributed in the manner suggested by Omernik's ecoregion delineation, nor does it seem possible that any product of the ecoregion paradigm could be successful.

However, these results do suggest that the inclusion of spatial information into an understanding of water quality is important. This was shown by the difference between all the spatial methods and the random grouping. A previous analysis of the patterns of Secchi depth in this region did find spatial correlations of the distributions of this variable (Jenerette and others 1998). However, a division of the landscape into distinct ecological units seems inappropriate for describing the pattern of water quality distribution and managing large-scale water resources. This is the same conclusion reached by Jenerette and others (1998).

The failure of ecoregions to segregate distinct classes of lakes is in contrast to previous reports that have had favorable support of ecoregion delineations (Heiskary and others 1987, Fulmer and Cooke 1990, Omernik and others 1991, Bernert and others 1997). In part, the previous acceptance of ecoregions has been the failure to properly contrast ecoregions against alternative spatial frameworks; instead they have been contrasted against a nonspatial framework. Because spatial heterogeneity exists in a correlated manner, virtually any spatial framework should perform better than a nonspatial framework. The subjective analysis of the variation within and among regions may also have contributed to the acceptance of regionalization. While some cases exist where alternative ecoregional delineations have been constructed using objective and repeatable techniques, these studies have not examined the pattern of a response variable that was not included in the delineation (Bernert and others 1997). Continued research into the existence of ecoregions is warranted where alternative spatial models are contrasted with ecoregions or any homogeneous regionalization using a response variable not incorporated in its delineation.

The difficulties of enacting a management program such as ecoregions that requires the cooperation of multiple state legislatures does not seem warranted for the northeast United States. As more data become available, similar tests can be conducted in other regions and for other classes of environmental parameters. While not supportive of the ecoregion approach, we also are not advocating an individual-state-based approach to managing water quality either, state-based groupings performed poorly as well. Political boundaries are primarily generated independently of the environmental variables that impact water quality. Because many political boundaries co-occur with streams and rivers, effectively dividing watersheds, a state-based spatial framework for water quality management is insufficient.

A spatially explicit alternative to the homogeneous regionalization approach needs to be generated for the understanding and management of environmental resources. It is likely that such an approach would take advantage of the suite of continuous variable, gradient statistical techniques such as ordination. Some potential characteristics of such an approach can be identified. A useful alternative should be independent of any particular scientist; similar inferences should be obtainable from any investigator. It should be scalable; variability at continental and regional scales needs to be comprehensibly addressable by any robust framework. Additionally, it should take advantage of extensive data sets. In particular, as remote sensing techniques continue to advance, it is conceivable that water quality for every body of water in a region could be estimated virtually simultaneously. A robust spatial framework should be able to take advantage of this information as opposed to using only a few identified reference sites. Developing such an approach, its implementation, and its evaluation is a critical challenge for ecologists.

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