Key Elements of Landscape Pattern Measures

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ABSTRACT / Describing patterns in the landscape and interpreting the effects of these patterns on flora, fauna, and other factors has been of long-standing interest. Many descriptors have been developed, and these aggregate factors into a single index. The identical numerical result for a multifactor index can be attained by using an array of very different values. We list six important factors for describing a mapped area: the area, the classes, proportion of dominant class, number of polygons, polygon size variance, and elevation range and suggest that these and their map statistics will encompass most of the observed phenomena associated with things perceived as land pattern.

A major part of landscape ecology (Forman and Godron 1986) is a study of how pattern in the landscape typically produced by communities of plants and mappable assemblages of forests can be analyzed. In this paper we address how observable patterns[2] in the landscape may be characterized so that some functional relations can be reported, studied, and then changed or interpreted meaningfully by forest managers and managers of other areas. We do not discuss plant or animal effects on pattern here. Responses to pattern are by individual animals and plants but are aggregated as population responses (e.g., as game or as pest population abundance). Eventually, these relations can be moved beyond being hypotheses based on experiences and perceptions and into working conceptual tools of the land manager. "Pattern" has not been defined by scientists, and many surrogates have been developed. Trani (1996) analyzed many expressions of landscape pattern (among many more) from the literature. We sought the common elements of these measures, believing that some had confounding influences and nonlinear relations. We suspect, but have had not yet tested in the field, the consequences of the simplifications reported briefly here.

A typical manager will ask: "What is the pattern?" We are intrigued with what would be done with a true answer if it were available. We believe people usually want to know about the magnitude or quality of some resource. They are prone to ask, for example: "If I cut timber, what will be the effects of the action on a bird species (symbolized as the presence or absence variable, p)?" "If I increase the road vegetation along both sides of the timber harvest areas, what will be the effects on turkey abundance (symbolized as q)?" "If I build a woodland pond, what will be the effect on the count of all terrestrial species present, variable r?" "People have heard that change in land use causes change in landscape pattern, and so they want to know the effects of such change on a resource. They may want more warblers, so they want to know more about what patterns result in abundant warbler nesting sites, a resource of interest. A particular resource, y, is usually a function of many factors ($x_1, x_2, \ldots, x_m$), and naming the factors, computing them, and using them to increase a resource (or decrease it if it represents a pest) is the manager's typical intent. The manager's question is how to include effectively the change in each factor when land use is changed, not just the change in the dependent variable, y. When a development or project occurs, every factor ($x_1, \ldots, x_n$) may change, but with such change there may be a pattern component (p) so that each ith factor is a function of itself in the prior state (t); p, the pattern (an index); and E, the error associated with field measures, thus

$$x_{i,t+1} = f(x_{i,t}, p, E_i) \tag{1}$$

As an example of how a single change in the land may have different values of p, a 10-ha square forest clear-cut made at the edge of a crop field probably does not have the same effect as the identical operation made nearby, deep in the forest. The location is different, but the effect on pattern (at least on "total edge length," one expression of pattern relevant to some animal populations) is also different. Potential differences in other factors resulting from pattern

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[2]We believe that there are patterns perceived by individual animals, probably not by people. We also believe that pattern, to humans, is three-dimensional and is often implicit in elevation information presented within the two dimensions of maps.
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Table 1. Variables hypothesized to be major correlates of measures of landscape pattern described by many observers

Fundamental variable	Derivative
1. Total area, x_1	
2. Total classes or relevant units of land use or cover, x_2	
3. Proportion of the area in the dominant class, x_3	4. Difference in the proportion of the dominant class and the proportion in the class if the largest three classes had even magnitude, x_4
	5. Chi-square value relating actual proportions, x_3, to hypothetical evenly-distributed proportions, m, that is x_5
6. Number of polygons, x_6	7. Mean polygon size, $x_7 = x_1/x_6$
	8. Variance of polygon size, x_8
	9. Ratio of mean polygon size to polygon variance, x_9
	10. Proportion of filled cells in a contiguity matrix for polygons, x_{10}
11. Estimated total edge length, x_{11}	
12. Elevation, x_{12}	13. Range in elevation, x_{13}

differences are readily surmised by the average ecologist. It seems important to tease apart x_i and p. Estimates of x_i typically have an accompanying estimate of error (E). It can be useful to include several estimates of pattern, p (linear or with declining effects), to shape or modify conventional independent variables in models. The efforts to measure pattern may be replaced by efforts to estimate effects of pattern on dependent variables.

Preliminary work on examining p suggests that it can be dealt with in terms of distance from and to an object, land unit, or resource in three-dimensional space. Distance for animals (and probably plants) becomes a surrogate for energy to gain benefits or life (e.g., energy, nutrients, water, pollen, propagules) or energy to avoid loss or costs (e.g., predation and competition). This factor-related concept of pattern is developed by Holling (1992).

We hypothesized that there were overlapping or simultaneous effects in landscape pattern from a land-use change, effects that are factor-specific but also aggregative (as in conventional expressions). We examined the major central components of many well-known expressions of pattern, many of which are computed by the program FRAGSTATS, and we now believe that we have isolated six fundamental variables (Table 1, column 1) for an area being analyzed. These provide the basis for deciding relevant pattern. Singly or together, they are the quantities needed to provide an expression for or estimate of p. We discuss each variable, how it may be derived, and derivatives of each fundamental variable.

Area

What is the area being analyzed? A relevant landscape needs to be specified. We believe that for the forester it is at least 200 ha (500 acres). The larger the landscape, the more likely it is that there will be interior differences and that patterns will vary. Pattern is a function of the size of an area (x_1). For most ecological problems (except rare and endangered species that often have narrow habitat requirements), the larger the area, the greater will be the probability of occurrence of resources for a plant or animal and the amount of that resource, the two usual interests in ecological studies or managerial effort. The larger the area, the less will be the likely influence of outside factors influencing the perceived pattern. The area, from the perspective of animal management, is simply needed to express density and how many home ranges can fit into a study area. The importance of area alone is central to island biogeography and the species–area curve (Primack 1993, Harris 1984, pp. 88–92).

Classes

How many relatively homogenous mappable units (i.e., land or cover classes) are there? The count, x_2, can be forest types, age classes, or areas with significantly different reflectance values (as from Landsat)—areas with any difference perceived to be of possible relevance to y, the dependent variable, the manager's resource output of interest.

There may be three classes as shown in Figure 1. Classes may be distributed in very different ways. The more classes, in general, the more resources there are if y is bird species count. The number of classes, as a singular factor, probably influences the number of species present because many are class-specific. Classes may contribute relatively little to developing strong equations (i.e., high R^2) for estimating the magnitude of y (e.g., abundance) for most animal species. Other factors such as total food supply and its stability, access to nesting and resting sites, and the presence of water in select periods are likely to be more dominant factors than pattern in influencing presence or abundance of most animal species in United States areas. The area in each relevant class is likely to be the controlling factor,

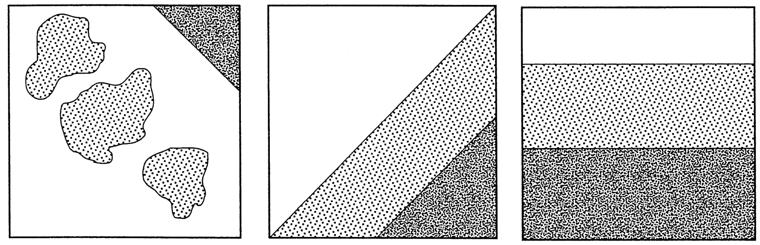

Figure 1. Three land use classes (x_2) on a map can have very different edge lengths, shapes, sizes, and proportions.

not the number of classes. The number of classes alone, however, may help explain why area *r* has more species than area *s*. The utility of classes, as for other variables, depends on the question being asked.

Proportion of Dominant Class

What is the proportion of land in class 1 (the type with greatest area, highest in rank order)? Most diversity measures are based on proportions (which contribute to their weakness as an independent variable or as the grounds for estimating *y*: many different conditions can produce the same proportion). We suggest dominance of class, the proportion of the area in the major class, x_3, as a variable worthy of study in gaining explanatory or predictive power over *y*. If this dominant proportion is small, the other classes are probably abundant and small. If large, there are probably few other classes or many very small ones. Not adequate alone, this single-dominant-class perspective nevertheless provides much information and predisposes future analyses of evenness, analyses that are popular as an expression of spatial pattern.

Other information often collected with proportions in land-use classes is likely to be highly variable and almost impossible to interpret. Where there are three classes in a map and one contains 96% of the area and the others 2% each, the types are not evenly distributed in space. We may compute a difference between the maximum value and an hypothetical value (one in which the three major classes are equal) and call it x_4. The difference between the dominant proportion x_3, which was 0.96 in the above example, and perfect evenness for a set number classes (x) [in this case 3, then ($m = 1/x$ or 0.33) is thus:

$$x_4 = (x_3 - m) = (0.96 - 0.33) = 0.63$$

A small value for x_4 would indicate a tendency toward evenness and conditions about equal for many plants and animals. A chi-square statistic (x_5), relating the observed area in each class to the expected areas calculated as if they were evenly distributed, is likely to provide more information than x_4. We believe that most plants and animals will be a function of the dominant class present. The probability of zero value makes using a transformation [log ($x + 1$)] very relevant (Green 1979). The difference in the two most abundant species, x_4, predisposes all other proportional values. The values will be in the average range of ($1.0 - x_4/x_2$). In most natural systems, the proportions in each class are highly variable and most are small. The dominant classes, when isolated, typically account for a high proportion of the total. Few natural situations have abundance evenly distributed. The interpretation of the effect of the many small proportions is beyond the knowledge that we now have (and the knowledge likely to be gained), thus we count and use the three dominant classes.

Polygons

Polygons are land units large enough and significantly different enough to be mappable. The number of polygons (regardless of class) per unit area is Monmonier's (1982) fragmentation index. The count is x_6.

Dividing x_6 into the area, x_1, results in a new variable x_7, simply the inverse of the fragmentation index, i.e., $x_7 = x_1/x_6$ and is the average size of the polygons. The average size allows an estimate to be made of, and virtually predisposes, the interior area for birds or other creatures for which behavior relative to edge zones can be estimated. Conversely, edge length may be approximated from average area and thus correlative edge-inhabiting biota estimated. Relationships between average patch size to bird species richness (Wilcove and others 1986, Van Dorp and Opdam 1987, Askins and others 1990) probably incorporate this phenomenon.

Polygon Size Variance

Is an expression of the average difference from the mean polygon size related to perceived patterns? The statistical variance, x_8, in the size of polygons will be the most tedious of all numbers suggested herein that needs to be computed to gain insight into and express a landscape pattern. Actual or estimated mean size (x_7) of polygons in an area is needed to compute this statistic. There are conspicuous tendencies in ecological variables associated with x_8. The larger the variance, the more likely it will be that many resources are available to biota. The larger the variance, the smaller the evenness scores and the smaller the conventional spatial diversity indices. The larger the value of x_8, the longer the edge length. The larger x_8, the larger the value of x_4 is likely to be. These observations, progressively, suggest that the measures of landscape pattern are derivatives of a few well known measurements.

When the mean-to-variance ratio in polygon size, x_9 is 1.0 ($x_9 = x_7/x_8$), polygons are said to be randomly distributed (i.e., Poissonal). When the variance (x_8) is low, the polygon centers tend to be uniformly distributed (as blocks in human residential areas or in a patterned tundra field). For a constant mean value, when the variance is large (thus the Poisson index is small), then polygons tend to be clustered. Clustering is typical in most natural systems (as seen from plants around a seed source, animals around a den, animals near water).

Polygon data can be used to form a contiguity matrix expressive of joins or connections. The triangular matrix has x_6 rows and columns with C^* potential entries, where $C^* = x_6\,(x_6 - 1)/z$. A ratio, x_{10}, may be computed of actual C to potential joins as $x_{10} = C/C^*$. This ratio may be a modifier to the polygon count (x_6). Since more polygons in a similar area result in more edge and edge length will be estimated as x_{11}, x_{10} may not be needed.

Edge Length

The average size of a polygon, x_7, determines minimum edge length, k, for such polygons. The relationship is

$$k = 2\pi\,(x_7/\pi)^{0.5} \text{ or } 6.93\,(x_7/3.46)^{0.5}$$

When these polygons are viewed as regular hexagons without overlap or interstitial spaces, then they have about half the edge length of irregular polygons

$$k = 6.93\,(x_7/3.4641)^{0.5}$$

but polygons share about half of their edges with other polygons, thus they cancel and the estimate of edge length for an average polygon is

$$k^* = 7\,(x_7/3.5)^{0.5}$$

and an estimate of total edge length, x_{10}, is

$$x_{10} = x_6 k^*$$

Using forest edge length by itself is of limited utility for long-term planning or species management, despite its frequency of use. The classes, width, heights, ages, change rates, and species-specific relevance of edge (omitting the effects of drying phenomena at the edge on forest fauna) must all be accounted for if it is to have meaning. To do so is unlikely. Edge rarely has much meaning in ecology unless used with a contiguity matrix, i.e., one expressive of the relative importance of every linear join or union of two habitats to each species of managerial importance. (This matrix excludes point touches.) Edge length can be used as a gross index of interspersion, but interspersion is probably equally efficiently estimated by x_9.

Elevation Range

Maps are two-dimensional but they often include information (such as contour lines) about elevation. It is likely that an estimate of elevation, x_{12}, will be at least as useful in understanding large ecological systems as an estimate for area (x_1 or horizontal distance between points). We believe that the difference between the minimum and maximum elevation within the area, x_{13}, can be very influential as an independent variable in estimating richness and other ecological topics of interest. The greater the range of elevation in a study area, the less likely the other values (x_1 to x_{11}) will be able to give managers control over their selected resource measure, y.

Discussion

We hypothesize that six factors, x_1, x_2, x_3, x_6, x_{11}, and x_{12}, will encompass most of the phenomena of observed pattern in the landscape (others are derivative.) They are of particular interest since each one can be hypothesized to influence some ecological or land and resource management topic of interest. For the "price" of a few data entries, major control can probably be gained influencing landscape pattern. With these, managers may hypothesize and plan for changes in pattern to influence plants, animals, communities, and other ecological topics to desired ends.

Trani (1996) has evaluated measures used in landscape ecology (Table 2). From her study of area measures, it can be seen that (with the exception of elevation) all measures can be estimated from a map or database if only the area and land class of each polygon are available. Other expressions of pattern listed by Trani may be useful in understanding a dependent-resource-related variable. After obtaining polygon sizes or estimating likely size (by using edge length), other values used in making expressions of landscape pattern can be derived. For example, distance between the centers of each polygon, one of Trani's listed measures, can be estimated. This distance tends to increase among

Table 2. Landscape pattern expressions and measures used to estimate each as studied by Trani (1996)

Area	
1	Area of interior forest
2	Area of each forest patch
3	Total area of forest cover
4	Total area of landscape
5	Area of each different land class
Distance	
6	Pixel[a] distance to nonforest locations
7	Edge-to-edge distance between forest patches
Edge length	
8	Total forest edge length
9	Edge length of each forest patch
Count of land units	
10	Number of landscape classes
11	Number of total map pixels
12	Number of different land classes
13	Number of forest patches
14	Number of openings within a forested landscape
15	Number of connections between forest patches
Roving window operations	
16	Number of different neighborhood classes
17	Number and position of contiguous forest cells
18	Adjacency matrix (proportion of cells i adjacent to cells j

[a]A pixel is a map cell, an equal-size square or rectangle in a grid over a map; a raster unit.

select types when roads or similar ‘‘developments’’ are made. It may be taken as one measure of fragmentation. (The corresponding decrease in distance between other types that also occurs with such development will have to be resolved by those who persist in using the value-laden word ‘‘fragmentation’’ e.g., fragmented forests may result in less fragmented fields.)

The roving window operation (items 16–18 in Table 2) (Murphy 1985) is a computer procedure (raster operation) of taking the characteristic of each cell in a computer map, relating it to all contiguous eight cells, then moving to the next map cell and repeating the process—until every cell in the map is processed similarly. Operationally interesting and efficient, it may deny the breadth of scale from which information is usually asserted by those working in landscape ecology, and indiscriminantly loads every cell with multiple information potentially related to the dependent variable, y. It was found by Trani (1996) to be readily measured and to be influenced significantly by most changes made in a landscape (e.g., roads built in a national forest). The statistic produced by the analysis is an agglomeration of the mean and variance of polygon size, polygon shape, selected cell size (or window size, thus number of iterations), and class. The statistics obtained for comparisons between any areas are very likely to be numerically different. While the statistics differ among areas, dissimilar patterns may produce identical statistics. The statistic may point to local variability of relevance to a species or to a manager. What any manager might do on the landscape to change the statistic and thereby influence a resource value, y, seems difficult to interpret.

The six factors discussed may relate well to quantitative expressions of landscape beauty, but that is beyond the scope of this paper. We suggest that the observed pattern in a large landscape be expressed in some simplistic way (any of these presented, x_1 to x_{13}). We think a few major measures are needed and that those have already been observed to relate to functional relations in ecosystems. Making other measures will waste time and money (and in some cases provide erroneous information) for managers seeking additional significant control over typical expression of the resource being managed. Comparisons can be made between and among areas, practices, times, and policy using the measures suggested. If landscape pattern is influential in determining y, we believe it will be expressed well in the variables described herein.

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