Characterizing landscape patterns – conceptual foundation

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Assigned Reading: Turner et al. 2001 (Chapter 5); Gustafson (1998)

Objective: Provide a basic understanding of how to characterize and quantify landscape pattern. Highlight importance of landscape definition in landscape pattern analysis and the difference between measured and functional heterogeneity.

Topics covered:
1. Pattern analysis in context
2. The importance of scale
3. Scope of analysis
4. Levels of heterogeneity
5. Components of landscape structure
6. Structural versus functional metrics
7. Limitations in the use and interpretation of metrics
1. Pattern Analysis in Context

Landscape ecology, if not ecology in general, is largely founded on the notion that environmental patterns strongly influence ecological processes. The habitats in which organisms live, for example, are spatially structured at a number of scales, and these patterns interact with organism perception and behavior to drive the higher level processes of population dynamics and community structure (Johnson et al. 1992). Anthropogenic activities (e.g. development, timber harvest) can disrupt the structural integrity of landscapes and is expected to impede, or in some cases facilitate, ecological flows (e.g., movement of organisms) across the landscape (Gardner et al. 1993). A disruption in landscape patterns may therefore compromise its functional integrity by interfering with critical ecological processes necessary for population persistence and the maintenance of biodiversity and ecosystem function (With 2000). Consequently, much emphasis has been placed on developing methods to quantify landscape patterns, which is considered prerequisite to the study of pattern-process relationships (e.g., O'Neill et al. 1988, Turner 1990, Turner and Gardner 1991, Baker and Cai 1992, McGarigal and Marks 1995). This has resulted in the development of hundreds of indices of landscape patterns. Unfortunately, according to Gustafson (1998), “the distinction between what can be mapped and measured and the patterns that are ecologically relevant to the phenomenon under investigation or management is sometimes blurred.”
2. Importance of Scale

There are at least two different aspects of scale regarding categorical map patterns that have important implications for the choice and interpretation of individual landscape metrics.

(1) *Spatial Scale.* - It is important to recognize the practical implications of the choice of grain and extent for a particular application. Many of the landscape metrics are particularly sensitive to grain. Metrics involving edge or perimeter will be affected; edge lengths will be biased upwards in proportion to the grain size—larger grains result in greater bias. Edge lengths can vary by as much as 25-50% over vector calculations depending on grain size. Metrics based on cell adjacency information such as the contagion index of Li and Reynolds (1993) will be affected as well, because grain size effects the proportional distribution of adjacencies. In this case, as resolution is increased (grain size reduced), the proportional abundance of like adjacencies (cells of the same class) increases, and the measured contagion increases. Similarly, the measured landscape patterns will often vary with extent. Intuitively this makes sense, because as the landscape extent increases, new patch types may be encountered and habitat configurations may change in response to underlying environmental or land use gradients.
The ratio of grain to extent for a particular analysis warrants special consideration. If the ratio is very small (i.e., a coarse-grained map), the boundary of the landscape can have a profound influence on the value of certain metrics. Landscape metrics are computed solely from patches contained within the landscape boundary. If the landscape extent is small relative to the scale of the phenomenon under consideration and the landscape is an “open” system relative to that organism or process, then any metric will have questionable meaning. Metrics based on nearest neighbor distance or employing a search radius can be particularly misleading. In general, boundary effects increase as the landscape extent decreases relative to the patchiness or heterogeneity of the landscape. The key point is that some landscape metrics are likely to be very sensitive to this ratio (e.g., those based on nearest-neighbor distances such as the mean proximity index.)
(2) *Thematic Resolution.*—Thematic resolution has dramatic influences on the types of associations that can be made and on the nature of the patterns that can be mapped from that variable. Thematic resolution typically has a pronounced influence on both the composition and configuration of the map and thus directly affects all quantitative measures of landscape pattern. At the simplest level, for example, thematic resolution determines the number of classes or patch types represented and thus affects all composition metrics such as the measures of landscape diversity.
3. Scope of Analysis

The scope of analysis pertains to the scale and or focus of the investigation. There are three levels of analysis that represent fundamentally different conceptualizations of landscape patterns and that have important implications for the choice and interpretation of individual landscape metrics and the form of the results.

(1) **Focal patch analysis**—Under the patch mosaic model of landscape structure the focus of the investigation may be on individual patches (instead of the aggregate properties of patches); specifically, the spatial character and/or context of individual focal patches. This is a “patch-centric” perspective on landscape patterns in which the scope of analysis is restricted to the characterization of individual focal patches. In this case, each focal patch is characterized according to one or more patch-level metrics (see below). The results of a focal patch analysis is typically given in the form of a table, where each row represents a separate patch and each column represents a separate patch metric.

(2) **Local landscape structure**—In many applications it may be appropriate to assume that organisms experience landscape structure as local pattern gradients that vary through space according to the perception and influence distance of the particular organism or process. Thus, instead of analyzing global landscape patterns, e.g., as measured by conventional landscape metrics for the entire landscape (see below), we would be better served by quantifying the local
landscape pattern across space as it may be experienced by the organism of interest, given their perceptual abilities. The local landscape structure can be examined by passing a “moving window” of fixed or variable size across the landscape one cell at a time. The window size and form should be selected such that it reflects the scale and manner in which the organism perceives or responds to pattern. If this is unknown, the user can vary the size of the window over several runs and empirically determine which scale the organism is most responsive to. The window moves over the landscape one cell at a time, calculating the selected metric within the window and returning that value to the center cell. The result is a continuous surface which reflects how an organism of that perceptual ability would perceive the structure of the landscape as measured by that metric. The surface then would be available for combination with other such surfaces in multivariate models to predict, for example, the distribution and abundance of an organism continuously across the landscape.

(3) **Global landscape structure**.—The traditional application of landscape metrics involves characterizing the structure of the entire landscape with one or more landscape metrics. For example, traditional landscape pattern analysis would measure the total contrast-weighted edge density for the entire landscape. This would be a global measure of the average property of that landscape. This is a “landscape-centric” perspective on landscape patterns in which the scope of analysis is restricted to the characterization of the entire patch mosaic in aggregate. In this case, the landscape is characterized according to one or more landscape-level metrics (see below). The results of a global landscape structure analysis is typically given in the form of a vector of measurements, where each element represents a separate landscape metric.
4. Levels of Heterogeneity

Patches form the basis (or building blocks) for categorical maps. Depending on the method used to derive patches (and therefore the data available), they can be characterized compositionally in terms of variables measured within them. This may include the mean (or mode, central, or max) value and internal heterogeneity (variance, range). However, in most applications, once patches have been established, the within-patch heterogeneity is ignored. Landscape pattern metrics instead focus on the spatial character and distribution of patches. While individual patches possess relatively few fundamental spatial characteristics (e.g., size, perimeter, and shape), collections of patches may have a variety of aggregate properties, depending on whether the aggregation is over a single class (patch type) or multiple classes, and whether the aggregation is within a specified subregion of a landscape or across the entire landscape. Thus, the common hierarchical organization of categorical maps is patch → class → landscape. However, the fundamental spatial unit in a grid data model is the cell. Therefore, for grid representations of categorical patterns, the cell represents an additional (and finest) level of heterogeneity.

(1) Cell-level metrics: cell-level metrics are defined for individual cells, and characterize the spatial context or ecological neighborhood of each cell without explicit regard to any patch or class affiliation. In other words, cell metrics are not patch-centric. Cell metrics provide the finest spatial unit of resolution for characterizing spatial patterns. Each cell has a spatial context defined by the composition and configuration of its neighborhood, and that context may
influence the ecological properties of the focal cell. For example, an individual organism dispersing from its natal habitat interacts with the structure of the landscape in the neighborhood surrounding that initial location. Thus, the ability to traverse across the landscape from that location may be a function of the landscape character within some ecological neighborhood defined by dispersal distance. Cell metrics may be computed for a targeted set of focal cells representing specific locations of interest (e.g., nest sites, capture locations, etc.), in which case the standard output would consist of a vector of cell-based measurements reported in tabular form (i.e., one record for each focal cell). Cell metrics may also be computed exhaustively for every cell in the landscape, in which case the standard output would consist of a continuous surface grid or map.

(2) **Patch-level metrics**—patch-level metrics are defined for individual patches, and characterize the spatial character and context of patches. In most applications, patch metrics serve primarily as the computational basis for several of the landscape metrics, for example by averaging patch attributes across all patches in the class or landscape; the computed values for each individual patch may have little interpretive value. However, sometimes patch indices can be important and informative in landscape-level investigations. For example, many vertebrates require suitable habitat patches larger than some minimum size (e.g., Robbins et al. 1989), so it would be useful to know the size of each patch in the landscape. Similarly, some species are adversely affected by edges and are more closely associated with patch interiors (e.g., Temple 1986), so it would be useful to know the size of the core area for each patch in the landscape. The probability of occupancy and persistence of an organism in a patch may be related to patch insularity (sensu Kareiva 1990), so it would be useful to know the nearest neighbor of each patch and the degree of contrast between the patch and its neighborhood. The utility of the patch characteristic information will ultimately depend on the objectives of the investigation.

(3) **Class-level metrics**—Class-level metrics are integrated over all the patches of a given type (class). These may be integrated by simple averaging, or through some sort of weighted-averaging scheme to bias the estimate to reflect the greater contribution of large patches to the overall index. There are additional aggregate properties at the class level that result from the unique configuration of patches across the landscape. In many applications, the primary interest is in the amount and distribution of a particular patch type. A good example is in the study of habitat fragmentation. Habitat fragmentation is a landscape-level process in which contiguous habitat is progressively sub-divided into smaller, geometrically more complex (initially, but not necessarily ultimately), and more isolated habitat fragments as a result of both natural processes and human land use activities (McGarigal and McComb 1999). This process involves changes in landscape composition, structure, and function and occurs on a backdrop of a natural patch mosaic created by changing landforms and natural disturbances. Habitat loss and fragmentation is the prevalent trajectory of landscape change in several human-dominated regions of the world, and is increasingly becoming recognized as a major cause of declining biodiversity (Burgess and Sharpe 1981, Whitcomb et al. 1981, Noss 1983, Harris 1984, Wilcox and Murphy 1985, Terborgh 1989, Noss and Cooperrider 1994). Class indices separately quantify the amount and spatial configuration of each patch type and thus provide a means to quantify the extent and fragmentation of each patch type in the landscape.
Landscape-level metrics—Landscape-level metrics are integrated over all patch types or classes over the full extent of the data (i.e., the entire landscape). Like class metrics, these may be integrated by a simple or weighted averaging, or may reflect aggregate properties of the patch mosaic. In many applications, the primary interest is in the pattern (i.e., composition and configuration) of the entire landscape mosaic. A good example is in the study of wildlife communities. Aldo Leopold (1933) noted that wildlife diversity was greater in more diverse and spatially heterogenous landscapes. Thus, the quantification of landscape diversity and heterogeneity has assumed a preeminent role in landscape ecology. Indeed, the major focus of landscape ecology is on quantifying the relationships between landscape pattern and ecological processes. Consequently, much emphasis has been placed on developing methods to quantify landscape pattern (e.g., O'Neill et al. 1988, Li 1990, Turner 1990, Turner and Gardner 1991) and a great variety of landscape-level metrics have been developed for this purpose.

It is important to note that while most metrics at higher levels are derived from patch-level attributes, not all metrics are defined at all levels. In particular, collections of patches at the class and landscape level have aggregate properties that are undefined (or trivial) at lower levels. The fact that most higher-level metrics are derived from the same patch-level attributes has the further implication that many of the metrics are correlated. Thus, they provide similar and perhaps redundant information (see below). Even though many of the class- and landscape-level metrics represent the same fundamental information, naturally the algorithms differ slightly (see below).

In addition, while many metrics have counterparts at all levels, their interpretations may be somewhat different. Patch-level metrics represent the spatial character and context of individual patches. Class-level metrics represent the amount and spatial distribution of a single patch type and may be interpreted as fragmentation indices. Landscape-level metrics represent the spatial pattern of the entire landscape mosaic and may be interpreted more broadly as landscape heterogeneity indices because they measure the overall landscape structure. Hence, it is important to interpret each metric in a manner appropriate to its level (patch, class, or landscape).
5. Components of Landscape Structure

The common usage of the term “landscape metrics” refers to indices developed for categorical map patterns. Landscape metrics are algorithms that quantify specific spatial characteristics of patches, classes of patches, or entire landscape mosaics. A plethora of metrics has been developed to quantify categorical map patterns. An exhaustive review of all published metrics is beyond the scope of this chapter. These metrics fall into two general categories: those that quantify the composition of the map and those that quantify the spatial configuration of the map.

(1) **Composition**—composition is easily quantified and refers to features associated with the variety and abundance of patch types within the landscape, but without considering the spatial character, placement, or location of patches within the mosaic. There are many quantitative measures of landscape composition, including the proportion of the landscape in each patch type, patch richness, patch evenness, and patch diversity. Indeed, because of the many ways in which diversity can be measured, there are literally hundreds of possible ways to quantify landscape composition. Unfortunately, because diversity indices are derived from the indices used to summarize species diversity in community ecology, they suffer the same interpretative drawbacks. It is incumbent upon the investigator or manager to choose the formulation that best represents their concerns.
The principle measures of composition are:

- **Proportional Abundance of each Class**—One of the simplest and perhaps most useful pieces of information that can be derived is the proportion of each class relative to the entire map.

- **Richness**—Richness is simply the number of different patch types.

- **Evenness**—Evenness is the relative abundance of different patch types, typically emphasizing either relative dominance or its compliment, equitability. There are many possible evenness measures corresponding to the many diversity measures. Evenness is usually reported as a function of the maximum diversity possible for a given richness; i.e., evenness is given as 1 when the patch mosaic is perfectly diverse given the observed patch richness, and approaches 0 as evenness decreases. Evenness is sometimes reported as its complement, dominance, by subtracting the observed diversity from the maximum for a given richness. In this case, dominance approaches 0 for maximum equitability and increases >0 for higher dominance.

- **Diversity**—Diversity is a composite measure of richness and evenness and can be computed in a variety of forms (e.g., Shannon and Weaver 1949, Simpson 1949), depending on the relative emphasis placed on these two components.
(2) Configuration—configuration is much more difficult to quantify and refers to the spatial character and arrangement, position, or orientation of patches within the class or landscape. Some aspects of configuration, such as patch isolation or patch contagion, are measures of the placement of patch types relative to other patches, other patch types, or other features of interest. Other aspects of configuration, such as shape and core area, are measures of the spatial character of the patches. There are many aspects of configuration and the literature is replete with methods and indices developed for representing them (see previous references).

Configuration can be quantified in terms of the landscape unit itself (i.e., the patch). The spatial pattern being represented is the spatial character of the individual patches, even though the aggregation is across patches at the class or landscape level. The location of patches relative to each other is not explicitly represented. Metrics quantified in terms of the individual patches (e.g., mean patch size and shape) are spatially explicit at the level of the individual patch, not the class or landscape. Such metrics represent a recognition that the ecological properties of a patch are influenced by the surrounding neighborhood (e.g., edge effects) and that the magnitude of these influences are affected by patch size and shape. These metrics simply quantify, for the class or landscape as a whole, some attribute of the statistical distribution (e.g., mean, max, variance) of the corresponding patch characteristic (e.g., size, shape). Indeed, any patch-level metric can be summarized in this manner at the class and landscape levels. Configuration also can be quantified in terms of the spatial relationship of patches and patch types (e.g., nearest neighbor, contagion). These metrics are spatially explicit at the class or landscape level because
the relative location of individual patches within the patch mosaic is represented in some way. Such metrics represent a recognition that ecological processes and organisms are affected by the overall configuration of patches and patch types within the broader patch mosaic.

A number of configuration metrics can be formulated either in terms of the individual patches or in terms of the whole class or landscape, depending on the emphasis sought. For example, perimeter-area fractal dimension is a measure of shape complexity (Mandelbrot 1982, Burrough 1986, Milne 1991) that can be computed for each patch and then averaged for the class or landscape, or it can be computed from the class or landscape as a whole by regressing the logarithm of patch perimeter on the logarithm of patch area. Similarly, core area can be computed for each patch and then represented as mean patch core area for the class or landscape, or it can be computed simply as total core area in the class or landscape. Obviously, one form can be derived from the other if the number of patches is known and so they are largely redundant; the choice of formulations is dependent upon user preference or the emphasis (patch or class/landscape) sought. The same is true for a number of other common landscape metrics. Typically, these metrics are spatially explicit at the patch level, not at the class or landscape level.

The principle aspects of configuration and a sample of representative metrics are:

- **Patch size distribution and density.**—The simplest measure of configuration is patch size, which represents a fundamental attribute of the spatial character of a patch. Most landscape metrics either directly incorporate patch size information or are affected by patch size. Patch size distribution can be summarized at the class and landscape levels in a variety of ways (e.g., mean, median, max, variance, etc.), or, alternatively, represented as patch density, which is simply the number of patches per unit area.

- **Patch shape complexity.**—Shape complexity relates to the geometry of patches—whether they tend to be simple and compact, or irregular and convoluted. Shape is an extremely difficult spatial attribute to capture in a metric because of the infinite number of possible patch shapes. Hence, shape metrics generally index overall shape complexity rather than attempt to assign a value to each unique shape. The most common measures of shape complexity are based on the relative amount of perimeter per unit area, usually indexed in terms of a perimeter-to-area ratio, or as a fractal dimension, and often standardized to a simple Euclidean shape (e.g., circle or square). The interpretation varies among the various shape metrics, but in general, higher values mean greater shape complexity or greater departure from simple Euclidean geometry. Other methods have been proposed—radius of gyration (Pickover 1990), contiguity (LaGro 1991), linearity index (Gustafson and Parker 1992), and elongation and deformity indices (Baskent and Jordan 1995)—but these have not yet become widely used (Gustafson 1998).

- **Core Area.**—Core area represents the interior area of patches after a user-specified edge buffer is eliminated. The core area is the area unaffected by the edges of the patch. This “edge effect” distance is defined by the user to be relevant to the phenomenon under consideration and can either be treated as fixed or adjusted for each unique edge type.
area integrates patch size, shape, and edge effect distance into a single measure. All other things equal, smaller patches with greater shape complexity have less core area. Most of the metrics associated with size distribution (e.g., mean patch size and variability) can be formulated in terms of core area.

- **Isolation/Proximity** --Isolation/proximity refers to the tendency for patches to be relatively isolated in space (i.e., distant) from other patches of the same or similar (ecologically friendly) class. Because the notion of “isolation” is vague, there are many possible measures depending on how distance is defined and how patches of the same class and those of other classes are treated. If \( d_{ij} \) is the nearest-neighbor distance from patch \( i \) to another patch \( j \) of the same type, then the average isolation of patches can be summarized simply as the mean nearest-neighbor distance over all patches. Alternatively, isolation can be formulated in terms of both the size and proximity of neighboring patches within a local neighborhood around each patch using the isolation index of Whitcomb et al. (1981) or proximity index of Gustafson and Parker (1992), where the neighborhood size is specified by the user and presumably scaled to the ecological process under consideration. The original proximity index was formulated to consider only patches of the same class within the specified neighborhood. This binary representation of the landscape reflects an island biogeographic perspective on landscape pattern. Alternatively, this metric can be formulated to consider the contributions of all patch types to the isolation of the focal patch, reflecting a landscape mosaic perspective on landscape patterns.

- **Contrast** --Contrast refers to the relative difference among patch types. For example, mature forest next to younger forest might have a lower-contrast edge than mature forest adjacent to open field, depending on how the notion of contrast is defined. This can be computed as a contrast-weighted edge density, where each type of edge (i.e., between each pair of patch types) is assigned a contrast weight. Alternatively, this can be computed as a neighborhood contrast index, where the mean contrast between the focal patch and all patches within a user-specified neighborhood is computed based on assigned contrast weights. Relative to the focal patch, if patch types with high contrast lead to greater isolation of the focal patch, as is often the case, then contrast will be inversely related to isolation (at least for those isolation measures that consider all patch types).

- **Dispersion** --Dispersion refers to the tendency for patches to be regularly or contagiously distributed (i.e., clumped) with respect to each other. There are many dispersion indices developed for the assessment of spatial point patterns, some of which have been applied to categorical maps. A common approach is based on nearest-neighbor distances between patches of the same type. Often this is computed in terms of the relative variability in nearest-neighbor distances among patches; for example, based on the ratio of the variance to mean nearest neighbor distance. Here, if the variance is greater than the mean, then the patches are more clumped in distribution than random, and if the variance is less than the mean, then the patches are more uniformly distributed. This index can be averaged over all patch types to yield an average index of dispersion for the landscape. Alternative indices of dispersion based on nearest neighbor distances can be computed, such as the familiar Clark and Evans (1954) index.
Contagion & Interspersion.—Contagion refers to the tendency of patch types to be spatially aggregated; that is, to occur in large, aggregated or “contagious” distributions. Contagion ignores patches per se and measures the extent to which cells of similar class are aggregated. Interspersion, on the other hand, refers to the intermixing of patches of different types and is based entirely on patch (as opposed to cell) adjacencies. There are several different approaches for measuring contagion and interspersion. One popular index that subsumes both dispersion and interspersion is the contagion index based on the probability of finding a cell of type i next to a cell of type j (Li and Reynolds 1993). This index increases in value as a landscape is dominated by a few large (i.e., contiguous) patches and decreases in value with increasing subdivision and interspersion of patch types. This index summarizes the aggregation of all classes and thereby provides a measure of overall clumpiness of the landscape. McGarigal and Marks (1995) suggest a complementary interspersion/juxtaposition index that increases in value as patches tend to be more evenly interspersed in a "salt and pepper" mixture. These and other metrics are generated from the matrix of pairwise adjacencies between all patch types, where the elements of the matrix are the proportions of edges in each pairwise type. There are alternative methods for calculating class-specific contagion using fractal geometry (Gardner and O’Neill 1991). Lacunarity is an especially promising method borrowed from fractal geometry by which contagion can be characterized across a range of spatial scales (Plotnick et al. 1993 and 1996, Dale 2000). The technique involves using a moving window and is concerned with the frequency with which one encounters the focal class in a window of different sizes. A log-log plot of lacunarity against window size expresses the contagion of the map, or its tendency to aggregate into discrete patches, across a range of spatial scales.

Subdivision.—Subdivision refers to the degree to which a patch type is broken up (i.e., subdivided) into separate patches (i.e., fragments), not the size (per se), shape, relative location, or spatial arrangement of those patches. Because these latter attributes are usually affected by subdivision, it is difficult to isolate subdivision as an independent component. Subdivision can be evaluated using a variety of metrics already discussed; for example, the number, density, and average size of patches and the degree of contagion all indirectly evaluate subdivision. However, a suite of metrics derived from the cumulative distribution of patch sizes provide alternative and more explicit measures of subdivision (Jaeger 2000). When applied at the class level, these metrics can be used to measure the degree of fragmentation of the focal patch type. Applied at the landscape level, these metrics connote the graininess of the landscape; i.e., the tendency of the landscape to exhibit a fine- versus coarse-grain texture. A fine-grain landscape is characterized by many small patches (highly subdivided); whereas, a coarse-grain landscape is characterized by fewer large patches.

Connectivity.—Connectivity generally refers to the functional connections among patches. What constitutes a "functional connection" between patches clearly depends on the application or process of interest; patches that are connected for bird dispersal might not be connected for salamanders, seed dispersal, fire spread, or hydrologic flow. Connections might be based on strict adjacency (touching), some threshold distance, some decreasing function of distance that reflects the probability of connection at a given distance, or a
resistance-weighted distance function. Then various indices of overall connectedness can be derived based on the pairwise connections between patches. For example, one such index, *connectance*, can be defined on the number of functional joinings, where each pair of patches is either connected or not. Alternatively, from *percolation theory*, connectedness can be inferred from patch density or be given as a binary response, indicating whether or not a spanning cluster or percolating cluster exists; i.e., a connection of patches of the same class that spans across the entire landscape (Gardner et al. 1987). Connectedness can also be defined in terms of *correlation length* for a raster map comprised of patches defined as clusters of connected cells. Correlation length is based on the average extensiveness of connected cells. A map's correlation length is interpreted as the average distance one might traverse the map, on average, from a random starting point and moving in a random direction, i.e., it is the expected traversibility of the map (Keitt et al. 1997).
Landscape configuration metrics measure the spatial aspects of the landscape structure, however, they do so at two different levels of spatial explicitness. Many metrics are spatially explicit at the patch level, meaning that they describe the spatial character of individual patches, and may be summarized at the class or landscape level by taking the average, area-weighted average, median, range, standard deviation or coefficient of variation of the patch measurements. Some metrics are spatially explicit at the landscape level, meaning that they describe the spatial character of the landscape, as opposed to the individual patches, because the relative location of individual patches within the landscape is represented. Before using a landscape metric, it is useful to know whether it is spatially explicit at the patch or landscape level, because the former represents a patch-centric focus for the analysis, whereas the latter represents more of a landscape-centric focus for the analysis.
6. Structural versus Functional Metrics

Landscape metrics can also be classified according to whether or not they measure landscape patterns with explicit reference to a particular ecological process. **Structural metrics** are those that measure the structure of the patch mosaic without explicit reference to an ecological process. The functional relevance of the computed value is left for interpretation during a subsequent step. **Functional metrics**, on the other hand, are those that explicitly measure landscape pattern in a manner that is functionally relevant to the process under consideration. Functional metrics require additional parameterization prior to calculation, such that the same metric can return multiple values depending on user specifications. The difference between structural and functional metrics is best illustrated by example. Mean nearest neighbor distance is based on the distances between neighboring patches of the same class; the mosaic is in essence treated as a binary landscape (i.e., patches of the focal class versus everything else). Consequently, the same landscape can only return a single value for this metric. Clearly, this is a structural metric because the functional meaning of any computed value is left to subsequent interpretation. Conversely, connectivity metrics that consider the permeability of various patch types to movement of the organism or process of interest are functional. Here, every patch in the mosaic contributes to the calculation of the metric. Moreover, there are an infinite number of values that can be returned from the same landscape, depending on the permeability coefficients assigned to each patch type. Given a particular parameterization, the computed metric is in terms that are already deemed functionally relevant.
7. Limitations in the Use and Interpretation of Metrics

The quantitative analysis of landscape patterns is fraught with numerous difficult issues. Four broad issues that currently limit the effective use and interpretation of landscape metrics are considered here:

1. Defining a relevant landscape for a particular application.
2. Gaining a theoretical and empirical understanding of metric behavior to guide interpretation.
3. Coping with redundancy among metrics in search of metric parsimony.
4. Establishing a reference framework to guide the ecological interpretation of metric values.
7.1. Defining a relevant landscape

All landscape metrics represent some aspect of landscape pattern. However, the user must first define the landscape before any of these metrics can be computed. This involves choosing a landscape grain and extent, delineating a boundary, defining the thematic content and resolution, and selecting a structural model (categorical versus continuous) and data format (vector versus raster). The computed value of any metric is entirely a function of how the investigator chooses to define and scale the landscape. In addition, for functional metrics, the user must specify additional input parameters such as edge effect distance, edge contrast weights, and search distance. If the measured pattern of the landscape (i.e., measured heterogeneity) does not correspond to a pattern that is functionally meaningful for the organism or process under consideration (i.e., functional heterogeneity), then the results will be meaningless. For example, the criteria for defining a patch may vary depending on how much variation will be allowed within a patch, on the minimum size of patches that will be mapped, and on the components of the system that are deemed ecologically relevant to the phenomenon of interest (Gustafson 1998). Ultimately, patches occur on a variety of scales, and a patch at any given scale has an internal structure that is a reflection of patchiness at finer scales, and the mosaic containing that patch has a structure that is determined by patchiness at broader scales (Kotliar and Wiens 1990). Thus, regardless of the basis for defining patches, a landscape does not contain a single patch mosaic, but contains a hierarchy of patch mosaics across a range of scales. Indeed, patch boundaries are artificially imposed and are in fact meaningful only when referenced to a
particular scale (i.e., grain size and extent). It is incumbent upon the investigator to establish the basis for delineating among patches and at a scale appropriate to the phenomenon under consideration. Extreme caution must be exercised in comparing the values of metrics computed for landscapes that have been defined and scaled differently.

Given the subjectivity in defining patches, surface pattern techniques can provide an objective means to help determine the scale of patchiness (Gustafson 1998). In many studies, the identification of patches reflects a minimum mapping unit that is chosen for practical or technical reasons and not for ecological reasons. Surface pattern analysis can provide insight into the scale of patchiness and whether there are hierarchies of scale. This information can then provide the empirical basis for choosing the scale for mapping patches, rather than relying on subjective and somewhat arbitrary criteria. Despite the complimentary nature of surface pattern and categorical map pattern techniques, few studies have adopted this approach.

The format (raster versus vector) and scale (grain and extent) of the data can have a profound influence on the value of many metrics. Because vector and raster formats represent lines differently, metrics involving edge or perimeter will be affected by the choice of formats. Edge lengths will be biased upward in raster data because of the stair-step outline, and the magnitude of this bias will vary in relation to the grain or resolution of the image. In addition, the grain-size of raster format data can have a profound influence on the value of certain metrics. Metrics involving edge or perimeter will be affected; edge lengths will be biased upwards in proportion to the grain size—larger grains result in greater bias. Metrics based on cell adjacency information such as the contagion index of Li and Reynolds (1993) will be affected as well, because grain size effects the proportional distribution of adjacencies. In this case, as resolution is increased (grain size reduced), the proportional abundance of like adjacencies (cells of the same class) increases and the measured contagion increases.

Finally, the boundary of the landscape can have a profound influence on the value of certain metrics. Landscape metrics are computed solely from patches contained within the landscape boundary. If the landscape extent is small relative to the scale of the organism or ecological process under consideration and the landscape is an “open” system relative to that organism or process, then any metric will have questionable meaning. Metrics based on nearest neighbor distance or employing a search radius can be particularly misleading since they do not take into account potential neighbors just outside the landscape boundary. In addition, those metrics that employ a search radius (e.g., proximity index) will be biased for patches near the landscape boundary because the searchable area will be much less than a patch in the interior of the landscape. In general, boundary effects will increase as the landscape extent decreases relative to the patchiness or heterogeneity of the landscape.
7.2. Gaining a theoretical and empirical understanding metric behavior

In addition to these technical issues, current use of landscape metrics is constrained by the lack of a proper theoretical and empirical understanding of metric behavior. The proper interpretation of a landscape metric is contingent upon having an adequate understanding of how it responds to variation in landscape patterns (e.g., Gustafson and Parker 1992, Hargis et al. 1998, Jaeger 2000, Neel et al. 2004). Failure to understand the theoretical behaviour of the metric can lead to erroneous interpretations (e.g., Jaeger 2000). Neutral models (Gardner et al. 1987, Gardner and O’Neill 1991, With 1997) provide an excellent way to examine metric behaviour under controlled conditions because they control the process generating the pattern, allowing unconfounded links between variation in pattern and the behaviour of the index (Gustafson 1998). Unfortunately, existing neutral models are extremely limited in the types of patterns that can be generated, so developing a better theoretical understanding of metric behaviour through the use of neutral models is somewhat limited at this time.
7.3. Metric redundancy: In search of parsimony

Although the literature is replete with metrics now available to describe landscape pattern, there are still only two major components – composition and configuration, and only a few aspects of each of these. Metrics often measure multiple aspects of this pattern. Thus, there is seldom a one-to-one relationship between metric values and pattern. Most of the metrics are in fact correlated among themselves (i.e., they measure a similar or identical aspect of landscape pattern) because there are only a few primary measurements that can be made from patches (patch type, area, edge, and neighbor type), and most metrics are then derived from these primary measures. Some metrics are inherently redundant because they are alternate ways of representing the same basic information (e.g., mean patch size and patch density). In other cases, metrics may be empirically redundant; not because they measure the same aspect of landscape pattern, but because for the particular landscapes under investigation, different aspects of landscape pattern are correlated.
Several investigators have attempted to identify the major components of landscape pattern for the purpose of identifying a parsimonious suite of independent metrics (e.g., Li and Reynolds 1995, McGarigal and McComb 1995, Ritters et al. 1995, Cain et al. 1997, Scanes and Bunce 1997, Tinker et al. 1998, Griffith et al. 2000, Lausch and Herzog 2002, Cifaldi et al. 2000, Schindler et al. 2007). Although these studies suggest that patterns can be characterized by only a handful of components, consensus does not exist on the choice of individual metrics. These studies were constrained by the pool of metrics existing at the time of the investigation. Given the expanding development of metrics, particularly functional metrics, it seems unlikely that a single universal set exists. Ultimately, the choice of metrics should reflect some hypothesis about the observed landscape pattern and what processes or constraints might be responsible for that pattern.
The interpretation of landscape metrics is further plagued by the lack of a proper spatial and temporal reference framework. Landscape metrics quantify the pattern of a landscape at a snapshot in time. Yet it is often difficult, if not impossible, to determine the ecological significance of the computed value without understanding the range of natural variation in landscape pattern. For example, in disturbance-dominated landscapes, patterns may fluctuate widely over time in response to the interplay between disturbance and succession processes (e.g., Wallin et al. 1996, He and Mladenoff 1999, Haydon et al. 2000, Wimberly et al. 2000). It is logical, therefore, that landscape metrics should exhibit statistical distributions that reflect the natural spatial and temporal dynamics of the landscape. By comparison to this distribution, a more meaningful interpretation can be assigned to any computed value. Unfortunately, despite widespread recognition that landscapes are dynamic, there is a dearth of empirical work quantifying the range of natural variation in landscape pattern metrics. This remains one of the greatest challenges confronting landscape pattern analysis.
In summary, the importance of fully understanding each landscape metric before it is selected for interpretation cannot be stressed enough. Specifically, these questions should be asked of each metric before it is selected for interpretation:

- Does it represent landscape composition or configuration, or both?
- What aspect of composition or configuration does it represent?
- Is it spatially explicit, and, if so, at the patch-, class-, or landscape-level?
- How is it affected by the designation of a matrix element?
- Does it reflect an island biogeographic or landscape mosaic perspective of landscape pattern?
- How does it behave or respond to variation in landscape pattern under controlled conditions?
- What is the range of variation in the metric under an appropriate spatio-temporal reference framework?
- Does it represent landscape structure in a manner relevant to the phenomenon under consideration?

Based on the answers to these questions, does the metric represent landscape pattern in a manner and at a scale ecologically meaningful to the phenomenon under consideration? Only after answering these questions should one attempt to draw conclusions about the pattern of the landscape.