FRAGSTATS HELP

21 April 2015

Kevin McGarigal,
Sole proprietor, LandEco Consulting
Professor, Department of Environmental Conservation
University of Massachusetts, Amherst
mcgarigalk@eco.umass.edu

Table of Contents

WHAT'S NEW IN VERSION 4

The major changes in version 4 are as follows:

1. Version 4 is a major internal architectural revision to accommodate several new features, including a wide variety of sampling methods to facilitate analyzing sub-landscapes (v4.2), cell metrics (v4.3), and continuous surface metrics (i.e., landscape gradient model)(v4.4).

2. The graphical user interface is entirely new and is described in detail in the user guidelines, but has the same functionality as version 3.

3. The ancillary tables used to specify the class properties (i.e., class descriptors, which specify a character description for each numeric class value, whether to output the statistics for each class, and whether to treat each class as background) and parameterize the functional metrics associated with core area metrics, contrast metrics, and similarity index have a new table structure (see user guidelines).

4. The batch file table used to import a batch file (i.e., multiple input landscapes) has a new argument for the Nodata cell value, and thus the syntax has changed, starting with v4.2.

5. Supported image formats beginning with version 4.1 include: (1) ASCII grid, (2-4) 8-, 16- and 32-bit integer grids, (5) ESRI grid (or raster), (6) GeoTIFF grid, (7) VTP binary terrain format grid, (8) ESRI header labelled grid, (9) ERDAS Imagine grid, (10) PCRaster grid, and (11) SAGA GIS binary format grid. Support for the latter six image formats is via the GDAL library.ASCII grid, 8-, 16- and 32-bit integer grids, ESRI grid (or raster), GeoTIFF grid, VTP binary terrain format grid, ESRI header labelled grid, ERDAS Imagine grid, PCRaster grid, and SAGA GIS binary format grid. Support for the latter six image formats is via the GDAL library.

6. The model file (i.e., full parameterization of FRAGSTATS) is saved with the filename extension .fca instead of .frg. The .fca stands for "fragstats categorical model" and reflects the forthcoming extensions in version 4.4 and higher to accommodate landscape gradients or continuous surface patterns which will have a different model structure and be saved with a different extension (.fco).

7. You can no longer input a unique patch ID grid. We realized too many conflicts with the user-provided patch ID file not being consistent with the user-specified model; e.g., input patches defined using a 4-neighbor rule but the model parameterized using an 8-neighbor rule. For the time being, we removed the option of inputting a patch ID file, but maintained the option of outputting a patch ID file.

BACKGROUND

Introduction

Landscape ecology, if not ecology in general, is largely founded on the notion that environmental patterns strongly influence ecological processes (Turner 1989). 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 health (With 2000). For these and other reasons, much emphasis has been placed on developing methods to quantify landscape patterns, which is considered a 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 literally hundreds of indices of landscape patterns. This progress has been facilitated by recent advances in computer processing and geographic information (GIS) technologies. 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."

What Is a Landscape?

Landscape ecology by definition deals with the ecology of landscapes. Surprisingly, there are many different interpretations of the term "landscape." The disparity in definitions makes it difficult to communicate clearly, and even more difficult to establish consistent management policies. Definitions of landscape invariably include an area of land containing a mosaic of patches or landscape elements (see below). Forman and Godron (1986) defined landscape as a heterogeneous land area composed of a cluster of interacting ecosystems that is repeated in similar form throughout. The concept differs from the traditional ecosystem concept in focusing on groups of ecosystems and the interactions among them. There are many variants of the definition depending on the research or management context.

For example, from a wildlife perspective, we might define landscape as an area of land containing a mosaic of *habitat* patches, often within which a particular "focal" or "target" habitat patch is embedded (Dunning et al. 1992). Because habitat patches can only be defined relative to a particular organism's perception and scaling of the environment (Wiens 1976), landscape size would differ among organisms. However, landscapes generally occupy some spatial scale intermediate between an organism's normal home range and its regional distribution. In-other-words, because each organism scales the environment differently (i.e., a salamander and a hawk view their environment on different scales), there is no absolute size for a landscape; from an organism-centered perspective, the size of a landscape varies depending on what constitutes a mosaic of habitat or resource patches meaningful to that particular organism.

This definition most likely contrasts with the more anthropocentric definition that a landscape corresponds to an area of land equal to or larger than, say, a large basin (e.g., several thousand hectares). Indeed, Forman and Godron (1986) suggested a lower limit for landscapes at a "few kilometers in diameter", although they recognized that most of the principles of landscape ecology apply to ecological mosaics at any level of scale. While this may be a more pragmatic definition than the organism-centered definition and perhaps corresponds to our human perception of the environment, it has limited utility in managing wildlife populations if you accept the fact that each organism scales the environment differently. From an organism-centered perspective, a landscape could range in absolute scale from an area smaller than a single forest stand (e.g., a individual log) to an entire ecoregion. If you accept this organism-centered definition of a landscape, a logical consequence of this is a mandate to manage habitats across the full range of spatial scales; each scale, whether it be the stand or watershed, or some other scale, will likely be important for a subset of species, and each species will likely respond to more than one scale.

Key Point *It is not our intent to argue for a single definition of landscape. Rather, we wish to point out that there are many appropriate ways to define landscape depending on the phenomenon under consideration. The important point is that a landscape is not necessarily defined by its size; rather, it is defined by an interacting mosaic of patches relevant to the phenomenon under consideration (at any scale). It is incumbent upon the investigator or manager to define landscape in an appropriate manner. The essential first step in any landscape-level research or management endeavor is to define the landscape, and this is of course prerequisite to quantifying landscape patterns.*

Classes of Landscape Pattern

Real landscapes contain complex spatial patterns in the distribution of resources that vary over time; quantifying these patterns and their dynamics is the purview of landscape pattern analysis. Landscape patterns can be quantified in a variety of ways depending on the type of data collected, the manner in which it is collected, and the objectives of the investigation. Broadly considered, landscape pattern analysis involves four basic types of spatial data corresponding to different representations of spatial heterogeneity (or models of landscape structure), although in practice these fundamental conceptual models of landscape structure are sometimes combined in various ways. These basic classes of landscape pattern look rather different numerically, but they share a concern with the characterization of spatial heterogeneity:

(1) *Spatial point patterns* – Spatial point patterns represent collections of entities where the geographic locations of the entities are of primary interest, rather than any quantitative or qualitative attribute of the entity itself. A familiar example is a map of all trees in a forest stand, wherein the data consists of a list of trees referenced by their geographic locations. Typically, the points would be labeled by species, and perhaps further specified by their sizes (a marked point pattern). The goal of point pattern analysis with such data is to determine whether the points are more or less clustered than expected by chance and/or to find the spatial scale(s) at which the points tend to be more or less clustered than expected by chance, and a variety of methods have been developed for this purpose (Greig-Smith 1983, Dale 1999).

(2) *Linear network patterns* – Linear network patterns represent collections of linear landscape elements that intersect to form a network. A familiar example is a map of shelterbelts in an

agricultural landscape, wherein the data consists of nodes (intersections of the linear features) and segments (linear features that connect nodes); the intervening area is considered the matrix and is typically ignored (i.e., treated as ecologically neutral). Often, the nodes and segments are further characterized by composition (e.g., vegetation type) and spatial character (e.g., width). As with point patterns, it is the geographic location and arrangement of nodes and segments that is of primary interest. The goal of linear network pattern analysis with such data is to characterize the physical structure (e.g., network density, mesh size, network connectivity and circuitry) of the network, and a variety of metrics have been developed for this purpose (Forman 1995).

(3) *Surface patterns* – Surface patterns represent quantitative measurements that vary continuously across the landscape (i.e., there are no explicit boundaries between patches). Hence, this type of spatial pattern is also referred to as a "landscape gradient". Here, the data can be conceptualized as representing a three-dimensional surface, where the measured value at each geographic location is represented by the height of the surface. A familiar example is a digital elevation model, but any quantitative measurement can be treated this way (e.g., plant biomass, leaf area index, soil nitrogen, density of individuals). Analysis of the spatial dependencies (or autocorrelation) in the measured characteristic is the purview of geostatistics, and a variety of techniques exist for measuring the intensity and scale of this spatial autocorrelation (Legendre and Fortin 1989, Legendre and Legendre 1999). Techniques also exist that permit the kriging or modeling of these spatial patterns; that is, to interpolate values for unsampled locations using the empirically estimated spatial autocorrelation (Bailey and Gatrell 1995). These geostatistical techniques were developed to quantify spatial patterns from sampled data (n). When the data is exhaustive (i.e., the whole population, N) over the study landscape, like it is with the case of remotely sensed data, other techniques (e.g., quadrat variance analysis, Dale 1999; spectral analysis, Ford and Renshaw 1984, Renshaw and Ford 1984, Legendre and Fortin 1989; wavelet analysis, Bradshaw and Spies 1992, Dale and Mah 1998; or lacunarity analysis, Plotnick et al. 1993 and 1996, Dale 2000) are more appropriate. All of these geostatistical techniques share a goal of describing the intensity and scale of pattern in the quantitative variable of interest. In all cases, while the location of the data points (or quadrats) is known and of interest, it is the values of the measurement taken at each point that are of primary concern. Here, the basic question is, "Are samples that are close together also similar with respect to the measured variable?" Alternatively, "What is the distance(s) over which values tend to be similar?", and "What is the dominant scale(s) of variability in the measured variable?"

While the geostatistical properties of surface patterns has been the focus of nearly all surface pattern analysis in landscape ecology, recently it was revealed that surface metrology (derived from the field of structural and molecular physics) offers a variety of surface metrics for quantifying landscape gradients akin to the more familiar patch metrics described below for categorical maps (McGarigal and Cushman 2005). Like their analogous patch metrics, surface metrics describe both the nonspatial and spatial character of the surface as a whole, including the variability in the overall height distribution of the surface (nonspatial) and the arrangement, location or distribution of surface peaks and valleys (spatial). Here, the goal of the analysis is to describe the spatial structure of the entire surface in a single metric, and a variety of surface metrics have been developed for this purpose (McGarigal et al. 2009).

(4) *Categorical (or thematic; choropleth) map patterns* – Categorical map patterns represent data in which the system property of interest is represented as a mosaic of discrete patches. Hence, this type of

spatial pattern is also referred to as a "patch mosaic". From an ecological perspective, patches represent relatively discrete areas of relatively homogeneous environmental conditions at a particular scale. The patch boundaries are distinguished by abrupt discontinuities (boundaries) in environmental character states from their surroundings of magnitudes that are relevant to the ecological phenomenon under consideration (Wiens 1976, Kotliar and Wiens 1990). A familiar example is a map of land cover types, wherein the data consists of polygons (vector format) or grid cells (raster format) classified into discrete land cover classes. There are a multitude of methods for deriving a categorical map (patch mosaic) which has important implications for the interpretation of landscape pattern metrics (see below). Patches may be classified and delineated qualitatively through visual interpretation of the data (e.g., delineating vegetation polygons through interpretation of aerial photographs), as is typically the case with vector maps constructed from digitized lines. Alternatively, with raster grids (constructed of grid cells), quantitative information at each location may be used to classify cells into discrete classes and to delineate patches by outlining them, and there are a variety of methods for doing this. The most common and straightforward method is simply to aggregate all adjacent (touching) areas that have the same (or similar) value on the variable of interest. An alternative approach is to define patches by outlining them: that is, by finding the edges around patches (Fortin 1994, Fortin and Drapeau 1995, Fortin et al. 2000). An edge in this case is an area where the measured value changes abruptly (i.e., high local variance or rate of change). An alternative is to use a divisive approach, beginning with a single patch (the entire landscape) and then successively partitioning this into regions that are statistically homogeneous patches (Pielou 1984). A final method to create patches is to cluster them hierarchically, but with a constraint of spatial adjacency (Legendre and Fortin 1989).

Regardless of data format (raster or vector) and method of classifying and delineating patches, the goal of categorical map pattern analysis with such data is to characterize the composition and spatial configuration of the patch mosaic, and a plethora of metrics has been developed for this purpose (Forman and Godron 1986, O'Neill et al. 1988, Turner 1990, Musick and Grover 1991, Turner and Gardner 1991, Baker and Cai 1992, Gustafson and Parker 1992, Li and Reynolds 1993, McGarigal and Marks 1995, Jaeger 2000, McGarigal et al. 2002). While these patch metrics are quite familiar to landscape ecologists, scaling techniques for categorical map data are less commonly employed in landscape ecology. This is because in applications involving categorical map patterns, the relevant scale of the mosaic is often defined a priori based on the phenomenon under consideration. In such cases, it is usually assumed that it would be meaningless to determine the so-called characteristic scale of the mosaic after its construction. However, there are many situations when the categorical map is created through a purely objective classification procedure and the scaling properties of the patch mosaic is of great interest. Lacunarity analysis is one technique borrowed from fractal geometry by which class-specific aggregation can be characterized across a range of scales to examine the scale(s) of clumpiness (Plotnick et al. 1993 and 1996, Dale 2000).

Key Point *There are several major classes of landscape patterns that fall within the purview of landscape pattern analysis. These classes of pattern are not intrinsic to the landscape under consideration, but rather reflect a human construct pertaining to the spatial heterogeneity of interest to the investigator or manager. It is incumbent upon the investigator or manager to choose the appropriate class of pattern for the question under consideration. FRAGSTATS currently deals with categorical map patterns (v4.2 and earlier) and surface patterns (scheduled for v4.4).*

Patch-Corridor-Matrix Model

Landscapes are composed of elements – the spatial components that make up the landscape. A convenient and popular model for conceptualizing and representing the elements in a categorical map pattern (or patch mosaic) is known as the *patch-corridor-matrix model* (Forman 1995). Under this model, three major landscape elements are typically recognized, and the extent and configuration of these elements defines the pattern of the landscape.

(1) *Patch* – Landscapes are composed of a mosaic of patches (Urban et al. 1987). Landscape ecologists have used a variety of terms to refer to the basic elements or units that make up a landscape, including ecotope, biotope, landscape component, landscape element, landscape unit, landscape cell, geotope, facies, habitat, and site (Forman and Godron 1986). Any of these terms, when defined, are satisfactory according to the preference of the investigator. Like the landscape, patches comprising the landscape are not self-evident; patches must be defined relative to the phenomenon under consideration. For example, from a timber management perspective a patch may correspond to the forest stand. However, the stand may not function as a patch from a particular organism's perspective. From an ecological perspective, patches represent relatively discrete areas (spatial domain) or periods (temporal domain) of relatively homogeneous environmental conditions where the patch boundaries are distinguished by discontinuities in environmental character states from their surroundings of magnitudes that are perceived by or relevant to the organism or ecological phenomenon under consideration (Wiens 1976). From a strictly organism-centered view, patches may be defined as environmental units between which fitness prospects, or "quality", differ; although, in practice, patches may be more appropriately defined by nonrandom distribution of activity or resource utilization among environmental units, as recognized in the concept of "Grain Response".

Patches are dynamic and occur on a variety of spatial and temporal scales that, from an organism-centered perspective, vary as a function of each animal's perceptions (Wiens 1976 and 1989, Wiens and Milne 1989). 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. For example, from an organism-centered perspective, the smallest scale at which an organism perceives and responds to patch structure is its "grain" (Kotliar and Wiens 1990). This lower threshold of heterogeneity is the level of resolution at which the patch size becomes so fine that the individual or species stops responding to it, even though patch structure may actually exist at a finer resolution (Kolasa and Rollo 1991). The lower limit to grain is set by the physiological and perceptual abilities of the organism and therefore varies among species. Similarly, "extent" is the coarsest scale of heterogeneity, or upper threshold of heterogeneity, to which an organism responds (Kotliar and Wiens 1990, Kolasa and Rollo 1991). At the level of the individual, extent is determined by the lifetime home range of the individual (Kotliar and Wiens 1990) and varies among individuals and species. More generally, however, extent varies with the organizational level (e.g., individual, population, metapopulation) under consideration; for example the upper threshold of patchiness for the population would probably greatly exceed that of the individual. Therefore, from an organism-centered perspective, patches can be defined hierarchically in scales ranging between the grain and extent for the individual, deme, population, or range of each species.

Patch boundaries are artificially imposed and are in fact meaningful only when referenced to a particular scale (i.e., grain size and extent). For example, even a relatively discrete patch boundary between an aquatic surface (e.g., lake) and terrestrial surface becomes more and more like a continuous gradient as one progresses to a finer and finer resolution. However, most environmental dimensions possess one or more "domains of scale" (Wiens 1989) at which the individual spatial or temporal patches can be treated as functionally homogeneous; at intermediate scales the environmental dimensions appear more as gradients of continuous variation in character states. Thus, as one moves from a finer resolution to coarser resolution, patches may be distinct at some scales (i.e., domains of scale) but not at others.

Key Point *It is not my intent to argue for a particular definition of patch. Rather, I wish to point out the following: (1) that patch must be defined relative to the phenomenon under investigation or management; (2) that, regardless of the phenomenon under consideration (e.g., a species, geomorphological disturbances, etc), patches are dynamic and occur at multiple scales; and (3) that patch boundaries are only meaningful when referenced to a particular scale. It is incumbent upon the investigator or manager to establish the basis for delineating among patches and at a scale appropriate to the phenomenon under consideration.*

(2) *Corridor* – Corridors are linear landscape elements that can be defined on the basis of structure or function. Forman and Godron (1986) define corridors as "narrow strips of land which differ from the matrix on either side. Corridors may be isolated strips, but are usually attached to a patch of somewhat similar vegetation." These authors focus on the structural aspects of the linear landscape element. As a consequence of their form and context, structural corridors may function as habitat, dispersal conduits, or barriers. Three different types of structural corridors exist: (1) *line corridors*, in which the width of the corridor is too narrow to allow for interior environmental conditions to develop; (2) *strip corridors*, in which the width of the corridor is wide enough to allow for interior conditions to develop; and (3) *stream corridors*, which are a special category.

Corridors may also be defined on the basis of their function in the landscape. At least four major corridor functions have been recognized, as follows:

1. Habitat Corridor – Linear landscape element that provides for survivorship, natality, and movement (i.e., habitat), and may provide either temporary or permanent habitat. Habitat corridors passively increase landscape connectivity for the focal organism(s).

2. Facilitated Movement Corridor – Linear landscape element that provides for survivorship and movement, but not necessarily natality, between other habitat patches. Facilitated movement corridors actively increase landscape connectivity for the focal organism(s).

3. Barrier or Filter Corridor – Linear landscape element that prohibits (i.e., barrier) or differentially impedes (i.e., filter) the flow of energy, mineral nutrients, and/or species across (i.e., flows perpendicular to the length of the corridor). Barrier or filter corridors actively decrease matrix connectivity for the focal process.

4. Source of Abiotic and Biotic Effects on the Surrounding Matrix – Linear landscape element that modifies the inputs of energy, mineral nutrients, and/or species to the surrounding matrix and thereby effects the functioning of the surrounding matrix.

Most of the attention and debate has focused on *facilitated movement corridors*. It has been argued that this corridor function can only be demonstrated when the immigration rate to the target patch is increased over what it would be if the linear element was not present (Rosenberg et al. 1997). Unfortunately, as Rosenberg et al. point out, there have been few attempts to experimentally demonstrate this. In addition, just because a corridor can be distinguished on the basis of structure, it does not mean that it assumes any of the above functions. Moreover, the function of the corridor will vary among organisms due to the differences in how organisms perceive and scale the environment.

Key Point *Corridors are distinguished from patches by their linear nature and can be defined on the basis of either structure or function or both. If a corridor is specified, it is incumbent upon the investigator or manager to define the structure and implied function relative to the phenomena (e.g., species) under consideration.*

(3) *Matrix* – A landscape is composed typically of several types of landscape elements (usually patches). Of these, the matrix is the most extensive and most connected landscape element type, and therefore plays the dominant role in the functioning of the landscape (Forman and Godron 1986). For example, in a large contiguous area of mature forest embedded with numerous small disturbance patches (e.g., timber harvest patches), the mature forest constitutes the matrix element type because it is greatest in areal extent, is mostly connected, and exerts a dominant influence on the area flora and fauna and ecological processes. In most landscapes, the matrix type is obvious to the investigator or manager. However, in some landscapes, or at a certain point in time during the trajectory of a landscape, the matrix element will not be obvious. Indeed, it may not be appropriate to consider any element as the matrix. Moreover, the designation of a matrix element is largely dependent upon the phenomenon under consideration. For example, in the study of geomorphological processes, the geological substrate may serve to define the matrix and patches; whereas, in the study of vertebrate populations, vegetation structure may serve to define the matrix and patches. In addition, what constitutes the matrix is dependent on the scale of investigation or management. For example, at a particular scale, mature forest may be the matrix with disturbance patches embedded within; whereas, at a coarser scale, agricultural land may be the matrix with mature forest patches embedded within.

It is important to understand how measures of landscape pattern are influenced by the designation of a matrix element. If an element is designated as matrix and therefore presumed to function as such (i.e., has a dominant influence on landscape dynamics), then it should not be included as another "patch" type in any metric that simply averages some characteristic across all patches (e.g., mean patch size, mean patch shape). Otherwise, the matrix will dominate the metric and serve more to characterize the matrix than the patches within the landscape, although this may itself be meaningful in some applications. From a practical standpoint, it is important to recognize this because in FRAGSTATS, the matrix can be excluded from calculations by designating its class value as background. If the matrix is not excluded from the calculations, it may be more meaningful to use the class-level statistics for each patch type and simply ignore the patch type designated as the matrix. From a conceptual standpoint, it is important to recognize that the choice and interpretation of landscape metrics must ultimately be evaluated in terms of their ecological meaningfulness, which is dependent upon how the landscape is defined, including the choice of patch types and the designation of a matrix.

Key Point *It is incumbent upon the investigator or manager to determine whether a matrix element exists and should be designated given the scale and phenomenon under consideration.*

The Importance of Scale

The pattern detected in any ecological mosaic is a function of scale, and the ecological concept of spatial scale encompasses both extent and grain (Forman and Godron 1986, Turner et al. 1989, Wiens 1989). *Extent* is the overall area encompassed by an investigation or the area included within the landscape boundary. From a statistical perspective, the spatial extent of an investigation is the area defining the population we wish to sample. *Grain* is the size of the individual units of observation. For example, a fine-grained map might structure information into 1-ha units, whereas a map with an order of magnitude coarser resolution would have information structured into 10-ha units (Turner et al. 1989). Extent and grain define the upper and lower limits of resolution of a study and any inferences about scale-dependency in a system are constrained by the extent and grain of investigation (Wiens 1989). From a statistical perspective, we cannot extrapolate beyond the population sampled, nor can we infer differences among objects smaller than the experimental units. Likewise, in the assessment of landscape pattern, we cannot detect pattern beyond the extent of the landscape or below the resolution of the grain (Wiens 1989).

As with the concept of landscape and patch, it may be more ecologically meaningful to define scale from the perspective of the organism or ecological phenomenon under consideration. For example, from an organism-centered perspective, grain and extent may be defined as the degree of acuity of a stationary organism with respect to short- and long-range perceptual ability (Kolasa and Rollo 1991). Thus, grain is the finest component of the environment that can be differentiated up close by the organism, and extent is the range at which a relevant object can be distinguished from a fixed vantage point by the organism (Kolasa and Rollo 1991). Unfortunately, while this is ecologically an ideal way to define scale, it is not very pragmatic. Indeed, in practice, extent and grain are often dictated by the scale of the imagery (e.g., aerial photo scale) being used or the technical capabilities of the computing environment.

It is critical that extent and grain be defined for a particular study and represent, to the greatest possible degree, the ecological phenomenon or organism under study, otherwise the landscape patterns detected will have little meaning and there is a good chance of reaching erroneous conclusions. For example, it would be meaningless to define grain as 1-ha units if the organism under consideration perceives and responds to habitat patches at a resolution of 1-m^2. A strong landscape pattern at the 1-ha resolution may have no significance to the organism under study. Likewise, it would be unnecessary to define grain as 1-m^2 units if the organism under consideration perceives habitat patches at a resolution of 1-ha. Typically, however, we do not know what the appropriate resolution should be. In this case, it is much safer to choose a finer grain than is believed to be important Remember, the grain sets the minimum resolution of investigation. Once set, we can always dissolve to a coarser grain. In addition, we can always specify a minimum mapping unit that is coarser than the grain. That is, we can specify the minimum patch size to be represented in a landscape, and this can easily be manipulated above the resolution of the data. It is important to note that the technical capabilities of GIS with respect to image resolution may far exceed the technical capabilities of the remote sensing equipment. Thus, it is possible to generate GIS images at too fine a resolution for the spatial data being represented, resulting in a more complex representation of the landscape than can truly be obtained from the data.

Information may be available at a variety of scales and it may be necessary to extrapolate information from one scale to another. In addition, it may be necessary to integrate data represented at different spatial scales. It has been suggested that information can be transferred across scales if both grain and extent are specified (Allen et al. 1987), yet it is unclear how observed landscape patterns vary in response to changes in grain and extent and whether landscape metrics obtained at different scales can be compared. The limited work on this topic suggests that landscape metrics vary in their sensitivity to changes in scale and that qualitative and quantitative changes in measurements across spatial scales will differ depending on how scale is defined (Turner et al. 1989). Therefore, in investigations of landscape pattern, until more is learned, it is critical that any attempts to compare landscapes measured at different scales be done cautiously.

Key Point *One of the most important considerations in any landscape ecological investigation or landscape structural analysis is (1) to explicitly define the scale of the investigation or analysis, (2) to describe any observed patterns or relationships relative to the scale of the investigation, and (3) to be especially cautious when attempting to compare landscapes measured at different scales.*

Landscape Context

Landscapes do not exist in isolation. Landscapes are nested within larger landscapes, that are nested within larger landscapes, and so on. In other words, each landscape has a context or regional setting, regardless of scale and how the landscape is defined. The landscape context may constrain processes operating within the landscape. Landscapes are "open" systems; energy, materials, and organisms move into and out of the landscape. This is especially true in practice, where landscapes are often somewhat arbitrarily delineated. That broad-scale processes act to constrain or influence finer-scale phenomena is one of the key principles of hierarchy theory (Allen and Star 1982) and 'supply-side' ecology (Roughgarden et al. 1987). The importance of the landscape context is dependent on the phenomenon of interest, but typically varies as a function of the "openness" of the landscape. The "openness" of the landscape depends not only on the phenomenon under consideration, but on the basis used for delineating the landscape boundary. For example, from a geomorphological or hydrological perspective, the watershed forms a natural landscape, and a landscape defined in this manner might be considered relatively "closed". Of course, energy and materials flow out of this landscape and the landscape context influences the input of energy and materials by affecting climate and so forth, but the system is nevertheless relatively closed. Conversely, from the perspective of a bird population, topographic boundaries may have little ecological relevance, and the landscape defined on the basis of watershed boundaries might be considered a relatively "open" system. Local bird abundance patterns may be produced not only by local processes or events operating within the designated landscape, but also by the dynamics of regional populations or events elsewhere in the species' range (Wiens 1981, 1989b, Vaisanen et al. 1986, Haila et al. 1987, Ricklefs 1987).

Landscape metrics quantify the pattern of the landscape within the designated landscape boundary only. Consequently, the interpretation of these metrics and their ecological significance requires an acute awareness of the landscape context and the openness of the landscape relative to the phenomenon under consideration. These concerns are particularly important for nearest-neighbor metrics. For example, nearest-neighbor distances 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 processes under consideration and the landscape is an "open" system relative to that organism or process, then nearest-neighbor results can be misleading. Consider a small subpopulation of a species occupying a patch near the boundary of a somewhat arbitrarily defined (from the organism's perspective) landscape. The nearest neighbor within the landscape boundary might be quite far away, yet in reality the closest patch might be very close, but just outside the landscape boundary. The magnitude of this problem is a function of scale. Increasing the size of the landscape relative to the scale at which the organism under investigation perceives and responds to the environment will generally decrease the severity of this problem. In general, the larger the ratio of extent to grain (i.e., the larger the landscape relative to the average patch size), the less likely these and other metrics will be dominated by boundary effects.

Key Point *The important point is that a landscape should be defined relative to both the spatial pattern within the landscape as well as the landscape context. Moreover, consideration should always be given to the landscape context and the openness of the landscape relative to the phenomenon under consideration when choosing and interpreting landscape metrics.*

Perspectives on Categorical Map Patterns

There are at least two different perspectives on categorical map patterns (or patch mosaics) that have profoundly influenced the development of landscape metrics and have important implications for the choice and interpretation of individual landscape metrics.

(1) *Island Biogeographic Model* – In the island biogeographic model, the emphasis is on a single patch type; disjunct patches (e.g., habitat fragments) are viewed as analogues of oceanic islands embedded in an inhospitable or ecologically neutral background (matrix). This perspective emerged from the theory of island biogeography (MacArthur and Wilson 1967) and subsequent interest in habitat fragmentation (Saunders et al. 1991). Under this perspective, there is a binary patch structure in which the focal patches (fragments) are embedded in a neutral matrix. Here, the emphasis is on the extent, spatial character, and distribution of the focal patch type without explicitly considering the role of the matrix. Under this perspective, for example, connectivity may be assessed by the spatial aggregation of the focal patch type without consideration of how intervening patches affect the functional connectedness among patches of the focal class. The island biogeography perspective has been the dominant perspective since inception of the theory. The major advantage of the island model is its simplicity. Given a focal patch type, it is quite simple to represent the structure of the landscape in terms of focal patches contrasted sharply against a uniform matrix, and it is relatively simple to devise metrics that quantify this structure. Moreover, by considering the matrix as ecologically neutral, it invites ecologists to focus on those patch attributes, such as size and isolation, that have the strongest effect on species persistence at the patch level. The major disadvantage of the strict island model is that it assumes a uniform and neutral matrix, which in most real-world cases is a drastic over-simplification of how organisms interact with landscape patterns.

(2) *Landscape Mosaic Model* – In the landscape mosaic model, landscapes are viewed as spatially complex, heterogeneous assemblages of patch types, which can not be simply categorized into discrete elements such as patches, matrix, and corridors (With 2000). Rather, the landscape is viewed

from the perspective of the organism or process of interest. Patches are bounded by patches of other patch types that may be more or less similar to the focal patch type, as opposed to highly contrasting and often hostile habitats, as in the case of the island model. Connectivity, for example, may be assessed by the extent to which movement is facilitated or impeded through different patch types across the landscape. The landscape mosaic perspective derives from landscape ecology itself (Forman 1995) and has emerged as a viable alternative to the island biogeographic model. The major advantage of the landscape mosaic model is its more realistic representation of how organisms perceive and interact with landscape patterns. Few organisms, for example, exhibit a binary (all or none) response to habitats (patch types), but rather use habitats proportionate to the fitness they confer to the organism. Moreover, movement among suitable habitat patches usually is a function of the character of the intervening habitats, which usually vary in the resistance they offer to movement. The major disadvantage of the landscape mosaic model is that it requires detailed understanding of how organisms interact with landscape pattern, and this has complicated the development of additional metrics that adopt this perspective.

Key Point *There are two major perspectives, or "models", of categorical map patterns, or patch mosaics: 1) the island biogeographic model, and 2) the landscape mosaic model. Both models fall within the purview of categorical map patterns and neither are intrinsic to the landscape under consideration, but rather reflect a human construct pertaining to the patch mosaic of interest to the investigator or manager. It is incumbent upon the investigator or manager to choose the appropriate patch mosaic model for the question under consideration and then choose landscape metrics that are relevant for this model.*

Scope of Analysis

The scope of analysis pertains to the scale and or focus of the investigation. There are three levels of analysis, at least for categorical map patterns (or patch mosaics), that represent fundamentally different perspectives on landscape pattern analysis 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 Neighborhood 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.

Key Point *There are three levels of analysis, at least for categorical map patterns (or patch mosaics), that represent fundamentally different perspectives on landscape pattern analysis and that have important implications for the choice and interpretation of individual landscape metrics and the form of the results: 1) focal patch analysis, 2) local neighborhood structure analysis, and 3) global landscape structure analysis. It is incumbent upon the investigator or manager to choose the appropriate scope of analysis for the question under consideration and then choose appropriate landscape metrics that reflect this scope of analysis.*

Levels of Heterogeneity

Patches form the basis (or building blocks) for categorical maps (or patch mosaics). 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, median, or max) value and internal heterogeneity (variance, range). However, in most applications, once patches have been established, the within-patch heterogeneity is ignored and the patches are assigned a nominal class value to represent the composition of the patch. Landscape pattern metrics focus on the spatial character and distribution of patches in the neighborhood of each cell or across the landscape as a whole. 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 (e.g., the neighborhood of each focal cell) or across the entire landscape. Consequently, landscape metrics can be defined at four levels corresponding to a logical hierarchical organization of spatial heterogeneity in patch mosaics.

(1) *Cell-level metrics* – Cell metrics provide the finest spatial unit of resolution for characterizing spatial patterns in categorical maps (when defined as a raster image). They are defined for individual grid cells, and characterize the spatial context (i.e., ecological neighborhood) of cells without explicit

regard to patch or class affiliation. In other words, cell metrics are not patch-centric, even though the ecological neighborhood (defined by the user) is characterized by the structure of the patch mosaic surrounding the cell. The result is a single value for each 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 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 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.

(4) *Landscape-level metrics* – Landscape 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 many metrics have counterparts at several levels, their interpretations may be somewhat different. *Cell metrics* represent the spatial context of local neighborhoods centered on each cell. *Patch metrics* represent the spatial character and context of individual patches. *Class metrics* represent the amount and spatial distribution of a single patch type and are interpreted as fragmentation indices. *Landscape metrics* represent the spatial pattern of the entire landscape mosaic and generally 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 (cell, patch, class, or landscape).

In addition, 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.

In addition, while many metrics have counterparts at all levels, their interpretations may be somewhat different. Cell-level metrics represent the spatial context of individual cells. 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 (cell, patch, class, or landscape).

Lastly, class and landscape metrics are typically computed for the entire extent of the landscape; i.e., they quantify the structure of the individual class or the entire mosaic over the full extent of the data. This is referred to as "global landscape structure", even though the focus may be on a single class within the landscape. However, both class and landscape metrics can also be computed for local windows (defined by the user) placed over each cell one at a time, via a moving window, where the value of the class or landscape metric in each window is returned to the focal cell. The result is new grid in which the cell value represents the "local neighborhood structure". This is very similar to the cell metrics described above, since both focus on the structure of a local neighborhood around a focal cell; the main difference is that cell metrics employ unique algorithms that are defined only at the cell level, whereas here the metrics are literally the same as the class and landscape metrics only they are applied to local windows around each focal cell.

Key Point *Landscape metrics for categorical map patterns can be defined at four levels corresponding to a logical hierarchical organization of spatial heterogeneity in patch mosaics: 1) cell-level metrics, 2) patch-level metrics, 3) class-level metrics, and 4) landscape-level metrics. Each level of the hierarchy reflects a different focus on spatial heterogeneity. It is incumbent upon the investigator or manager to choose the appropriate level of heterogeneity for the question under consideration and then choose appropriate landscape metrics that reflect this level of heterogeneity.*

Patch-based Metrics

The common usage of the term "landscape metrics" refers exclusively to numerical indices developed to quantify categorical map patterns (or patch mosaics). Under the patch mosaic perspective, landscape metrics are algorithms that quantify specific spatial characteristics of patches, classes of patches, or entire landscape mosaics, or the spatial context of individual cells within a patch mosaic, and a plethora of metrics have been developed for this purpose. An exhaustive review of all published metrics, therefore, is beyond the scope of this document. These metrics fall into two general categories: those that quantify the *composition* of the map without reference to spatial attributes, and those that quantify the *spatial configuration* of the map, requiring spatial information for their calculation (McGarigal and Marks 1995, Gustafson 1998).

(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. Because composition requires integration over all patch types, composition metrics are only applicable at the landscape-level. 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 (or dominance) measures corresponding to the many diversity measures. Evenness is usually reported as a function of the maximum diversity possible for a given richness. That is, 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) *Spatial configuration* – Spatial 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 area and edge* – 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.). Patch size is typically computed as the total area of the patch, regardless of its spatial character. However, patch size can also be characterized by its spatial extent; i.e., how far-reaching it is. This is known as the patch radius of gyration, which measures how far across the landscape a patch extends its reach on average, given by the mean distance between cells in a patch. The radius of gyration can be considered a measure of the average distance an organism can move within a patch before encountering the patch boundary from a random starting point. When summarized for the class or landscape as a whole using an area-weighted mean, this metric is also known as correlation length and gives the distance that one might expect to traverse the map while staying in a particular patch, from a random starting point and moving in a random direction (Keitt et al. 1997). The boundaries between patches (or edges) represent another fundamental spatial attribute of a patch mosaic. The length of edge can be summarized at the patch level as the perimeter of the patch, and at the class and landscape levels as the total length of edge involving the focal class or across the entire mosaic, respectively.

- *Patch shape complexity* – Shape complexity refers 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 or morphology. 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 measures emphasize particular aspects of patch shape, such as compaction/elongatedness (contiguity index, 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 refers the interior area of patches after a user-specified edge buffer is eliminated. The edge buffer represents the distance at which the "core" or interior of a patch is unaffected by the edge 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. Core 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 patch area (e.g., mean patch size and variability) can be formulated in terms of core area.

- *Contrast* – Contrast refers to the relative difference among patch types. For example, mature forest next to young 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. Note, contrast is an attribute of the edge itself, whereas core area is an attribute of the patch interior after accounting for adverse edge effects that penetrate into patches (and thus have a corresponding depth-of-edge effect).

- *Aggregation* – Aggregation refers to the degree of aggregation or clumping of patch types. This property is also often referred to as landscape texture. Aggregation is an umbrella term used to describe several closely related concepts: 1) dispersion, 2) interspersion, 3) subdivision, and 4) isolation. Each of these concepts relates to the broader concept of aggregation, but is distinct from the others in subtle but important ways. Aggregation metrics deal variously with the spatial properties of dispersion and interspersion. *Dispersion* refers to the spatial distribution of a patch type (i.e., how spread out or disperse it is) without explicit reference to any other patch types. *Interspersion* refers to the spatial intermixing of different patch types without explicit reference to the dispersion of any patch type. In the real world, however, these properties are often correlated. Not surprisingly, therefore, some aggregation metrics deal with dispersion solely, others deal with interspersion solely, and others deal with both, and thus there are a bewildering variety of metrics in this group. Many of the metrics in this group are derived from the cell adjacency matrix, in which the adjacency of patch types is first summarized in an adjacency or co-occurrence matrix, which shows the frequency with which different pairs of patch types (including like adjacencies between the same patch type) appear side-by-side on the map.

- *Subdivision* – Subdivision refers to the degree to which the landscape 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. Note, subdivision and dispersion are closely related concepts. Both refer generally to the aggregation of the landscape, but subdivision deals explicitly with the degree to which the landscape is broken up into disjunct patches, whereas the concept and measurement of dispersion does not honor patches per se (since it is based on cell adjacencies). In the real world, these two aspects of landscape structure are often highly correlated. Subdivision can be measured quite simply by the number or density of patches. 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.

- *Isolation* – Isolation refers to the tendency for patches to be relatively isolated in space (i.e., distant) from other patches of the same or ecologically similar class. Isolation is closely related to the concept of subdivision; both refer to the subdivision per se of patch types, but isolation deals explicitly with the degree to which patches are spatially isolated from each other, whereas subdivision doesn't address the distance between patches, only that they are disjunct. 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. Isolation can also 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, as in the similarity index (McGarigal et al. 2002). Importantly, in all of these measures of isolation, distance need not be defined as Euclidean (i.e., straight line) distance. Instead, the functional distance between patches might be based on some nonlinear function of Euclidean distance that reflects the probability of connection at a given distance, or a resistance-weighted distance function that reflects the cost distance between patches on a resistant (cost) surface.

Key Point *Patch-based metrics (i.e., for categorical map patterns or patch mosaics) fall into two general categories: 1) those that quantify the composition of the map without reference to spatial attributes, and 2) those that quantify the spatial configuration of the map, requiring spatial information for their calculation. Each category contains a variety of metrics for quantifying different aspects of pattern. It is incumbent upon the investigator or manager to choose the appropriate metrics for the question under consideration.*

Surface Metrics

While the term "landscape metrics", in practice, typically refers to numerical indices developed to quantify categorical map patterns (or patch mosaics), the term more generally refers to numerical indices that quantity any spatial heterogeneity (or landscape patterns), which includes not only categorical map patterns, but also surface patterns (or landscape gradients), linear networks and spatial point patterns. A wide variety of methods have been developed for quantifying the intensity and scale of pattern in regionalized quantitative variables; i.e., continuous variables that can be represented as a continuous surface (or landscape gradient). Surface metrics fall into two general categories: *autocorrelation structure functions* that quantify the spatial dependencies of the quantitative attribute, and *surface metrology metrics* that quantify other aspects of the spatial structure of a surface (McGarigal et al 2009).

(1) *Autocorrelation Structure Functions* – The most basic and common measures of pattern in regionalized quantitative variables (i.e., landscape gradients) are based on autocorrelation structure functions, including for example Moran's I autocorrelation coefficient and semivariance, which we described previously as scaling techniques for continuous gradient data. Both measures are typically used to describe the magnitude of autocorrelation as a function of distance between locations, as expressed by the correlogram and variogram (or semi-variogram), respectively. There are many other structure functions for analyzing the intensity and scale of pattern with continuous data, especially when the data is collected along continuous transects or two-dimensional surfaces, including quadrat-variance analysis, spectral analysis, wavelet analysis and lacunarity analysis. Like the autocorrelation structure functions, these techniques are typically used to quantify spatial dependencies in a quantitative variable in relation to scale (distance, in this case).

(2) *Surface Metrology Metrics* – The autocorrelation and other related structure functions described above can provide useful indices to quantitatively compare the intensity and extent of

autocorrelation in quantitative variables among landscapes. However, while they can provide information on the distance at which the measured variable becomes statistically independent, and reveal the scales of repeated patterns in the variable, if they exist, they do little to describe other interesting aspects of the surface. For example, the degree of relief, density of troughs or ridges, and steepness of slopes are not measured. Fortunately, a number of gradient-based metrics that summarize these and other interesting properties of continuous surfaces have been developed in the physical sciences for analyzing three-dimensional surface structures (Barbato et al. 1996, Sout et al. 1994, Villarrubia 1997). In the past ten years, researchers involved in microscopy and molecular physics have made tremendous progress in this area, creating the field of surface metrology (Barbato et al. 1996).

In surface metrology, several families of surface pattern metrics have become widely utilized. One so-called family of metrics quantify intuitive measures of surface amplitude in terms of its overall roughness, skewness and kurtosis, and total and relative amplitude. Another family records attributes of surfaces that combine amplitude and spatial characteristics such as the curvature of local peaks. Together these metrics quantify important aspects of the texture and complexity of a surface. A third family measures certain spatial attributes of the surface associated with the orientation of the dominant texture. A final family of metrics is based on the surface bearing area ratio curve (or Abbott curve). The Abbott curve is computed by inversion of the cumulative height distribution histogram. The curve describes the distribution of mass in the surface across the height profile. A number of indices have been developed from the proportions of this cumulative height-volume curve which describe structural attributes of the surface.

Many of the patch-based metrics for analyzing categorical landscapes have analogs in surface metrology. For example, compositional metrics such as patch density, percent of landscape and largest patch index are matched with peak density, surface volume, and maximum peak height. Configuration metrics such as edge density, nearest neighbor index and fractal dimension index are matched with mean slope, mean nearest maximum index and surface fractal dimension. Many of the surface metrology metrics, however, measure attributes that are conceptually quite foreign to conventional landscape pattern analysis. Landscape ecologists have not yet explored the behavior and meaning of these new metrics; it remains for them to demonstrate the utility of these metrics, or develop new surface metrics better suited for landscape ecological questions.
McGarigal et al. (2009) examined landscapes in Turkey defined using both the landscape gradient and patch mosaic models according to a variety of landscape definition schemes and conducted multivariate statistical analyses to identify the universal, consistent and important components of surface patterns and their relationship to patch-based metrics. They observed four relatively distinct components of landscape structure based on empirical relationships among 17 surface metrics across 18 landscape gradient models:

- *Surface roughness* – The dominant structural component of the surfaces was actually a combination of two distinct sub-components: (1) the overall variability in surface height and (2) the local variability in slope. The first sub-component refers to the nonspatial (composition) aspect of the vertical height profile; that is, the overall variation in the height of the surface without reference to the horizontal variability in the surface, and is represented by three surface amplitude metrics: average roughness (Sa), root mean square roughness (Sq), and ten-point height (S10z). These metrics are analogous to the patch type diversity measures (e.g., Simpson's diversity index) in the patch mosaic paradigm, whereby greater variation in surface height equates to greater landscape diversity. Importantly, while these metrics reflect overall variability in surface height, they say nothing about the spatial heterogeneity in the surface.

The second sub-component refers to the spatial (configuration) aspect of surface roughness with respect to local variability in height (or steepness of slope), and includes two surface metrics: surface area ratio (Sdr) and root mean square slope (Sdq). These metrics are analogous to the edge density and contrast metrics (e.g., contrast-weighted edge density, total edge contrast index) in the patch mosaic paradigm, whereby greater local slope variation equates to greater density and contrast of edges. Interestingly, while these surface metrics reflect something akin to edge contrast, they do so without the need to supply edge contrast weights because they are structural metrics. These two metrics appear to have the greatest overall analogy to the patch-based measures of spatial heterogeneity and overall patchiness. A fine-grained patch mosaic (as represented by any number of common patch metrics, such as mean patch size or density) is conceptually equivalent to a rough surface with high local variability.

On conceptual and theoretical grounds, these spatial and nonspatial aspects of surface roughness are independent components of landscape structure; however, in the landscape gradients we examined these two aspects were highly correlated empirically. This distinction between conceptually and/or theoretically related metrics and groupings based on their empirical behavior has also been demonstrated for patch metrics.

- *Shape of the surface height distribution* – Another important nonspatial (composition) component of the surfaces we examined was the shape of the surface height distribution. This component was comprised of five metrics: skewness (Ssk), kurtosis (Sku), surface bearing index (Sbi), valley fluid retention index (Svi), and core fluid retention index (Sci). All of these metrics measure departure from a Gaussian distribution of surface heights, but emphasize different aspects of departure from normality. Ssk and Sku measure the familiar skewness and kurtosis of the surface height distribution, while the surface bearing metrics, Sbi, Sci and Svi, measure different aspects of the surface height distribution in its cumulative form. This component was universally present across landscape models, but the composition of metrics varied somewhat among models reflecting the complexities inherent in measuring non-parametric shape distributions. There were no strong patch mosaic analogs to these surface metrics; however, departure from a Gaussian distribution of surface heights was weakly correlated with, and conceptually most closely related to, patch-based measures of landscape dominance (or its compliment, evenness) such as Simpson's evenness index (SIEI) and largest patch index (LPI). Importantly, these five surface metrics measure the 'shape' of the surface height distribution and are not affected by the surface roughness (as defined above) per se.

- *Angular texture* – A third prominent component of the surfaces we examined was the angular orientation (direction) of the surface texture and its magnitude. This component is inherently spatial, since the arrangement of surface peaks and valleys determines whether the surface has a particular orientation or not, and is represented by four spatial metrics: dominant texture direction (Std), texture direction index (Stdi), and two texture aspect ratios (Str20 and Str37). The computational methods behind these metrics are too complex to describe here, but are based on common geostatistical methods (Fourier spectral analysis and autocorrelation functions) that determine the degree of anisotropy (orientation) in the surface. Not surprisingly given our knowledge of the study landscape, we did not observe sample landscapes with a strong texture orientation. We did observe mild levels of texture orientation in some landscapes, but many were without apparent orientation. Importantly, the measurement of texture direction has no obvious analog in the patch mosaic paradigm; indeed, we observed no pairwise correlation greater than ±0.22 between any of these four surface metrics and any of the 28 patch metrics.

- *Radial texture* – The fourth prominent component of the surfaces we examined was the radial texture of the surface and its magnitude. Radial texture refers to repeated patterns of variation in surface height radiating outward in concentric circles from any location. Like angular texture, this component is inherently spatial, since the arrangement of surface peaks and valleys determines whether the surface has any radial texture or not, and is represent by three spatial metrics: dominant radial wavelength (Srw), radial wave index (Srwi), and fractal dimension (Sfd). Again, the computational methods behind these metrics are based on common geostatistical methods. A limitation of these and other metrics based on Fourier spectral analysis and autocorrelation functions is that they are only sensitive to repeated, regular patterns. We observed that in the absence of a prominent radial texture, the dominant radial wavelength (Srw) ends up being equal to the diameter of the sample landscape. As a result, in some of our landscape gradient models we observed too little variation in this metric and were forced to drop it from the final analyses. Despite these limitations, we observed sample landscapes with varying degrees of radial texture based on the other two metrics. In contrast to angular texture, the measurement of radial texture has at least one conceptual analog in the patch mosaic paradigm - mean and variability in nearest neighbor distance. On conceptual grounds, Srw should equate to mean nearest neighbor distance, and Srwi and Sfd should equate to the coefficient of variation in nearest neighbor distance. However, in our study the corresponding pairwise correlations did not exceed ±0.22, nor were there any pairwise correlations greater than ±0.40 between either of these surface metrics and any of the 28 patch metrics.

Key Point *Surface metrics (i.e., for continuous surface patterns or landscape gradients) fall into several categories, loosely reflecting different aspects of the composition or spatial configuration of the map. Each category contains a variety of metrics for quantifying different aspects of pattern. It is incumbent upon the investigator or manager to choose the appropriate metrics for the question under consideration.*

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* can be defined as those that measure the physical composition or configuration 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. Most landscape metrics are of this type.

- *Functional metrics*, on the other hand, can be defined as those that explicitly measure landscape pattern in a manner that is functionally relevant to the organism or process under consideration. Functional metrics require additional parameterization prior to their calculation, such that the same metric can return multiple values depending on the user specifications.

The difference between structural and functional metrics is best illustrated with an example. As conventionally computed, 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). The composition and configuration of the intervening matrix is ignored. 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 particular 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 metrics. 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.

Key Point *Landscape metrics can be classified as either "structural" metrics, that measure the physical composition or configuration of the patch mosaic without explicit reference to an ecological process, or "functional" metrics, that explicitly measure landscape pattern in a manner that is functionally relevant to the organism or process under consideration and require additional parameterization prior to their calculation. It is incumbent upon the investigator or manager to choose the appropriate metrics, structural and/or functional, for the question under consideration.*

Limitations in the Use and Interpretation of Metrics

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

(1) *Defining a relevant landscape* – All landscape metrics represent some aspect of landscape pattern. However, the user must first define the landscape, including its thematic content and resolution, spatial grain and extent, and boundary before any of these metrics can be computed. In addition, for the functional metrics, the user must specify additional input parameters such as edge effect distances, edge contrast weights, resistance coefficients, and search distance. Hence, the computed value of any metric is merely a function of how the investigator chose to define and scale the landscape and parameterize the metric, if appropriate. If the measured pattern of the landscape does not correspond to a pattern that is functionally meaningful for the organism or process under consideration, 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, scaling 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. Scaling techniques such as those described previously 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. Better yet, given the myriad ways to the define the landscape for the phenomenon under investigation, it may be may be desirable to evaluate alternative landscape definitions against ecological data and empirically determine the best definition. Few studies have adopted this approach, but see Thompson and McGarigal (2002) for an example.

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 of the image. In addition, the grain-size of raster 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 most of the aggregation metrics will be affected as well, because grain size effects the proportional distribution of adjacencies. For example, 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. Consider, for example, a local population of a bird species occupying a patch near the boundary of a somewhat arbitrarily defined landscape. The nearest neighbor within the landscape boundary might be quite far away; yet, in reality, the closest patch might be very close but just outside the designated 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.

(2) *Gaining a theoretical and empirical understanding of metric behavior* – In addition to these technical issues, current use of landscape metrics is constrained by the lack of a proper theoretical understanding of metric behavior. The 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). Failure to understand the theoretical behavior 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 behavior under controlled conditions because they control the process generating the pattern, allowing unconfounded links between variation in pattern and the behavior of the index (Gustafson 1998, Neel et al. 2004). 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.

(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 statistically 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, Cushman et al. 2008). 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 each investigation. Given the expanding development of functional metrics, particularly those based on a landscape mosaic perspective, it seems unlikely that a single parsimonious set exists. Ultimately, the choice of metrics should explicitly reflect some hypothesis about the observed landscape pattern and what processes or constraints might be responsible for that pattern.

(4) *A reference framework for interpreting landscape metrics* – In practice, the interpretation of landscape metrics is plagued by the lack of a proper reference framework. Landscape metrics quantify the pattern of a single 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 in space and time. 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 a. 2000). It is logical, therefore, that landscape metrics should exhibit statistical distributions that reflect the natural 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 metrics. In part, this stems from the difficulty of defining a meaningful temporal reference, but more often it stems from the lack of historical spatial data. In the absence of historical data, however, a spatial reference framework may be a viable option in some cases, whereby the focal landscape is compared to other

landscapes within the broader regional context (e.g., Cardille et al. 2005). Establishing a reference framework to aid in the interpretation of landscape metrics should be a priority in future landscape pattern analyses.

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 effected 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?
- What is the range of variation in the metric under an appropriate spatio-temporal reference framework?

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.

Key Point *There are numerous challenges to the use and proper interpretation of landscape metrics, including: 1) defining a relevant landscape for the phenomenon or question under consideration, 2) gaining a proper theoretical and empirical understanding of metric behavior to aid in the interpretation of each metric, 3) understanding the theoretical and empirical redundancies among metrics to ensure their parsimonious use, and 4) developing a proper reference framework for ecologically interpreting the computed value of each metric. There is no cookbook approach to dealing with these challenges; in general, it must come from experience. It is incumbent upon the investigator or manager to be aware of these limitations and interpret and present the results of their analyses within these limits.*

USER GUIDELINES

Overview

What is FRAGSTATS

FRAGSTATS is a spatial pattern analysis program for quantifying the structure (i.e., composition and configuration) of landscapes. The landscape subject to analysis is user-defined and can represent any spatial phenomenon. FRAGSTATS simply quantifies the spatial heterogeneity of the landscape as represented in either a categorical map (i.e., landscape mosaic) or continuous surface (i.e., landscape gradient, expected in version 4.4); it is incumbent upon the user to establish a sound basis for defining and scaling the landscape in terms of thematic content and resolution and spatial grain and grain. We strongly recommend that you read the FRAGSTATS Background section before using this program. Importantly, the output from FRAGSTATS is meaningful only if the landscape as defined is meaningful relative to the phenomenon under consideration.

Scale Considerations

FRAGSTATS requires the spatial grain or resolution of the grid to be > 0.001 m, but it places no limit on the spatial extent of the landscape per se, although there are memory limitations on the size of the grid that can be loaded. However, the distance- and area-based metrics computed in FRAGSTATS are reported in meters and hectares, respectively. Thus, landscapes of extreme extent and/or resolution may result in rather cumbersome numbers and/or be subject to rounding errors. However, FRAGSTATS outputs data files in ASCII format that can be manipulated using any database management program to rescale metrics or to convert them to other units (e.g., converting hectares to acres).

Computer Requirements

FRAGSTATS is a stand-alone program written in Microsoft Visual C++ for use in the Windows operating environment and is a 32-bit process (even if running on a 64-bit machine). FRAGSTATS was developed and tested on the Windows 7 operating systems, although it should run under all Windows operating systems. Note, FRAGSTATS is highly platform dependent, as it was developed in the Microscroft environment, so portability to other platforms is not easily accomplished. FRAGSTATS is a compute-intensive program; its performance is dependent on both processor speed and computer memory (RAM). Ultimately, the ability to process an image is dependent on the availability of sufficient memory, and the speed of processing that image is dependent on processor speed.

Of particular note is the memory constraint. FRAGSTATS is a 32-bit process and, as such, can only use up to 2GB of memory; although if properly configured Windows can allow a 32-bit machine to see up to 3GB of memory (with the /3GB flag set in boot.ini) and a 64-bit machine to see up to 4 GB of memory (if it is available, although the operating system reserves at least 1GB to itself because it is built with /LARGEADDRESSAWARE flag set). FRAGSTATS loads the input grid into memory and then computes all requested calculations. Thus, you must have sufficient memory to load the grid and then enough leftover for processing and other operating system needs. As a guide to help you determine whether you have sufficient memory to process a particular grid, you can use the following formula: #cells*4bytes. Thus, if you have a 256 rows by 256 columns grid, the memory requirement is 256 kb (256*256*4/1024 bytes/kb) just to load the grid; you still need lots more memory to process the grid and meet your other operating system needs. Unfortunately, it is nearly impossible for us to determine the exact memory requirement beyond that needed to load the grid, because it depends on many unknown factors such as how many patches there are. The memory requirement is not particularly constraining in a standard analysis, unless you are working with very large images and limited computer memory. One potential solution to this problem if it arises – unfortunately – is to get more memory, but this still has limits as noted above. Another solution is to resample the grid to a coarser resolution to effectively reduce the grid size, but this is only viable if the coarser resolution is meaningful ecologically given the specific application. An alternative solution is to break up the landscape into several smaller landscapes and analyze each separately. Indeed, in most applications, landscapes that are too large to fit in memory are more than likely too large to be meaningful landscapes for purposes of analyzing landscape patterns (see the Background document for a discussion of defining meaningful landscapes).

The memory requirement is especially constraining in the moving window analysis because FRAGSTATS requires enough memory for the input grid plus one output grid, plus enough leftover for other processing needs and system needs. If the moving window analysis is selected, FRAGSTATS checks to see if it can allocate enough memory for three grids (i.e., 1 input grid + 1 output grid + enough leftover to insure performance). In the above example, you would need at least 768 kb of memory to conduct a moving window analysis. Not too terribly constraining for most computers when analyzing relatively small landscapes. However, consider a 10,000x10,000 input grid; to conduct a moving window analysis you would need 1.14 Gb of RAM.

Data Formats

FRAGSTATS accepts raster images in a variety of formats (below). All input data formats have the following common requirements:

- All input grids should be **signed integer** grids (i.e., each cell should be assigned an integer value corresponding to its class membership or patch type). Note, assigning the zero value to a class may cause problems when the landscape contains a border because zero cannot be negative and all border cells must be negative. Note, **unsigned integer** grids are acceptable if you do not have a "border" (with negative cell values).

- All input grids must consist of perfectly **square cells** with cell size specified in **meters**. For certain input formats (ASCII and BINARY), this is not an issue because cells are assumed to be square and you are required to enter the cell size (in meters) in the graphical user interface. FRAGSTATS assumes all other grid formats include header information that defines cell size. Consequently these grids must have a metric projection (e.g., UTM) to ensure that cell size is given in metric units. With the exception of ESRI ArcGrids (see below), FRAGSTATS accepts cells that exhibit differences between height and width less than 0.1%. This means that cells need to be approximately square, usually out to several decimal places. With respect to ESRI ArcGrids, FRAGSTATS cannot accept anything but perfectly square cells. Importantly, this is a hidden problem with ESRI ArcGrids in some cases. Although the grid description will say the cells are square, this can be an artifact of the rounding done for display purposes. Sometimes the non-square problem is beyond the first 14 decimal places, and ESRI does not allow you to see more precision, even though it exist internally. The problem is that the error happens inside a FRAGSTATS call of an ESRI function, and there is nothing we can do except catch the exception and log it. Unfortunately, re-sampling the grid with the same cell size does solve the problem. However, re-sampling the grid with a different cell size does solve the problem. Note, the functions we are using from the ESRI library are those that were published and partially documented 10 years ago, because these are the only functions they will allow third party access to. In the meantime, they have added many more functions that ArcGIS uses but nobody else can access. There is simply no ESRI documentation for handling situations like the one we're facing here. Thanks again ESRI.

- All input grids must have a **cell size > 0.001 m**.

- Input grids should not have a **nodata** value that is the same as the designated **background** value (see below for discussion on nodata, backgrounds, borders, and boundaries). One of the basic assumptions of FRAGSTATS is that the **nodata** and **background** are distinct values, even though the **nodata** is re-classified into negative **background** before any processing takes place. Importantly, it is possible for the model to run fine and give correct results even when this assumption is broken, but only if there is no actual **background** in the landscape. If there is any **background**, it will be confused with **nodata** and re-classified incorrectly. With the image formats containing header information (i.e., all but raw ASCII and Binary), the value of **nodata** will be read from the image header and cannot be changed in FRAGSTATS. It is incumbent on the user to specify a different value for the **background**, recognizing that it will only matter if the image contains true **background**. With the image formats that do not contain header information (i.e., raw ASCII and Binary), the user is required to enter a **nodata** value and ensure that it is different from the specified **background** value, again recognizing that it will only matter if the image contains true **background**.

- If by chance you are working with the same grid in different image formats (see below), it is best to store these grids in separate folders, because there are some peculiar conflicts that can arise via the use of the GDAL library to read certain grid formats that can cause the program to crash.

- Lastly, the path (directory) name containing the input grid should not contain any symbols, Greek characters or anything but English letters and/or numbers.

There are some additional special considerations for each input data format, as follows:

- **ESRI ArcGrid** – Note, FRAGSTATS does not accept ArcGIS vector coverages or shapefiles. To use ESRI ArcGrids (referred to as a "Raster" data format in ArcGIS) you must have ArcGIS 10 (or earlier) with a license for Spatial Analyst or ArcView 3.3 Spatial Analyst installed on your computer and FRAGSTATS must have access to the dll libraries found in the "Bin" directory (for ArcGIS installation) or the "Bin32" directory (for ArcView 3.3 installation). Note, the paths to the Bin or Bin32 may differ depending on your version and installation. The path to the corresponding bin directory should be specified in the windows system environmental variable

PATH (or path). In Windows 7, the Environmental variables can be accessed and edited from the Control Panel - System and Security - System - Advanced system settings under the "Advanced" tab and by clicking on "Environment Variables". In the list of System variables, select the "path" variable and select "edit" and add the path to the corresponding bin directory. The path may look something like this (but check to make sure you use the correct path for your system): ";c:\Program Files (x86)\ArcGIS\Desktop10.0\Bin". Note, the semicolon in the path is used to separate items in the path list.

Importantly, do NOT add any file name (e.g. aigridio.dll) to the end of the path; the path should end with "Bin". In addition, make sure that the path to the Bin directory is the FIRST path listed that contain ArcGIS.

In addition, if you are using ArcGrids, you cannot have spaces in the path to the directory containing the grids. Note, this pertains to the path to the grids, not the path to the Bin folder as the example above illustrates. For example, the following path to your input grids is illegal: "c:\Users\Smith\My Documents\Grids" because of the space between "My" and "Documents". Note, this limitation applies only to ArcGrids; all other image formats can accommodate spaces in the path.

- **Raw ASCII grid, no header** – Each record should contain 1 image row. Cell values should be separated by a comma or a space(s). Note, it will be necessary to strip (delete) the header information from the image file if it exists, but be sure to keep it for later reference regarding background cell value, # rows, # columns, cell size, and nodata value. The default file name extension for a raw ascii grid is .asc for file navigation purposes, but any extension can be used.

- **Raw 8-, 16-, or 32-bit (binary) integer grid, no header** – The only limitation on 8- and 16-bit binary files is that they are not suitable for moving window analysis, which requires the output grids to be floating points (32 bit files). Note, it will be necessary to strip (delete) the header information from the image file if it exists, but be sure to keep it for later reference regarding background cell value, # rows, # columns, cell size, and nodata value. The default file name extension for a raw binary grid is .raw for file navigation purposes, but any extension can be used.

- **GeoTIFF grid** – The default file name extension for a GeoTIFF grid is .tif for file navigation purposes, but any extension can be used.

- **VTP binary terrain format grid** – The default file name extension for a VTP binary terrain format grid is .bt for file navigation purposes, but any extension can be used.

- **ESRI header labelled grid** – The default file name extension for an ESRI header labelled grid is .bil for file navigation purposes, but any extension can be used.

- **ERDAS Imagine grid** – The default file name extension for an ERDAS Imagine grid is .img for file navigation purposes, but any extension can be used.

- **PCRaster grid** – The default file name extension for a PCRaster grid is .map for file navigation purposes, but any extension can be used.

- **SAGA GIS binary format grid** – The default file name extension for a SAGA GIS binary format grid is .sdat for file navigation purposes, but any extension can be used.

Raster Considerations

It is important to realize that the depiction of edges in raster images is fundamentally constrained by the lattice grid structure. Consequently, raster images portray lines in stair-step fashion. The result is an upward bias in the measurement of edge length; that is, the measured edge length is always more than the true edge length. The magnitude of this bias depends on the grain or resolution of the image (i.e., cell size), and the consequences of this bias with regards to the use and interpretation of edge-based metrics must be weighed relative to the phenomenon under investigation.

Vector to Raster Conversion

In some investigations, it may be necessary to convert a vector image into a raster image in order to run FRAGSTATS. It is critical that great care be taken during the rasterization process and that the resulting raster image be carefully scrutinized for accurate representation of the original image. For example, during the rasterization process, it is possible for disjunct patches to join and vice versa. This problem can be quite severe (e.g., resulting in numerous 1-cell patches and disrupting the continuity of linear landscape elements) if the cell size chosen for the rasterization is too large relative to the minimum patch dimension in the vector image. In general, a cell size less than ½ the narrowest dimension of the smallest patches is necessary to avoid these problems.

Levels of Metrics

FRAGSTATS (v4.2 and earlier) computes 3 levels of metrics corresponding to: (1) each patch in the mosaic; (2) each patch type (class) in the mosaic; and (3) the landscape mosaic as a whole. These metrics are described in detail in the FRAGSTATS Metrics section. In addition, FRAGSTATS computes the adjacency matrix (i.e., tally of the number of cell adjacencies between each pairwise combination of patch types, including like-adjacencies between cells of the same class), which is used in the computation of several class- and landscape-level aggregation metrics. Note, cell-level metrics are scheduled to be included in version 4.3.

Output Files

Depending on which metrics are selected by the user, FRAGSTATS currently creates 4 output files corresponding to the three levels of metrics and the adjacency matrix (cell-level metrics will be included in v4.3). The user supplies a "basename" for the output files and FRAGSTATS appends the extensions .patch, .class, .land, and .adj to the basename. All files created are *comma-delimited ASCII files* and viewable. These files are formatted to facilitate input into spreadsheets and database management programs:

- **"basename".patch file**.–Contains the patch metrics; the file contains 1 record (row) for each patch in the landscape; columns represent the selected patch metrics. If a batch file is analyzed, the file contains 1 record for each patch in each landscape specified in the batch file. The first record is a column header consisting of the acronyms for all the metrics that follow. For a single landscape, the patch output file would be structured as follows:

LID,	PID,	TYPE,	AREA,	PERIM,	GYRATE,	CORE
D:\testgrid,	9,	forest,	1.0000,	400.0000,	38.1195,	0.1600
D:\testgrid,	0,	shrub,	4.0000,	800.0000,	76.4478,	1.9600
Etc.						

- **"basename".class file**.–Contains the class metrics; the file contains 1 record (row) for each class in the landscape; columns represent the selected class metrics. If a batch file is analyzed, the file contains 1 record for each class in each landscape specified in the batch file. The first record is a column header consisting of the acronyms for all the metrics that follow. For a single landscape, the class output file would be structured as follows:

LID,	TYPE,	CA,	PLAND,	NP,	PD,	LPI
D:\testgrid,	forest,	8.0000,	22.5000,	4,	5.0000,	15.0000
D:\testgrid,	shrub,	21.0000,	26.2500,	3,	3.7500,	12.5000
Etc.						

- **"basename".land file**.–Contains the landscape metrics; the file contains 1 record (row) for the landscape; columns represent the selected landscape metrics. If a batch file is analyzed, the file contains 1 record for each landscape specified in the batch file. The first record is a column header consisting of the acronyms for all the metrics that follow. For a single landscape, the landscape output file would be structured as follows:

LID,	TA,	NP,	PD,	LPI,	TE,	ED
D:\testgrid,	80.0000,	12,	15.0000,	15.0000,	7800.0000,	97.5000

- **"basename".adj file**.–Contains the class adjacency matrix; the file contains a simple header in addition to 1 record (row) for each class in the landscape, and is given in the form of a 2-way matrix. Specifically, first record contains the input file name, including the full path. The second record and first column contain the class IDs (i.e., the grid integer values associated with each class), and the elements of the matrix are the tallies of cell adjacencies for each pairwise combination of classes. For a single landscape, the adjacency output file would be structured as follows:

D:\testgrid

Class ID / ID,	2,	3,	4,	5,	Background
2,	6840,	130,	120,	10,	0
3,	120,	7960,	160,	40,	10
4,	100,	140,	9880,	40,	20
5,	10,	40,	30,	3080,	16

Note, the adjacency tallies are generated from the *double-count method* in which each cell side is counted twice–at least for all positively-valued nonbackground cells–and only the *4 orthogonal neighbors* are considered. In addition, the matrix may not be symmetrical if a landscape border is present because landscape boundary edges are only counted once. For example, a cell of class 3 (inside the landscape) adjacent to a cell of class -5 (in the landscape border) results in an adjacency for class 3; specifically, a 3 (row) -5 (column) adjacency. It does not result in an adjacency for class 5 (row), because the border cells themselves are not evaluated. For this reason, the adjacency matrix must be read as follows: each row represents the adjacency tallies for cells of that class, and the sum of adjacencies across all columns represents the total number of adjacencies for that class. These *row totals* should equal the number of positively-valued cells (i.e., inside the landscape) of the corresponding class times 4 (i.e., 4 surfaces for each cell). These row totals are used in several of the aggregation metrics. Note that the adjacency matrix includes a column for background adjacencies, which represent cell surfaces of the corresponding class adjacent to designated background. If there is no specified background in the input landscape and a landscape border is not present, then the background adjacencies represent the cell surfaces along the landscape boundary–which are treated as background in the absence of a border. If a border is provided and no background is specified, then the background adjacencies will equal zero because every cell surface, including those along the landscape boundary, will be adjacent to a real non-background class. If a batch file is analyzed, the adjacency matrices corresponding to each landscape specified in the batch file are appended to the same file.

Nodata, Backgrounds, Borders, and Boundaries

FRAGSTATS accepts images in several forms, depending on whether the image contains **nodata** and/or **background**, and whether the landscape contains a **border** outside the landscape **boundary** (Fig. 1). The distinction among nodata, background, border, and boundary and how they affect the landscape analysis and the calculations of various metrics is a source of great confusion and thus great importance. Great care should be taken to fully understand these distinctions before trying to run FRAGSTATS. We strongly suggest that you read through this section twice, once to familiarize yourself with the terminology and a second time to understand the implications.

- **Nodata** – Some images will contain nodata cells – unclassified areas of the input grid. These areas may be inside the landscape boundary (see below) or, more typically, outside the landscape boundary. In either case, these are unclassified cells that are considered "external" to the landscape of interest and are essentially ignored by FRAGSTATS. For example, a non-rectangular landscape will have nodata cells surrounding it in order to fill out a rectangular grid, since all grids are at least internally stored as rectangular rasters. Often, the nodata cells are invisible to the user, since most GIS programs don't even display the nodata cells. Thus, it is easy to forget about the nodata cells and ignore their treatment in FRAGSTATS. However, this can be a mistake as it is important to distinguish between nodata cells, for which FRAGSTATS will always consider them to be "external" to the landscape of interest, and background cells (see below), which will be treated as "internal" to the landscape of interest if given positive cell values and thus contribute to the total landscape area. It is critically important to ensure that the nodata cell value is different than the user-specified background value – when background exists.

Importantly, all nodata cells will be reassigned negative (user-specified) background cell values by FRAGSTATS and treated as such. Therefore, all nodata cells will be considered "external" or "outside" the landscape of interest, even if they are located within the landscape boundary.

Figure 1. Alternative image formats with regards to background (given a class value of 99 here) and border. The thick solid line represents the landscape boundary. Positive values are 'inside' the landscape of interest and contribute to the computed total landscape area; negative values are 'outside' the landscape of interest and are only utilized to determine edge types for patches along the landscape boundary.

- **Landscape boundary** – Every image will include a landscape boundary that defines the perimeter of the landscape and surrounds the patch mosaic of interest. The boundary is simply an invisible line around the landscape of interest. It is not given explicitly in the image; rather, it is defined by an imaginary line around the outermost cells of positively valued cells. The landscape boundary distinguishes between cells inside the landscape of interest from those outside, and thus ultimately determines the total landscape area. All positively valued cells are assumed to be inside the landscape of interest and are thus included in the total area of the landscape, regardless of whether they are classified as background (see below) or not. This is important, because many metrics include total landscape area in their calculation. Note, in most cases the landscape boundary will surround a single contiguous region of positively valued cells. However, it is possible to have disjunct regions of positively valued cells. In this case, the landscape boundary is not a single continuous line around the landscape of interest, but rather separate boundaries around each disjunct region of interest. The important point is that positively valued cells are inside the landscape of interest, while negatively valued cells are outside, and the landscape boundary is the imaginary line(s) that separates inside from outside. Hence, if the input image contains all positively valued cells, then the entire grid is assumed to be inside the landscape of interest and the landscape boundary represents an imaginary line around the entire grid. If the input image contains negatively valued cells, then those cells are assumed to be outside the landscape of interest and thus outside the landscape boundary. In this case, the edge between positively and negatively valued cells represents the landscape boundary. The landscape boundary is important in the absence of a landscape border (see below) because FRAGSTATS needs to know how to treat the edges along the boundary in all edge calculations. In the absence of a border, the landscape boundary will be treated according to user specifications (see below).

- **Background** – An image may include background – an undefined area either 'inside' or 'outside' the landscape of interest. Note that background can exist as 'holes' in the landscape and/or can partially or completely surround the landscape of interest. The background value can be any integer value. Positively valued cells of background are assumed to be 'inside' the landscape of interest; negatively valued cells of background are assumed to be 'outside' the landscape of interest. This distinction is important, as noted above, because positively valued background (interior background) will be included in the total landscape area, and thus will affect many metrics, even though it will not be treated as a patch per se (see below). Negatively valued background (external background) will be treated the same as nodata and can have a minor affect on the computed metrics if certain functional metrics requiring edge or patch adjacency information are selected (see below). Further, via the graphical user interface (see below), any class or combination of classes can be treated (i.e., reclassified) as background for a particular analysis. There are several critical issues regarding how background is handled by FRAGSTATS:

  1. Interior background (i.e., positively valued background) is included in the total landscape area and thus effects metrics that include total landscape area in their calculations. However, and this is quite tricky, interior background is in essence excluded from the total landscape area in a number of class and landscape metrics that involve summarizing patch or class metrics. For example, mean patch area is based on the average size of patches at the class or landscape level. If interior background is present, mean patch size as computed by

FRAGSTATS will not equal the total landscape area divided by the number of patches, because the total landscape area includes background area not accounted for in any patch. Similarly, the area-weighted mean of any patch metric (i.e., distribution statistics at the class and landscape level; see FRAGSTATS Metrics documentation) weights each patch by its proportional area representation. Here, the proportional area of each patch is not based on the total landscape area, but rather the sum of all patch areas, which is equivalent to the total landscape area minus interior background. Similarly, a number of landscape metrics are computed from the proportion of the landscape in each class (e.g., Shannon's and Simpson's diversity). Here, proportional area of each class is not based on total landscape area because the proportions must sum to 1 across all classes. Instead, the proportions are based on the sum of all class areas, which is equivalent to the total landscape area minus interior background. Given the subtle differences in how interior background affects various metrics, it behooves you to carefully read the FRAGSTATS Metrics documentation pertaining to each metric you choose, assuming of course that interior background is an issue.

2. Exterior background (i.e., negatively valued background) can have a minor effect on the analysis if functional metrics are selected. Note, all nodata cells are reclassified to exterior background internally by FRAGSTATS. Exterior background is assumed to be 'outside' the landscape of interest and thus has no effect on the area-based metrics; however, the border between exterior background and interior cells can effect the edge-based metrics (e.g., core area, edge contrast, and aggregation metrics). Thus, the "extent" of exterior background in the input landscape has no effect, but the "length of edge" between exterior background and interior landscape cells can have an effect.

3. Background (both interior and exterior) cells adjacent to non-background classes represent edges that must be accounted for in all edge-related metrics. The user specifies how background edge segments should be handled in all edge-related calculations (see below).

- **Landscape border** – An image also may include a landscape border; a strip of land surrounding the landscape of interest (i.e., outside the landscape boundary) within which patches have been delineated and classified. Patches in the border must be set to the negative of the appropriate patch type code. For example, if a border patch is a patch type of code 34, then its cell value must be -34 (negative 34). The border can be any width (as long as it is at least 1 cell wide) and provides information on patch type adjacency for patches on the edge of the landscape (i.e., along the landscape boundary). Essentially, patches in the border provide information on patch type adjacency for patches in the landscape of interest located along the landscape boundary; all other attributes of the patches in the border are ignored because they are *outside* the landscape of interest. Thus, the border affects only metrics where patch type adjacency is considered: core area, edge contrast, and aggregation metrics.

  Under most circumstances, it is probably not valid to assume that all edges function the same. Indeed, there is good evidence that edges vary in their affects on ecological processes and organisms depending on the nature of the edge (e.g., type of adjacent patches, degree of structural contrast, orientation, etc.). Accordingly, the user can specify a file containing *edge contrast weights* (described in more detail in the Contrast Metrics section of the FRAGSTATS Metrics documentation) for each combination of patch types (classes), including adjacencies involving background if it exists. Briefly, these weights represent the magnitude of edge contrast between adjacent patch types and must range between 0 (no contrast) and 1 (maximum contrast). Edge contrast weights are used to compute several edge-based metrics. If this weight file is not provided, these edge contrast metrics are simply not computed. Generally, if a landscape border is designated, a weight file will be specified as well, because one of the principal reasons for specifying a border is when information on edge contrast is deemed important. If a border is present, the edge contrast associated with all landscape boundary edge segments is made explicit due to knowledge of the abutting patch types. If a border is absent, then all edge segments along the landscape boundary are treated the same as background, as specified in the user-provided edge contrast weight file. Note, however, that the presence of a landscape border will have no affect on the edge contrast metrics if a contrast weight file is not specified – because these metrics will not be computed.

Similarly, the user can specify a file containing *edge depths* (described in more detail in the Core Area Metrics section of the FRAGSTATS Metrics documentation) for each combination of patch types (classes), including adjacencies involving background if it exists. Briefly, edge depths represent the distance at which edge effects penetrate into a patch and must be given in distance units (meters); edge depths can be any number ≥ 0. However, when implementing edge depths for the purpose of determining core areas, FRAGSTATS is constrained by the minimum resolution established by the cell size. Thus, in effect, edge depths will be rounded to the nearest distance in increments of the cell size. For example, if the cell size is 30 m, and you specify a 100 m edge depth, the edge mask used to mask cells along the edge of a patch (i.e., eliminate them from the "core" of the patch) will be 3 cells wide (90 m), because it is not possible to use a mask that is 3.3 cells wide. Similarly, a specified edge depth of 50 m will in effect be rounded up to 2 cells (60 m). Therefore, it is generally advisable to specify edge depths in increments equal to the cell size. Edge depths are used to compute several core area-based metrics. If this edge depth file is not provided, these core area metrics are simply not computed. Typically, if a landscape border is designated, an edge depth file will be specified as well, because one of the principal reasons for specifying a border is when information on edge effects is deemed important. If a border is present, the edge depths associated with all landscape boundary edge segments is made explicit due to knowledge of the abutting patch types. If a border is absent, then all edge segments along the landscape boundary are treated the same as background, as specified in the user-provided edge depth file. Note, however, that the presence of a landscape border will have no affect on the core area metrics if an edge depth file is not specified – because these metrics will not be computed.

A landscape border is also useful for determining *patch type adjacency* for many of the aggregation metrics. These metrics (described in more detail in the Aggregation Metrics section of the FRAGSTATS Metrics documentation) require information on cell adjacency; that is, the abutting class values for the side of every cell. The proportional distribution of cell adjacencies is used to compute a variety of landscape texture metrics. Although a landscape border is not often designated for the primary purpose of computing these texture metrics, a border will inform the calculation of these metrics. If a border is present, the adjacencies associated with all landscape boundary edge segments is made explicit due to knowledge of the abutting patch types. If a border is absent, then all edge segments along the landscape boundary are treated the same as background and the corresponding cell adjacencies are ignored in the calculation of these metrics.

Metrics based on edge length (e.g., total edge or edge density) are affected by these considerations as well. If a landscape border is present, then edge segments along the boundary are evaluated to determine which segments represent 'true' edge and which do not. For example, an edge segment between cells with class value 5 (inside the landscape of interest) and cells with class value -5 (outside the landscape of interest; i.e., in the border) does not represent a true edge; in this case, the landscape boundary artificially bisects an otherwise contiguous patch and the edge is not counted in the calculations of total edge length. Conversely, an edge segment between class 5 and -3 represents a true edge and is counted. If a landscape border is absent, then the entire boundary is treated as background and is treated according to a user-specified proportion. For example, if the user specifies that 50% of the landscape boundary should be treated as true edge, then 50% of the landscape boundary involving background will be incorporated into the edge length metrics. In other words, regardless of whether a landscape border is present or not, if a background class is specified, then a user-specified proportion of edge bordering background is treated as true edge and the remainder is ignored.

We recommend including a landscape border, especially if edge contrast, core area, or patch type adjacency is deemed important. In most cases, some portions of the landscape boundary will constitute 'true' edge (i.e., an edge with a contrast weight > 0) and others will not, and it will be difficult to estimate the proportion of the landscape boundary representing true edge. Moreover, it will be difficult to estimate the average edge contrast weight or edge depth for the entire landscape boundary. Thus, the decision on how to treat the landscape boundary will be somewhat subjective and may not accurately represent the landscape. In the absence of a landscape border, the affects of the decision regarding how to treat the landscape boundary on the landscape metrics will depend on landscape extent and heterogeneity. Larger and more heterogeneous landscapes will have a greater internal edge-to-boundary ratio and therefore the boundary will have less influence on the landscape metrics. Of course, only those metrics based on edge lengths and types are affected by the presence of a landscape border and the decision on how to treat the landscape boundary. When edge-based metrics are of particular importance to the investigation and the landscapes are small in extent and relatively homogeneous, the inclusion of a landscape border and the decision regarding the landscape boundary should be considered carefully.

So, let's try to put all of this together. There are five types of metrics affected by landscape boundary, background, and border designations: (1) total landscape area, (2) edge length metrics, (3) core area metrics, (4) contrast metrics, and (5) aggregation metrics. Let's consider several scenarios involving various combinations of background and border, and how each of these types of metrics will be treated under each scenario.

- **Scenario 1** – Input landscape contains all positively valued cells of non-background classes (Fig. 1a). In this case, the entire grid is assumed to be in the landscape of interest and every cell belongs to a non-background class. The landscape boundary surrounds the entire grid and there is no border or background present (this is probably the most common scenario).

Total landscape area.–All cells are included in the total landscape area calculation.

Edge length metrics.–User must specify the proportion of the landscape boundary to include as edge. All other edges are explicit.

Core area metrics.–The landscape boundary is treated like background; the user must specify the edge depth for cells abutting background in the edge depth file, and this depth is applied to the landscape boundary. All other edges are explicit; their edge depths are specified in the edge depth file.

Contrast metrics.–The landscape boundary is treated like background; the user must specify the edge contrast for cells abutting background in the edge contrast weight file, and this weight is applied to the landscape boundary. All other edges are explicit; their edge contrast weights are specified in the edge contrast weight file.

Aggregation metrics.–The landscape boundary is treated like background and is simply ignored since there is no information available on patch type adjacency.

- **Scenario 2** – Input landscape contains all positively valued cells, but includes a background class (Fig. 1b). In this case, the entire grid is assumed to be in the landscape of interest , but some cells belong to a background class. Here, the background is *interior* because it is positively valued and thus *inside* the landscape of interest. The landscape boundary surrounds the entire grid and there is no border present.

  Total landscape area.–All cells are included in the total landscape area calculation.

  Edge length metrics.–User must specify the proportion of the landscape boundary and background edges to include as edge. All other edges are explicit.

  Core area metrics.–The landscape boundary is treated like background; the user must specify the edge depth for cells abutting background in the edge depth file, and this depth is applied to both the landscape boundary and background edges. All other edges are explicit; their edge depths are specified in the edge depth file.

  Contrast metrics.–The landscape boundary is treated like background; the user must specify the edge contrast for cells abutting background in the edge contrast weight file, and this weight is applied to both the landscape boundary and background edges. All other edges are explicit; their edge contrast weights are specified in the edge contrast weight file.

  Aggregation metrics.–The landscape boundary and background are treated similarly; both are simply ignored when evaluating adjacencies since there is no information available on patch type adjacency in either case.

- **Scenario 3** – Input landscape contains a mixture of positively valued cells and negatively valued background cells (Fig. 1c). Note, it doesn't matter whether the negatively valued background cells are located entirely on the periphery of the positively valued cells (i.e., outside the landscape of interest) or located as holes in the interior of the landscape, or a combination of the two. In all cases, the positively valued cells are is assumed to be *inside* the landscape of interest, whereas the negatively valued background cells are assumed to be *outside* the landscape of interest and thus outside the landscape boundary. In figure 1c, the background is entirely *exterior* because it is all negatively valued and thus *outside* the landscape of interest (even though some of the exterior background patches are embedded as holes within the landscape). The landscape boundary separates contiguous regions of positively valued cells from the negatively valued cells and there is no border present. Alternatively, the exterior background could be considered border, but the use of border is generally reserved for situations involving negatively valued non-background cells.

Total landscape area.–All positively valued cells are included in the total landscape area calculation; negatively valued cells (here, all background) are ignored.

Edge length metrics.–User must specify the proportion of the landscape boundary and background edges (in this case, they are the same) to include as edge. All other edges are explicit.

Core area metrics.–The landscape boundary is treated like background; in this case, the entire landscape boundary is in fact also background. The user must specify the edge depth for cells abutting background in the edge depth file, and this depth is applied to the background edges (in this case, all on the landscape boundary). All other edges are explicit; their edge depths are specified in the edge depth file.

Contrast metrics.–The landscape boundary is treated like background; in this case, the entire landscape boundary is in fact also background. The user must specify the edge contrast for cells abutting background in the edge contrast weight file, and this weight is applied to the background edges (in this case, all on the landscape boundary). All other edges are explicit; their edge contrast weights are specified in the edge contrast weight file.

Aggregation metrics.–The landscape boundary and background (in this case, they are the same) are treated similarly; they are simply ignored when evaluating adjacencies since there is no information available on patch type adjacency.

- **Scenario 4** – Input landscape contains a mixture of positively valued cells, including some positively valued background cells, and negatively valued background cells (Fig. 1d). Note, as in scenario 3, it doesn't matter whether the negatively valued background cells are located entirely on the periphery of the positively valued cells (i.e., outside the landscape of interest) or located as holes in the interior of the landscape, or a combination of the two. In all cases, the positively valued cells are is assumed to be *inside* the landscape of interest , whereas the negatively valued background cells are assumed to be *outside* the landscape of interest and thus outside the landscape boundary. Here, the background is a combination of *interior* and *exterior* background. The landscape boundary separates contiguous regions of positively valued cells from the negatively valued cells and there is no border present. As noted in scenario 3, the exterior background could be considered border, but the use of border is generally reserved for situations involving negatively valued non-background cells.

Total landscape area.–All positively valued cells, including the 'interior' background, are included in the total landscape area calculation; negatively valued cells (here, all background) are ignored.

Edge length metrics.–User must specify the proportion of the landscape boundary (in this case, all background) and interior background edges to include as edge. All other edges are explicit.

Core area metrics.–The landscape boundary is treated like background; in this case, the entire landscape boundary is in fact also background. The user must specify the edge depth for cells abutting background in the edge depth file, and this depth is applied to all background edges (in this case, both on the landscape boundary and interior). All other edges are explicit; their edge depths are specified in the edge depth file.

Contrast metrics.–The landscape boundary is treated like background; in this case, the entire landscape boundary is in fact also background. The user must specify the edge contrast for cells abutting background in the edge contrast weight file, and this weight is applied to all background edges (in this case, both on the landscape boundary and interior). All other edges are explicit; their edge contrast weights are specified in the edge contrast weight file.

Aggregation metrics.–The landscape boundary (in this case, all background) and interior background are treated similarly; both are simply ignored when evaluating adjacencies since there is no information available on patch type adjacency in either case.

- **Scenario 5** – Input landscape contains a mixture of positively valued non-background cells and negatively valued non-background cells (i.e., a true border; Fig. 1e). In this case, the positively valued cells are is assumed to be *inside* the landscape of interest , whereas the negatively valued cells are assumed to be *outside* the landscape of interest and thus outside the landscape boundary. The landscape boundary separates contiguous regions of positively valued cells from the negatively valued cells; no background exists; and there is a true border present. This is unquestionably the *ideal scenario* because every cell is classified into a real class (i.e., no background) and a border is included to inform all edge, core, and adjacency calculations.

Total landscape area.–All positively valued cells are included in the total landscape area calculation; negatively valued cells are ignored.

Edge length metrics.–Because a border is present and there is no background, all edges are explicit; that is, the image provides explicit information on whether every edge segment along the boundary is a *true edge* or not. In this case, the user does not need to specify the proportion of the landscape boundary to include as edge. In fact, any user specification in this regard via the user interface will be disregarded.

Core area metrics.–Because a border is present and there is no background, all edges are explicit; that is, the image provides explicit information on the abutting patch types along the boundary. In this case, all edge depths are specified in the edge depth file.

Contrast metrics.–Because a border is present and there is no background, all edges are explicit;

that is, the image provides explicit information on the abutting patch types along the boundary. In this case, all edge contrast weights are specified in the edge contrast weight file.

Aggregation metrics.–Because a border is present and there is no background, all edges are explicit; that is, the image provides explicit information on the abutting patch types along the boundary. In this case, all boundary edge segments are included in the adjacency calculations.

- **Scenario 6** – Input landscape contains a mixture of positively valued cells, including both background and non-background classes, and negatively valued cells, including both background and non-background classes (Fig. 1f). This is the most complex scenario involving a complicated mixture in interior and exterior background and a border. In this case, all positively valued cells (including interior background) are is assumed to be *inside* the landscape of interest, whereas the negatively valued cells are assumed to be *outside* the landscape of interest and thus outside the landscape boundary. The landscape boundary separates contiguous regions of positively valued cells from the negatively valued cells. A true border is present, but it includes some background class. This is perhaps also an ideal scenario, like scenario 5, but contains a realistic, sometimes unavoidable, situation in which some areas must be classified as background, either because there is no information available from which to classify them, or because it is deemed desirable ecologically to treat these areas as undefined background.

Total landscape area.–All positively valued cells, including the interior background, are included in the total landscape area calculation; negatively valued cells are ignored.

Edge length metrics.–Because a border is present but contains some background and there is interior background, only a portion of edges are explicit; that is, some edges abut background (either interior or exterior) and it is not explicit whether they represent *true edge* or not. In this case, the user must specify the proportion of edges involving background to include as edge.

Core area metrics.–Because a border is present but contains some background and there is interior background, only a portion of edges are explicit. Here, all boundary edges involving background and interior background edges are treated the same. The user must specify the edge depth for cells abutting background in the edge depth file, and this depth is applied to all background edges (in this case, both on the landscape boundary and interior). All other edges are explicit; their edge depths are specified in the edge depth file.

Contrast metrics.–Because a border is present but contains background, and there is interior background, only a portion of edges are explicit. Here, all boundary edges involving background and interior background edges are treated the same. The user must specify the edge contrast weight for cells abutting background in the edge contrast weight file, and this weight is applied to all background edges (both on the landscape boundary and interior). All other edges are explicit; their contrast weights are specified in the edge contrast weight file.

Aggregation metrics.–Because a border is present but contains some background, and there is interior background, only a portion of edges are explicit. In this case, edge segments involving background (both on the landscape boundary and interior) are ignored in the adjacency calculations.

Installation

FRAGSTATS installation is quick and easy (hopefully). After downloading the zip file, simply extract the file to any folder, double click on the **frg_setup_4.*.exe** file and follow the instructions. To complete the installation you may need to disable your virus protection software, or at least disable the disk access protection. Note, to work with ArcGIS grids, see additional instructions in the Overview--Data Formats section. Once installed, FRAGSTATS is run by double clicking on the **frg_gui.exe** file or selecting it from the start menu or desktop.

Running via the Graphical User Interface

FRAGSTATS is run via a graphical user interface (GUI). This GUI is intended to facilitate the parameterization process and to provide maximum flexibility in the analysis. What follows is a step-by-step description of how to parameterize and run FRAGSTATS using the GUI:

Step 1. Starting the FRAGSTATS GUI
Step 2. Creating a Model
Step 3. Selecting Inputs
Step 4. Specifying Common Tables
Step 5. Setting Analysis Parameters
Step 6. Selecting and Parameterizing Patch, Class, and Landscape Metrics
Step 7. Executing FRAGSTATS
Step 8. Browsing and Saving the Results
Step 9. Getting Help

Step 1. Starting the FRAGSTATS GUI

To start FRAGSTATS, simply double click on the **frg_gui.exe** file and (hopefully) the opening window shown in figure 2 will display.

The anatomy of the opening window is quite simple and is similar to many windows-based programs:

- **Title bar** – The title bar lists the name of the current or open model file. The model file contains the current parameterization scheme (see below). When you first start FRAGSTATS, a model file does not exist. Consequently, the title is listed as "Fragstats 4.?" until you either create a **New** model or **Open** an existing (saved) model. After selecting a **New** model, the title bar lists "Unnamed" until the model is saved and named. After opening an existing (saved) model the title bar lists the name of the model file.

- **Menu bar** – The menu bar consists of a several items that are not particularly relevant until a

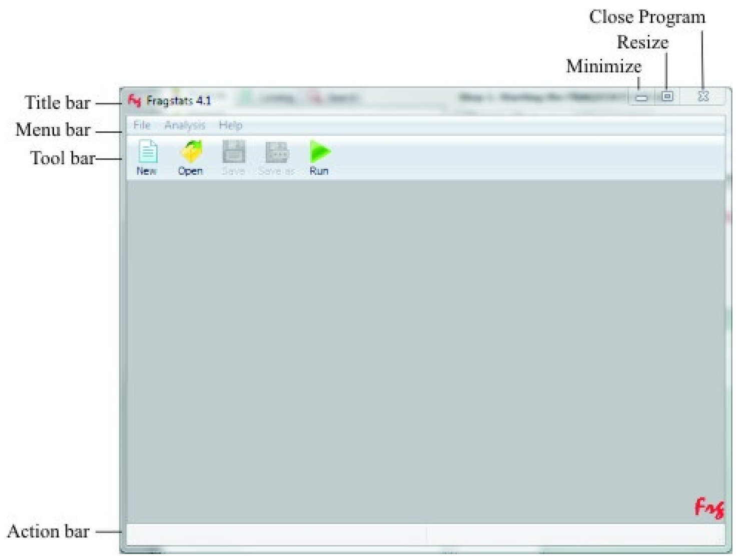

Figure 2. Anatomy of the FRAGSTATS opening user interface.

model is created or opened in the next step; as such, these items are discussed below.

- **Tool bar** – The tool bar consists of several common tools that are also accessible from the drop-down menus, as discussed below.

- **Action bar** – The action bar merely echos the action that will be taken by the menu option or tool button selected by the mouse. Thus, placing the mouse over the **New** button on the tool bar will echo "create a new file", which is the action that will happen if the button is selected.

- **Minimize** – Minimize window.

- **Resize** – Resize window.

- **Close Program** – Close FRAGSTATS.

Step 2. Creating a Model

The first time you run FRAGSTATS you must create a new model. A model is simply a FRAGSTATS formatted file that contains the model parameterization. Once a model has been created and saved, it can be opened and run, or modified before running. The following options are available from the tool bar or from the **File** drop-down menu:

- **New** – Creates a new (or blank) model file and opens the dialog shown in figure 3.

- **Open** – Opens an existing (previously saved) model file and the dialog shown in figure 3, but containing whatever parameters were previously saved.

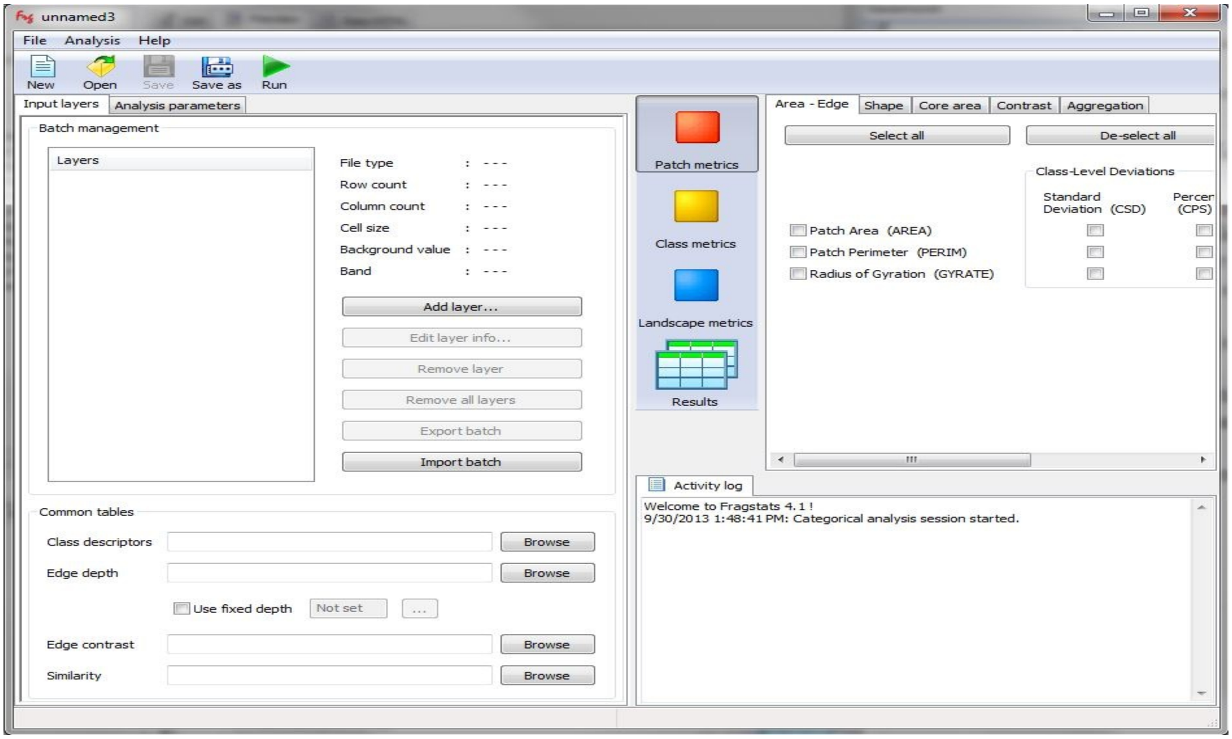

Figure 3. Model dialog for paramterizing FRAGSTATS, shown here for a "new" model that has yet to be parameterized, and with the "Input layers" tab in the left panel selected.

- **Save** – Saves the current model to a file with the extension .fca. Note, if you are saving a model file for the first time, you will be prompted to specify a location and file name. If you are saving model with the same name as one that already exists in the current directory, you will be asked whether to replace the existing file. This model file contains all the parameter settings in the dialog boxes (below) at the time the file was saved. This can be very useful if you are running FRAGSTATS repeatedly with the same or similar parameterization schemes.

- **Save as** – Saves the current model to a location and file name (with extension .fca) that you specify.

Step 3. Selecting Input Layers

Once a new model has been created (Fig. 3), the next step is to select input layers (i.e., input grids). Note, if you opened a saved model, you can modify the input parameters as well.

In the left pane of the model dialog window make sure the **Input layers** tab is selected. The top half of the left pane is labeled **Batch management** and this is where you select the input grids either singly (**Add layer**) or as a previously defined batch file (**Import batch**), and/or edit or modify the input layers (**Edit layer info**), as follows:

- **Add layer** – Click **Add layer** to add a grid to the model (to be analyzed). This will open the dialog shown in figure 4.

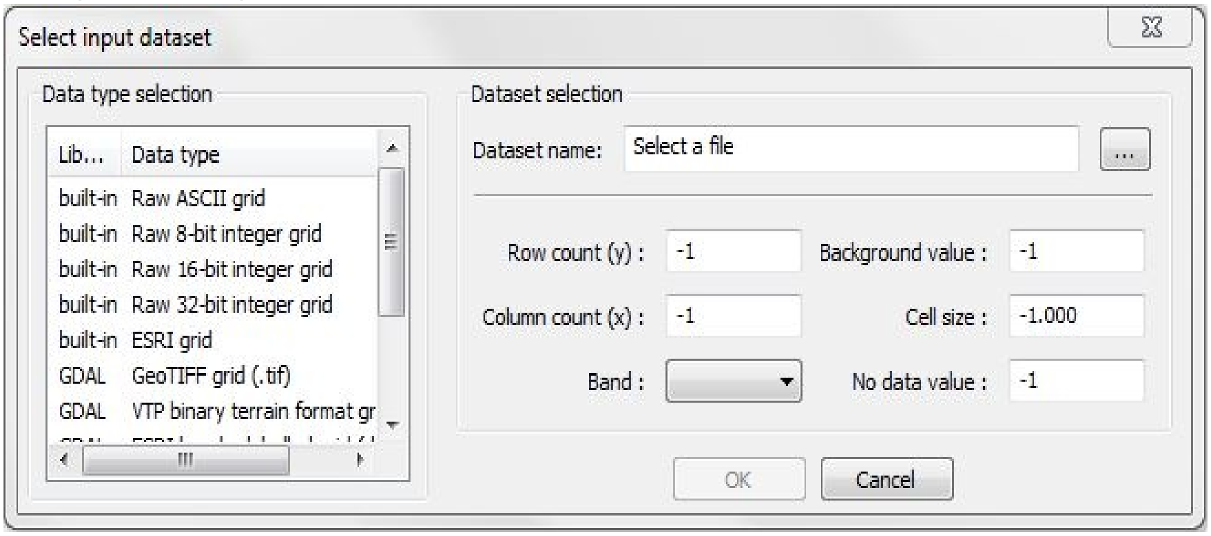

Figure 4. Dialog for adding a grid to the model.

First, select a **Data type** by clicking on the corresponding line in the left pane. FRAGSTATS accepts several types of input image data formats. See Overview –Data Formats section for details. Briefly, all input images should be integer grids (i.e., each cell should be assigned an integer value corresponding to its class membership or patch type). Note, assigning the value 0 to a class is problematic if that class exists in the landscape border, since negative zeros are not allowed, and thus 0 should not be used as a class value. In addition, all input grids should consist of *square* cells with the measurement units in *meters*. Choose one of the following:

1. **Raw ASCII grid**, ascii grid (without header)[.asc]
2. **Raw 8-bit integer grid**, binary grid (without header)[.raw]
3. **Raw 16-bit integer grid**, binary grid (without header)[.raw]
4. **Raw 32-bit integer grid**, binary grid (without header)[.raw]
5. **ESRI grid**, ArcGIS raster grid (contains header)
6. **GeoTIFF grid** (contains header)[.tif]
7. **VTP binary terrain format grid** (contains header)[.bt]
8. **ESRI header labelled grid** (contains header)[.bil]
9. **ERDAS Imagine grid** (contains header)[.img]
10. **PCRaster grid** (contains header)[.map]
11. **SAGA GIS binary format grid** (contains header)[.sdat]

Second, select a dataset by entering the full path and file name of the input grid in the **Dataset name** box, or click the navigate to button (**...**) and navigate to and select the desired input grid of the corresponding data type. Note, the navigation window is context sensitive, so that only files with the appropriate extension will be displayed by default (see default extensions in square brackets above). However, you can change the extension filter to "all types" in the navigation dialog by clicking the drop-down arrow to the right of the file name. Importantly, see the discussion on Data Formats above before trying to import data layers.

Lastly, depending on the **Data type**, you will need to enter some information about the grid. Note, only the text boxes that are required for the corresponding **Data type** will be active; all others will be grayed out. Fill in all text boxes that are active.

1. *Row count (y)* – Enter the number of rows in the input image. This is only required if the input **Data type** is ASCII or Binary; otherwise, the value is taken from the header of the input grid and cannot be changed.

2. *Column count (x)* – Enter the number of columns in the input image. This is only required if the input **Data type** is ASCII or Binary; otherwise, the value is taken from the header of the input grid and cannot be changed.

3. *Band* – Some of the data formats allow for images with multiple bands. Consequently, If your image has multiple bands (i.e., layers), you must select the band that you want to import. By default the first band will be imported.

4. *Background value* –[Optional] Enter the value to be used for background cells. Importantly, this value should not be equal to the nodata value if interior background exists, and thus it is safer to simply choose a different value from nodata. This is only required if there are cells interior or exterior to the landscape of interest that you want to treat as background (see Overview). Note, it is possible to specify multiple class values as background, but this must be done in the **Class descriptors** table (see below). When this is done, the designated classes are reclassified to the background value specified here in the grid attributes. Note, all background cells are assigned this cell value, and this can have important implications if you select core area metrics, edge contrast metrics, or the similarity metric. Specifically, if you wish to specify a non-zero edge depth or edge contrast weight to background edges or a non-unity similarity weight, you must include this background class value in the pairwise combination of classes given in the edge depth, edge contrast, and similarity weight files (see below).

5. *Cell size* (in meters) – Enter the size of cells in meters in the input image. Cells must be square. The length of 1 side of a cell should be input. This is only required if the input **Data type** is ASCII or Binary; otherwise, the value is taken from the header of the input grid and cannot be changed.

6. *Nodata value* – Enter the value for nodata cells. Note, this only matters if the grid contains nodata cells, which may or may not be the case depending on the shape of the landscape. This is only required if the input **Data type** is ASCII or 8-, 16- or 32-bit integer; otherwise, the value is taken from the header of the input grid and cannot be changed. It is important to note the following regarding the nodata value:

   - Some input data formats (e.g., ESRI grid) include the nodata value in the file header and it is generally "hidden" to the user, whereas in other input data formats (e.g., ASCII and

8-, 16- and 32-bit integer formats) you must specify it here since there is no header information in the image. Note, FRAGSTATS has a default nodata value for these latter input data formats (ASCII=9999, 8-bit integer=127, 16- and 32-bit integer=9999) and you need to be sure to change this value from the default if your input landscape contains a different nodata value, otherwise the nodata cells in the input landscape will be treated as a real class.

- In any case, the background value (see above) should not be the same as the nodata value (although this will only matter if you have true background). If the background value is the same as the nodata value and you have true background in the landscape, FRAGSTATS will not be able to distinguish between nodata and true background. In this case, both the nodata and positive background (i.e., inside the landscape) will be converted to negative background prior to the analysis, thus converting any real internal background (positively valued background) to external background (negatively valued background), and this will affect many of the metrics.

- The specific nodata value that FRAGSTATS lists in the grid attributes for an ESRI grid (and other formats with header files) may not match what you might see, for example, in ArcMAP. The difference is that we use the outsider's API and only get to load the grids in 32-bit signed integer format for which the nodata value is -2147483647 (the minimum value the format can hold), while ESRI has access to a more fine-grained API that allows ArcMAP to see that the dataset is actually stored in 16-bit signed integer format, RLE compressed, and the nodata value for it is -32768 (the minimum value the format can hold).

■ **Edit layer info** – Click **Edit layer** info to reopens the dialog shown in figure 4 and edit any of the grid parameters.

■ **Remove layer** – Click **Remove layer** to remove the selected grid from the batch manager.

■ **Remove all layers** – Click **Remove all layers** to remove all the grids from the batch manager.

■ **Export batch** – Click **Export batch** to export the loaded grids as a batch file (.fbt) in the format described below.

■ **Import batch** – Click **Import batch** to load a batch file that already contains a list of input grids to be analyzed. The batch file option is convenient if you want to analyze many landscapes. If you select this option, you must specify a properly formatted batch file by navigating to the appropriate file. Note, FRAGSTATS uses the file extension **.fbt** for batch files and will look for files with this extension by default when navigating. The .fbt extension is not mandatory, but using it can help keep files organized.

The batch file must be a *comma-delimited ASCII file*. Each line should specify the input landscape file name, cell size, background value, number of rows, number of columns, band number, nodata value, and input data type, in that order. The syntax for this file is as follows:

InputFileName, CellSize, Background, Rows, Columns, Band, Nodata, InputDataType

- ☐ *InputFileName* – is the full path and file name of the input landscape.
- ☐ *CellSize* – is an integer value corresponding to the cell size (in meters).
- ☐ *Background* – is an integer value corresponding to the designated background value. Note, any class designated as background in the **Class descriptors** file (see below) will be reclassified to this class value and treated as background. In addition, any nodata cells will be reclassified to negative background.
- ☐ *Rows* – is an integer value corresponding to the number of rows in the input image.
- ☐ *Columns* – is an integer value corresponding to the number of columns in the input image.
- ☐ *Band* – is an integer value corresponding to the desired band number (i.e., layer) to import from the input file.
- ☐ *Nodata* – is an integer value corresponding to the nodata value. Note, it doesn't matter whether you put a negative sign in front of the nodata value or not, regardless of whether the true nodata value is negative number, because FRAGSTATS treats any cell with the nodata value, positive or negative, as nodata and thus outside the landscape of interest. In fact, internally, FRAGSTATS will convert all nodata cells to negative the user-specified background value prior to the analysis.
- ☐ *InputDataType* – is a character string identifying the input data format, with the following options corresponding to the various input data format types listed above:

    - IDF_ASCII
    - IDF_8BIT
    - IDF_16BIT
    - IDF_32BIT
    - IDF_ARCGRID
    - IDF_GeoTIFF
    - IDF_BT
    - IDF_EHDR
    - IDF_EIMG
    - IDF_SagaGIS
    - IDF_PCRaster

The batch file should contain a record for each input landscape, and all arguments should be separated by a comma. The parameter values should reflect the input **Data type** for each input landscape; if it is ASCII or 8-, 16- or 32-bit integer, then the record must contain all of the parameters specified above. However, if it is any of the other formats, then the record need only contain the input landscape file name, the background value, and the Band number; the remaining parameters should be assigned "x", as illustrated in the following example:

D:\Foo\Bar\ASCII_filename, 25, 999, 250, 300, 1, 9999, IDF_ASCII
D:\Foo\Bar\8BIT_filename, 25, 999, 250, 300, 1, 127, IDF_8BIT
D:\Foo\Bar\16BIT_filename, 25, -9999,999, 250, 300, 1, 9999, IDF_16BIT
D:\Foo\Bar\32BIT_filename, 25, -9999,999, 250, 300,1, 9999, IDF_32BIT

D:\Foo\Bar\ARCGRID_folder, x, 999, x, x, 1, x, IDF_ARCGRID
D:\Foo\Bar\GeoTIFF_filename, x, 999, x, x,1, x, IDF_GeoTIFF
D:\Foo\Bar\VTP_binary_terrain_format_filename, x, 999, x, x, 1, x, IDF_BT
D:\Foo\Bar\ESRI_header_labelled_filename, x, 999, x, x, 1, x, IDF_EHDR
D:\Foo\Bar\ERDAS_Imagine_filename, x, 999, x, x, 1, x, IDF_EIMG
D:\Foo\Bar\PCRaster_filename, x, 999, x, x, 1, x, IDF_PCRaster
D:\Foo\Bar\SAGA_GIS_binary_format_filename, x, 999, x, x, 1, x, IDF_SagaGIS
etc.

NOTE, since ArcGrid files are actually folders containing multiple files, not single image files, the file naming convention is a bit different. In this case, the input file name should be given as the path to the ArcGrid folder (i.e., the file is the folder). In addition, regardless of input data type, the cell size, nodata value, background value, rows and columns, and band can be different for each input landscape.

NOTE, running from a batch file does not eliminate the necessity of completing the parameterization of FRAGSTATS; it only provides a mechanism for running FRAGSTATS on more than one landscape without having to parameterize and run each landscape separately. Specifically, you still must set analysis parameters and select and parameterize the individual metrics, as described below. The batch file only specifies the file name, input data type, and grid attributes for each input landscape; all other parameters must be specified according to the directions below.

Step 4. Specifying Common Tables [optional]

Once a new model has been created (Fig. 3) and the input grids have been added or imported from a batch file, the next optional step is to specify common tables (in the bottom left pane of the model dialog, figure 3) used to describe and attribute the classes (patch types) and assign edge depths, edge contrasts, and similarity coefficients used in the corresponding functional metrics, as described below:

- **Class descriptors [Optional]** – Click on the corresponding browse button and navigate to and select the desired file. Note, FRAGSTATS uses the file extension **.fcd** for class descriptor files and will look for files with this extension by default when navigating. The .fcd extension is not mandatory, but using it can help keep files organized. Each record in the file should contain a numeric class (patch type) value, the character descriptor for that patch type, a logical status indicator, and a local background indicator. The syntax for this *comma-delimited ASCII file* is as follows:

  ID, Name, Enabled, IsBackground
  - ☐ *ID* – is an integer value corresponding to a class value in the landscape.
  - ☐ *Name* – is a descriptive name of the class; descriptive names can be any length and contain any characters, including spaces, but cannot include commas. This descriptive name is reported in all patch and class output files for the variable TYPE.
  - ☐ *Enabled* – can take on the values: true, or t; and false, or f. (upper or lower case), and determines whether the corresponding class should be processed and added to the

results or simply ignored in the output files. A "true" or "t" indicates that the class is *enabled* and should be output in the patch and class output files. A "false" or "f" indicates that the class is *disabled* and should not be output. Note, enabling or disabling a class does not effect the computation of landscape metrics; disabled classes are still included, as necessary, in the computation of landscape metrics. Although there is some savings of computer processing by disabling a class, the primary effect is on the output. This feature allows you to "turn off" classes that you are not interested in so that you don't have to view their statistics in the output files.

- ☐ *IsBackground* – can take on the values: true, or t; and false, or f (upper or lower case), and determines whether the corresponding class should be reclassified and treated as background (i.e., assigned the background value specified in the grid attributes). Note, classifying a class as background will have an effect on many landscape metrics (see Overview).

The class descriptors file should contain a record for each class in the input landscape, and all arguments should be separated by a comma or space(s). For example:

```
ID, Name, Enabled, IsBackground
1,shrubs,true,false
2,conifers,true, false
3,deciduous,true,false
4,other,false,true
etc.
```

Note, the class descriptors file in FRAGSTATS must include the header line shown above (this is a change from FRAGSTATS 3.x). In addition, the class descriptors file can contain additional classes that do not exist in the input landscape, but all classes that exist should be listed in this file.

In summary, the class descriptors file allows you to do three things: (1) specify character descriptors for each class in order to facilitate interpretation of the output files, (2) limit the output files to only the classes of interest, and (3) reclassify classes to background.

NOTE, if the class descriptors file is provided, the class names will be written to the output files. Otherwise, the class IDs (numeric patch type codes) will be written to the output files.

- **Edge depth [Optional]** –The **Edge depth** table displays the "depth-of-edge" values to use in determining what constitutes the *core* of a patch in the core area metrics and is only relevant if one or more core area metrics are selected (see below). There are two options:

1. *Fixed edge depth* –If you wish to treat all edges the same, then check the corresponding check box (**Use fixed depth**), click the (**...**) button and enter a non-zero distance (in meters). By default this box contains a zero, but you should enter a non-zero distance because a zero depth-of-edge would result in the core area being equal to patch area, and thus would be redundant.

2. *Variable edge depths* –Alternatively, you can specify separate edge depths for each edge type (i.e., each pairwise combination of patch types). Click on the corresponding browse button and navigate to and select the desired file. Note, FRAGSTATS uses the file extension **.fsq** for edge depth files and will look for files with this extension by default when navigating. The .fsq extension is not mandatory, but using it can help keep files organized. The syntax for this *comma-delimited ASCII file* is as follows:

   FSQ_TABLE
   CLASS_LIST_LITERAL(*1stClassName, 2ndClassName, etc.)*
   CLASS_LIST_NUMERIC(*1stClassID, 2ndClassID, etc.)*
   EdgeDepth_1-1, EdgeDepth_1-2, etc.
   EdgeDepth_2-1, EdgeDepth_2-2, etc.
   etc.

   - Comment lines start with # and are allowed anywhere in the table.
   - FSQ_TABLE must be specified in the first line.
   - Two types of class lists are allowed CLASS_LIST_LITERAL() and CLASS_LIST_NUMERIC(), but only the first one encountered is considered, so you only need one of these lines.
   - Literal class names (*1stClassName, 2ndClassName, etc.,*) are character strings and cannot contain spaces.
   - Class Ids (*1stClassID, 2ndClassID, etc.*) are integer values corresponding to class values in the grid.
   - With regards to the edge depths, the order of rows and column is the one specified in the CLASS_LIST_LITERAL() or CLASS_LIST_NUMERIC(), whichever comes first. *EdgeDepth_i-j* is an integer value giving the depth-of-edge (in meters) for the corresponding edge type (i.e., for the focal class designated by the i^{th} *ClassID* and the adjacent class designated by the j^{th} *ClassID*). Note, it is advisable but not necessary to provide edge depths in increments equal to the cell size, because FRAGSTATS will always round up or down to the nearest cell when applying the edge mask (see Overview).

   The edge depth entries must be a square matrix (i.e., same number of rows and columns), must have the same list and order of ClassIDs as given in the CLASS_LIST_LITERAL or CLASS_LIST_NUMERIC, should contain a record for each unique pairwise combination of patch types (classes) in the input landscape (any missing class must be missing in both the rows and columns and will be assigned a zero edge depth for all edges involving that class), and all arguments should be separated by a comma. For example, given four classes, the following file would be suitable:

   FSQ_TABLE
   CLASS_LIST_NUMERIC(2, 3, 4, 5, 6)
   0, 30, 30, 30, 30
   70, 0, 40, 40, 40
   30, 40, 0, 50, 50
   30, 40, 50, 0, 60

30, 40, 50, 60, 0

NOTE, this table can be created and managed using any text editor and then simply saved as a comma delimited file (.csv).

NOTE, the edge depth matrix can be *asymmetrical*; that is, upper right and lower left triangles do not need to mirror each other. Accordingly, it is important to realize that the rows represent the focal class and the columns represent the adjacent or abutting class. Let's consider the edge depths for focal class A (or ID=2) in the example above, given in the first row of the edge depth matrix. An adjacent patch of class B (or ID=3) has an edge depth of 30 m; i.e., has an edge effect that penetrates 30 m into the patch of class A. Conversely, class A penetrates 70 m into class B (row 2, column 1). Thus, the edge effect penetrates less into class A than into class B. This asymmetry may be important in some applications; for example, when urban edge effects penetrate deeply into forest, but forest edge effects penetrate very little, if at all, into urban areas.

NOTE, the *diagonals* are typically given a zero edge depth, but it is possible to specify a non-zero diagonal. However, the only situation in which a patch can abut a patch of the same class is along the landscape boundary when a landscape border is present (see Overview). In this case, it is possible to specify a non-zero edge depth, although in most cases it would not be logical to do so.

NOTE, if you have *background* in the image, you need to include the background class value specified in the grid properties during data import, otherwise all background edges will be given a zero edge depth.

- **Edge contrast [Optional]** – The **Edge contrast** table displays the "edge contrast" values to use in determining the magnitude of contrast for each edge type (i.e., each pairwise combination of patch types) and is only relevant if one or more edge contrast metrics are selected (see below). Click on the corresponding browse button and navigate to and select the desired file. Note, FRAGSTATS uses the file extension **.fsq** for edge contrast files and will look for files with this extension by default when navigating. The .fsq extension is not mandatory, but using it can help keep files organized. The syntax for this *comma-delimited ASCII file* is as follows:

  FSQ_TABLE
  CLASS_LIST_LITERAL(*1stClassName, 2ndClassName, etc.)*
  CLASS_LIST_NUMERIC(*1stClassID, 2ndClassID, etc.)*
  ContrastWeight_1-1, ContrastWeight_1-2, etc.
  ContrastWeight_2-1, ContrastWeight_2-2, etc.
  etc.

  - Comment lines start with # and are allowed anywhere in the table.
  - FSQ_TABLE must be specified in the first line.
  - Two types of class lists are allowed CLASS_LIST_LITERAL() and CLASS_LIST_NUMERIC(), but only the first one encountered is considered.
  - Literal class names (*1stClassName, 2ndClassName, etc.,*) are character strings and cannot

contain spaces.

- Class Ids (*1stClassID, 2ndClassID, etc.*) are integer values corresponding to class values in the grid.
- With regards to the contrast weights, the order of rows and column is the one specified in the CLASS_LIST_LITERAL() or CLASS_LIST_NUMERIC(), whichever comes first. *ContrastWeight_i-j* is an integer value giving the depth-of-edge (in meters) for the corresponding edge type (i.e., for the focal class designated by the i^{th} *ClassID* and the adjacent class designated by the j^{th} *ClassID*).
- Contrast weights must range from 0 (no contrast) to 1 (maximum contrast).

The edge contrast entries must be a square matrix (i.e., same number of rows and columns), must have the same list and order of ClassIDs as given in the CLASS_LIST_LITERAL or CLASS_LIST_NUMERIC, should contain a record for each unique pairwise combination of patch types (classes) in the input landscape (any missing class must be missing in both the rows and columns and will be assigned an edge contrast weight of one (maximum)), and all arguments should be separated by a comma. For example, given four classes the following file would be suitable:

```
FSQ_TABLE
CLASS_LIST_NUMERIC(2, 3, 4, 5, 6)
0, 0.2, 0, 0.4, 0.6
0.2, 0, 0, 0.2, 0.4
0, 0, 0, 0, 0
0.4, 0.2, 0, 0, 0.2
0.6, 0.4, 0, 0.2, 0
```

NOTE, this table can be created and managed using any text editor and then simply saved as a comma delimited file (.csv).

NOTE, this matrix must be *symmetrical*; that is, upper right and lower left triangles must be mirror images, because edge contrast is a property of the edge itself.

NOTE, the *diagonals* are typically given a zero edge contrast since there is no contrast between patches of the same type, although any value can be specified. However, the only situation in which a patch can abut a patch of the same class is along the landscape boundary when a landscape border is present (see Overview). In this case, it is possible to specify a nonzero edge contrast, although in most cases it would not be logical to do so.

NOTE, if you have *background* in the image, you need to include the background class value specified in the grid properties during data import, otherwise all background edges will be given a zero edge contrast.

- **Similarity [Optional]** – The **Similarity** table displays the "similarity" values to use in determining the similarity between each pairwise combination of patch types and is only relevant if the similarity index is selected (see below). Click on the corresponding browse button and navigate to and select the desired file. Note, FRAGSTATS uses the file extension **.fsq** for

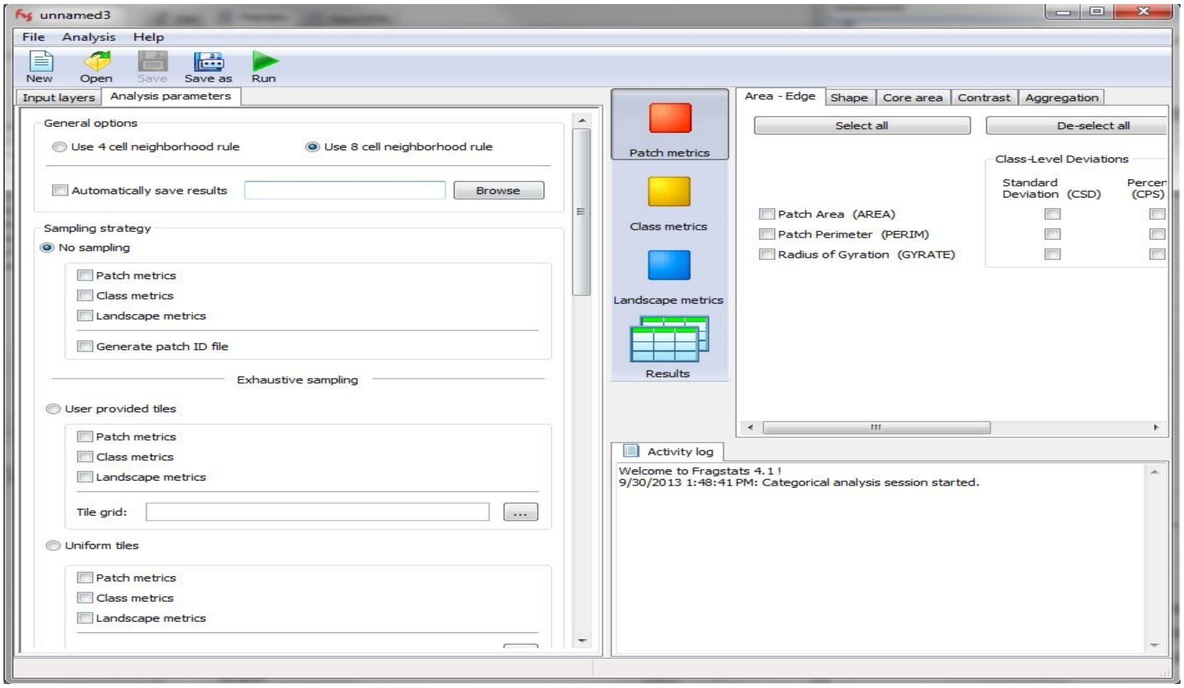

Figure 5. Model dialog for paramterizing FRAGSTATS, shown here for a "new" model that has yet to be parameterized, and with the "Analysis parameters" tab in the left panel selected. Note, the bottom left window (sampling strategy) has been truncated in this image.

similarity weights files and will look for files with this extension by default when navigating. The .fsq extension is not mandatory, but using it can help keep files organized. The syntax for this *comma-delimited ASCII file* is as follows:

FSQ_TABLE
CLASS_LIST_LITERAL(*1stClassName, 2ndClassName, etc.)*
CLASS_LIST_NUMERIC(*1stClassID, 2ndClassID, etc.)*
SimilarityWeight_1-1, SimilarityWeight_1-2, etc.
SimilarityWeight_2-1, SimilarityWeight_2-2, etc.
etc.

- Comment lines start with # and are allowed anywhere in the table.
- FSQ_TABLE must be specified in the first line.
- Two types of class lists are allowed CLASS_LIST_LITERAL() and CLASS_LIST_NUMERIC(), but only the first one encountered is considered.
- Literal class names (*1stClassName, 2ndClassName, etc.,*) are character strings and cannot contain spaces.
- Class Ids (*1stClassID, 2ndClassID, etc.*) are integer values corresponding to class values in the grid.
- With regards to the similarity weights, the order of rows and column is the one specified in the CLASS_LIST_LITERAL() or CLASS_LIST_NUMERIC(), whichever comes first. *SimilarityWeight_i-j* is an integer value giving the similarity weight for the for the focal class designated by the i^{th} *ClassID* and the adjacent class designated by the j^{th}

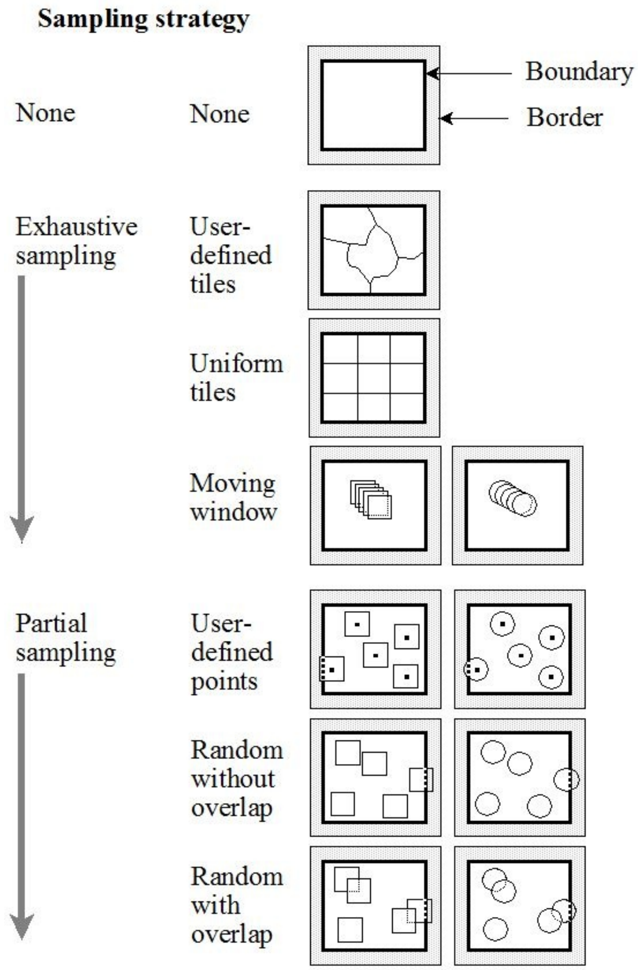

Figure 6. Schematic diagram of alternative landscape sampling strategies.

ClassID).

- Similarity weights must range from 0 (minimum similarity) to 1 (maximum similarity).

The similarity entries must be a square matrix (i.e., same number of rows and columns), must have the same list and order of ClassIDs as given in the CLASS_LIST_LITERAL or CLASS_LIST_NUMERIC, should contain a record for each unique pairwise combination of patch types (classes) in the input landscape (any missing class must be missing in both the rows and columns and will be assigned a zero similarity (minimum) for all comparisons involving that class), and all arguments should be separated by a comma. For example, given four classes the following file would be suitable:

FSQ_TABLE
CLASS_LIST_NUMERIC(2, 3, 4, 5, 6)
1, 0.8, 0, 0.6, 0.4
0.2, 1, 0, 0.8, 0.6

0, 0, 1, 0, 0
0.6, 0.8, 0, 1, 0.8
0.4, 0.6, 0, 0.8, 1

NOTE, this table can be created and managed using any text editor and then simply saved as a comma delimited file (.csv).

NOTE, the similarity matrix can be *asymmetrical*; that is, upper right and lower left triangles do not need to mirror each other. Accordingly, it is important to realize that the rows represent the focal class and the columns represent the adjacent or abutting class. Let's consider the similarity weights for focal class A (or ID=2) in the example above, given in the first row of the similarity matrix. Given a focal patch of class A, a neighboring patch of type B (or ID=3) has a similarity of 0.8. Conversely, given a focal patch of class B, a neighboring patch of class A has a similarity of 0.2. In most cases, however, it is more logical to think of similarity in terms of symmetrical weights.

NOTE, the *diagonals* are typically given a similarity weight of one, because the similarity of two patches of the same class is generally assumed to be maximum, but it is possible to specify a different value.

NOTE, if you have *background* in the image, you need to include the background class value specified in the grid properties during data import, otherwise all background edges will be given a zero weight.

Step 5. Setting Analysis Parameters

Once a dataset has been imported (step 3), and either before or after specifying any common tables (step 4), the next step is to set some global analysis parameters. Note, if you opened a previously saved model, you can modify the analysis parameters as well before executing the program.

In the left pane of the model dialog window make sure the **Analysis parameters** tab is selected, as shown in figure 5.

- **Neighbor rule** – Chose between the 4-cell and 8-cell rule for delineating patches. The 4-cell rule considers only the 4 adjacent cells that share a side with the focal cell (i.e., orthogonal neighbors) for determining patch membership. The 8-cell rule considers all 8 adjacent cells, including the 4 orthogonal and 4 diagonal neighbors. Thus, if the 4-cell rule is selected, two cells of the same class that are diagonally touching will be considered as part of separate patches; if the 8-cell rule is selected, these will be considered part of the same patch. The choice of patch neighbor rule will affect most of the configuration metrics, but will have no affect on the composition metrics. The 8-cell rule is the default.

- **Automatically save results** – You can automatically save the results to output files after execution by checking the **Automatically save results** check box. If you choose to automatically save results, you must also specify a "basename" for the output files by clicking on the browse button and navigating to the desired folder, and then entering a "basename" or selecting an existing file name to overwrite. This basename will be given the extensions .patch, .class, .land and .adj for the corresponding patch, class, and landscape metrics and adjacency matrix, as selected.

- Note, if you do NOT check the **Automatically save results** box, the results can always be saved after the execution from the results dialog box (see below).
- Note, if you check the **Automatically save results** box and fail to specify a basename file for the output, FRAGSTATS will not run and you will get an error message to that effect in the activity log.
- Note, if you specify the basename of a file that already exists, FRAGSTATS will automatically rename the extension of the existing files to *.bk1. The next time there is a conflict, the files will be renamed *.bk2, and so on. Appending the results to an existing file is not an option because there is no guarantee that the output file structure will be the same.
- Note, if you specify the basename of a file name that already exists, you need only include the basename of the file; i.e., the name up to the first period. You do not need to include the file extension, as it will be ignored.

■ **Sampling Strategy** – There are seven different sampling strategies to chose from that facilitate analyzing sub-landscapes, as illustrated in figure 6. You must chose a strategy, and only one strategy is allowed per run. Also, if you specify multiple input layers (i.e., a batch) in the **Input Layers** tab, then 'no sampling' (see below) is the only option allowed. All other sampling options are limited to a single input layer and an error will be sent to the activity log window indicating as much if multiple input layers are listed and one of the sampling options is selected.

1. *No sampling* – The default strategy is 'no sampling' – this is the conventional approach. In this strategy, each input landscape is analyzed as a single landscape. You have the option of computing metrics at the patch, class and landscape levels; you must select at least one level.

   ☐ *Patch metrics* – If selected, patch metrics can be computed. However, this merely enables (i.e., turns on) patch metrics; you still must select one or more individual patch metrics (see below), otherwise no patch metrics will be calculated.

   ☐ *Class metrics* – If selected, class metrics can be computed. However, this merely enables class metrics; you still must select one or more individual class metrics (see below), otherwise no class metrics will be calculated.

   ☐ *Landscape metrics* – If selected, landscape metrics can be computed. However, this merely enables landscape metrics; you still must select one or more individual landscape metrics (see below), otherwise no landscape metrics will be calculated.

   ☐ *Generate patch ID file* – You have the option of creating and outputting a Patch ID image. If you select this option, a patch ID image will be created by FRAGSTATS and output in the same data type format as the Input Data Type. The Patch ID image will contain a unique ID for each patch in the landscape. All background cells will be assigned a negative of the user-specified background value. This patch ID corresponds to the patch ID in the "basename".patch output file. This image is needed if you wish to associate the patch-level output with specific patches and view the results using a GIS. Note, the patch ID file will be named using the following convention and output to the same directory as the input image:

Input file name _4 or 8 (depending on neighbor rule) + ID

Thus, an input file named "test" analyzed with an 8-neighbor rule will be given the following patch ID file name: "test_8id". If you attempt to create and output an ID image that already exists, e.g., from a previous run, FRAGSTATS will ask you whether you want to overwrite the existing file. NOTE, if you are using ArcGrids and if you attempt to create and output an ID image with the same name as a grid that is currently open in another program, e.g., in ArcMap, the grid will be corrupted and an error message will be written to the log window. In this case, the grid folder must be deleted, even after closing ArcMap, before you can create and output an ID image with that name.

2. *User-provided tiles* – The first option for *exhaustive sampling* of the landscape is 'user-provided tiles', in which the landscape is subdivided into user-provided tiles representing sub-landscapes. If this option is selected, you must provide a tile grid that has the same input data format and identical cell size and geographical alignment as the input landscape. In the Tile grid box, click the navigate to button (**...**) and select the corresponding input data type and navigate to and select the desired tile grid. In addition, as described above, you have the option of computing metrics at the patch, class and/or landscape levels – you must select at least one level, and the output will consist of separate results for each sub-landscape.

   In addition, for each tile (or sub-landscape), FRAGSTATS will automatically add a one-cell wide 'border' around the landscape. Recall from the background section that a border is a strip of negatively-valued cells along the landscape boundary outside the landscape of interest. Negative cell values in the border denote that they are 'outside' the landscape of interest. The border provides information on cell adjacency for cells along the landscape boundary and informs both core area and edge contrast metrics (see background section). Note, any added border composed of 'nodata' will be assigned negative background class values.

3. *Uniform tiles* – The second option for *exhaustive sampling* of the landscape is 'uniform tiles', in which FRAGSTATS uniformly subdivides the landscape into square tiles representing sub-landscapes. If this option is selected, you must specify the size of the square tiles by specifying the length of one side (in meters). The default is 100 m. To change the size, click the (**...**) button and enter a new value. Note, the actual size of the tile created may not be equal exactly to the specified side length, because it is constrained to be a multiple of the cell size. Consequently, the actual side length of the tile will always be rounded down to the nearest multiple of the cell size. For example, if the cell size is 30 m and you specify a side length of 500 m, the actual window side length will be 480 m (16*30).

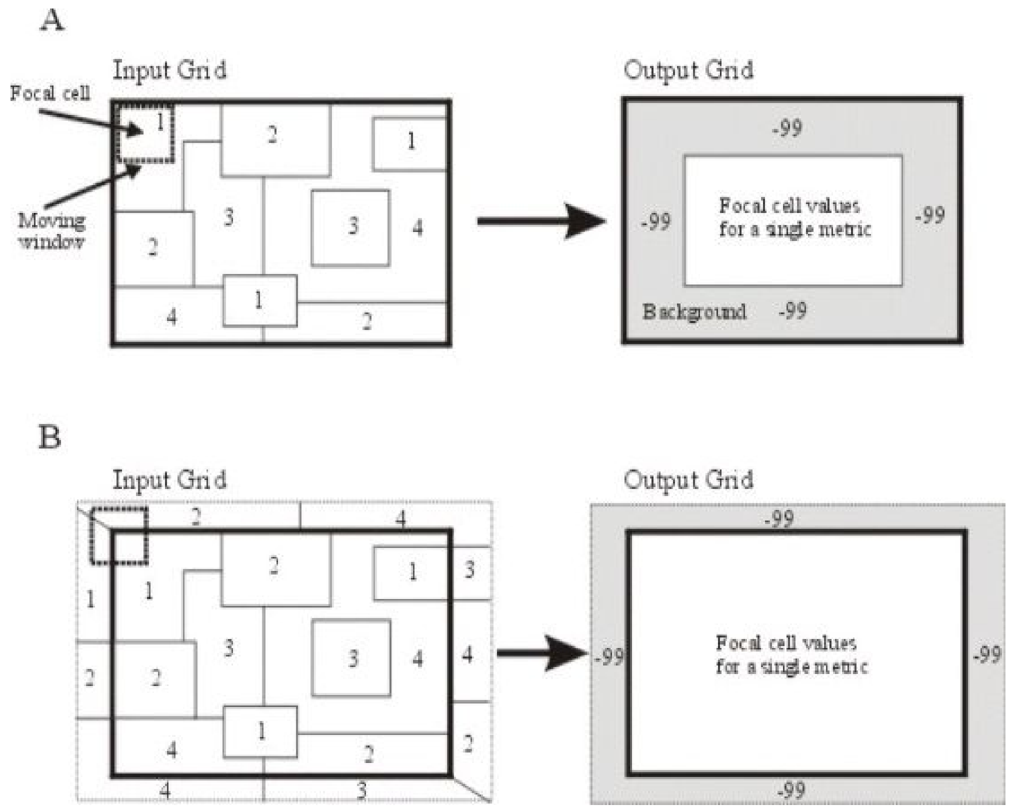

Figure 7. (A) Moving window applied to an input grid without a border produces an output grid for each unique class-metric combination in which a strip the width of the window around the periphery of the grid is given a background value in the output grid. (B) A landscape border at least as wide as the window allows all cells inside the landscape boundary (dark line) (i.e., positive values) to be given the computed focal cell value.

In addition, you also have the option of specifying a criterion for including tiles that contain a maximum percentage of border or nodata cells. The default is 0%, which means that a tile containing any border (negative cell values) or nodata cells will be ignored. If you specify, e.g., 20%, then up to 20% of the tile area can be comprised of border or nodata and the selected metrics will be calculated. Note, some metrics are sensitive to the absolute area of the landscape and, more specifically, to the area 'inside' the landscape (i.e., positive cell values), so modifying this value from the default of zero should be done cautiously and with complete understanding of the implications given the selected metrics.

Lastly, as described above, a border will automatically be included around every tile and you have the option of computing metrics at the patch, class and/or landscape levels – you must select at least one level, and the output will consist of separate results for each sub-landscape.

4. *Moving window* – The third option for *exhaustive sampling* of the landscape is a 'moving

window analysis'. Note, this is similar to the uniform tile strategy above, except that with the uniform tile strategy the tiles are non-overlapping (i.e., mutually exclusive and all inclusive), but with the moving window approach the tiles overlap. If you select the moving window option, then you must specify the level of heterogeneity (class and/or landscape) and the shape (round or square) and size (radius or length of side, in meters) of the window to be used. In addition, as described above, a border will automatically be included around every window and you also have the option of specifying the maximum percentage of the window comprised of border or nodata cells (see below).

A window of the specified shape and size is passed over every positively valued cell in the grid (i.e., all cells *inside* the landscape of interest). However, only cells in which the window does not extend beyond the edge of the rectangular grid and meets the threshold for maximum percentage of border/nodata (as described above) are evaluated (see below). Within each window, each selected metric at the class or landscape level is computed and the value returned to the focal (center) cell. Patch metrics are not allowed in the moving window analysis. The moving window is passed over the grid until every positively valued cell (including positively valued background cells) containing a valid window is assessed in this manner. Note, internal background cells containing real positively-valued classes in the window may receive a value in the output grid, despite the fact that the cell is background in the input grid. Specifically, if the entire window is internal background, then the cell will receive a minus background value in the output grid. There are several important considerations when conducting a moving window analysis:

- *Window shape and size* – The user-specified window size refers to the radius (in meters) of a near-circular window or the length of the side (in meters) of a square window, depending on the shape chosen. It is important to note that the actual area of the window as implemented algorithmically will vary slightly from the area calculated mathematically based on the geometry of a circle or square for two reasons. First, the radius is given as the distance from the focal cell to the edge of the window. For example, given a cell size of 10 m and a circular window, a 40 m radius would be implemented as a mask 4 cells wide. The diameter of the window would equal 90 m–twice the radius plus the size of the focal cell–as opposed to 80 m. The addition of the focal cell to the diameter of the window is necessary to force the focal cell to always be located at the exact center of the window. Second, the specified radius (in meters) is always rounded to the nearest cell. Thus, if the radius is not perfectly divisible by the cell size, the actual window will be somewhat smaller or larger. Essentially, the window will always be rounded to the nearest odd number of cells so that the focal cell is always located at the exact center of the window. In the case of a square window, for example, a user-specified side length of 500 m and a cell size of 50 m would result in a radius of 500/2/50 = 5 cells. The window size in number of cells would be 2 times the radius plus 1 ((2*5)+1=11) cells on a side or an 11x11 window (550x550 m). Note, a user-specified side length of 550 m would result in the same final window, since the radius is always rounded down to the nearest integer.

- *Boundary effects* – Cells located close to the edge of the landscape (i.e., near the landscape boundary) are biased in moving window calculations if the window intersects the landscape boundary. Consider a cell located on the landscape boundary. A normal window placed on that cell would extend well outside the landscape boundary; in fact, half the window would extend beyond the landscape where information on landscape structure is absent. Any cell within the specified radius of a round window or ½ the length of a side of a square window will be biased in this way. There are several alternative ways of handling this bias – none of which are entirely acceptable. FRAGSTATS lets you chose whether you want to include windows that contain border or nodata. The default, and conservative approach, is to not compute the metrics for focal cells containing a partial window (i.e., a window not fully contained within the landscape proper). In this case, FRAGSTATS returns the user-specified exterior (negative) background value for these cells. Thus, in practice, the output grid will contain a peripheral buffer of negatively-valued background cells surrounding the *core* of the landscape – only the core (cells containing a *full* window of positively-valued cells) will contain metric values (Fig. 7a). However, FRAGSTATS also allows you to relax this criterion and compute metrics for windows containing any percentage of border/nodata, but this should be done with caution and a complete understanding of the implications for the selected metrics. IMPORTANTLY, regardless of whether you change the percentage of border/nodata to something greater than 0%, the full window still must lie entirely within the input grid for the window to be considered valid. In other words, first the window must lie entirely within the input grid (including whatever is input as nodata cells, negatively-valued border cells and the positively-valued landscape cells). If the window lies entirely within the input grid, then the window is evaluated as to whether it meets the specified criterion for the minimum percentage of border/nodata cells. If that criterion is met, the window is considered valid and the metrics are computed.

Clearly, as landscape extent increases relative to window size, the magnitude and spatial extent of the boundary effect decreases. For this reason, care should be exercised in selecting a window size that minimizes the loss of information due to the boundary effect. An alternative approach for dealing with the boundary effect is to expand the extent of the input landscape to include a suitably wide *expansion strip* of positively valued, classified cells around the actual landscape of interest, where the width of this extension is equal to the radius of the window (Fig. 7b). In this manner, the *core* of the landscape in the output grid produced by the moving window analysis will align with the original landscape boundary of interest. It is important to realize that including a suitably wide *landscape border* (negatively valued, but classified cells) does not have the same effect. Border, by definition, consists of negatively valued cells outside the landscape of interest, and FRAGSTATS ignores all negatively valued cells when calculating metrics, except for the information they provide on adjacency to positively valued cells.

- *Input data types* – Moving window analysis is restricted to input data types that can effectively handle floating point values. Thus, the 8- and 16-bit binary data formats are not allowed in a moving window analysis. If these data type are included in a batch file used in conjunction with a moving window analysis, the corresponding records will be ignored.

- *Selection of classes and metrics* – For each selected metric and enabled class, FRAGSTATS outputs a separate grid (in the same format as the input grid). Thus, if the input landscape contains 10 classes and all of them are *enabled* in the class descriptors file (see above) and you select one class-level metric, then FRAGSTATS outputs 10 grids, one for each class for the selected metric. In this case, each output grid represents a separate class, and the cell values represent the computed values of the selected metric for that class. Specifically, a window is placed over the first cell in the input landscape, the selected metric is computed for the first class, and this value is output to the corresponding cell in a new grid for that specific metric-class combination. The process is repeated for the next class, and so on, until all classes have been assessed. Next, the window is placed over the next cell and the process is repeated. The process is repeated in this manner until all positively valued cells containing a full window in the input landscape have been evaluated. The end result is a new grid for each class, in which the cell values represent the values of the computed metric. Accordingly, if you select five class-level metrics, then FRAGSTATS outputs 50 grids, one for each class-metric combination. If, in addition to these class metrics, you also select three landscape metrics, FRAGSTATS outputs an additional three grids, one for each landscape metric. Clearly, the number of output grids can increase quickly with several classes and several metrics. Thus, it is important to carefully select the most parsimonious set of classes and metrics. Note, windows containing no cells of the corresponding class, or in some cases just a single cell of the corresponding class, will be assigned a background value in the output grid.

- *Computer processing and memory requirements* – The computer processing and memory demands of the moving window analysis are phenomenal. Consider a relatively small grid of 100 x 100 cells; i.e., 10,000 cells. The moving window analysis involves placing a window over every cell and computing one or more metrics. This is equivalent to doing 10,000 FRAGSTATS analyses. Now imagine that you have a larger grid of 1000 x 1000 cells; i.e., 1,000,000 cells. Clearly, the processing time quickly becomes overwhelming. In addition, the memory demands increase as a function of the size the input grid. FRAGSTATS must be able to allocate memory for at three grids, where each grid requires four bytes for every cell. See Computer Requirements in the Overview Section for a detailed description of the memory requirements. Clearly, given the limited memory available in most personal computers, it is quite possible that you will not have enough memory to do even a single unique class-metric combination, let alone the dozens or hundreds that could easily result if you selected several classes and several metrics. If more than one class-metric combinations are selected, FRAGSTATS will determine how many can be done given the available memory and then parse the job into separate passes. For example, if 20 class-metric combinations are selected, but available memory is sufficient for only four at a time, then FRAGSTATS will conduct five passes across the landscape, output four grids each pass. Given these considerations, it behooves you to use this option sparingly and with great patience until computer processing capabilities increase substantially. And don't be too surprised if your computer is simply unable to allocate sufficient memory to do any moving window analysis.

- *Output grid naming convention* – Given the number of possible output grids

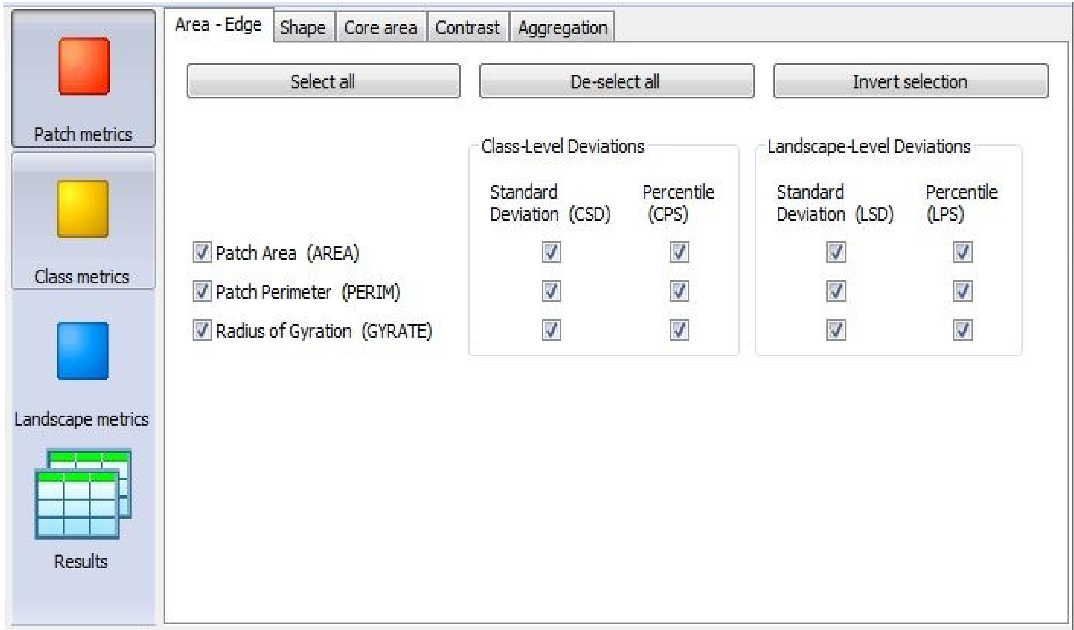

Figure 8. Dialog for selecting and parameterizing metrics.

produced from a moving window analysis and limits on the file name length with some data types (e.g., ArcGrids), the output file naming convention is somewhat cumbersome and limiting. If a moving window analysis is selected, FRAGSTATS will create a new subdirectory beneath the directory containing the input file by appending "_MW1" (for moving window #1) to the name of the input file. Thus, a directory named "Test" containing the input file named "TestGrid" will have a new subdirectory under the Test directory named "TestGrid_MW1". This subdirectory will contain an output grid for each class-metric combination and landscape metric selected. For landscape metrics, the output grids are named using the metric acronym. For example, the landscape-level *Contagion index* (CONTAG) would be given the grid name "contag". For class metrics, the metric acronym is combined with the class ID value (see Class descriptors) because each class has a separate output grid. For example, the class-level *Clumpiness index* (CLUMPY) for class ID #3 would be given the grid name: "clumpy_3". See the list of metrics in the FRAGSTATS Metrics section for the metric acronyms. If a second moving window analysis is conducted on the same input file (e.g., using a different window size), a second directory is created by appending "_MW2" to the name of the input file. And so on for each subsequent moving window analysis.

Importantly, for reasons unknown to us, ArcGrid names are limited to 13 characters. The naming convention above for some class metrics with long names (e.g., gyrate_am) is problematic at the class level if the numeric class value exceeds three digits. For example, a class value of 3000 for gyrate_am would end up with the name "gyrate_am_3000", which is one digit too long for ArcGIS. So, in a few cases the class metric names have been shortened (just for the moving window output grids) to accommodate up to a 4 digit class value, including the following metrics: "gyrate" becomes "gyra", "circle" becomes "circ", and "contig" becomes "cont". If the final grid is still too long because the class value is more than four digits, an error will be logged and you will need to shorten the numeric class values in your input grid.

5. *User-provided points* – The first option for *partial sampling* of the landscape is 'user-provided points', in which FRAGSTATS puts a window of specified size and shape around each user-provided point (focal cell) as the basis for defining sub-landscapes. Note, the actual window size may differ from the specified size for the reasons described above (see moving window). If you select this option, then you must provide either a grid or table that identifies the points (focal cells), and you must specify the level of heterogeneity (patch, class and/or landscape) and the shape (round or square) and size (radius or length of side, in meters) of the window to be used, and the output will consist of separate results for each sub-landscape (point). In addition, as described above, a border will automatically be included around every window and you also have the option of specifying the maximum percentage of the window comprised of border or nodata cells. Lastly, as described above for moving windows, any window that extends beyond the edge of the rectangular grid will be ignored.

   - *Points grid* – If you select the points grid as the means of designating the focal cells, then the points grid must have the same input data format and identical extent, cell size and geographical alignment as the input landscape. In the Points grid box, click the navigate to button (**...**) and select the corresponding input data type and navigate to and select the desired points grid. Note, if you have point layer in vector format, you must convert it to a raster grid to use this option. The grid should contain unique non-zero, positive integer values for the points (focal cells) and all other cells should be assigned nodata values.

   - *Points table* – If you select the point table as the means of designating the focal cells, then click on the corresponding browse to button (**...**) and navigate to and select the desired file. Note, FRAGSTATS uses the file extension .fpt for points files and will look for files with this extension by default when navigating. The .fpt extension is not mandatory, but using it can help keep files organized. The syntax for this *ASCII file* is as follows:

     FPT_TABLE
     [*first point id#*: *first point row#*: *first point col#*]
     [*second point id#*: *second point row#*: *second point col#*]
     etc.

     - Comment lines start with # and are allowed anywhere in the table.
     - FPT_TABLE must be specified in the first line.
     - Each bracketed item contains point coordinates of the following form: [id : row : column] or [id:row:column].
     - Point id values must be unique integer values, duplicates will be ignored.
     - Row and column values must be integer values within the ranges specific to the target dataset, and represent row and column numbers not geographic coordinates, starting from the top left corner and including the nodata portion of the grid (i.e., the

topmost row is row #1, and the leftmost column is col #1); out-of-range and duplicate coordinates will be ignored.

For example, for a table containing three focal points, the following file would be suitable:

FPT_TABLE
[1:2819:17300]
[2:2752:17300]
[3:1880:17303]

NOTE, this table can be created and managed using any text editor and then simply saved as an ASCII text file.

6. *Random points without overlap* – The second option for *partial sampling* of the landscape is 'random points without overlap' in which FRAGSTATS will select a user-specified number of focal cells at random and put a window of specified size and shape around each point as the basis for defining sub-landscapes. If you select this option, then you must specify the level of heterogeneity (patch, class and/or landscape), the shape (round or square) and size (radius or length of side, in meters) of the window to be used, and the target number of focal cells (to be selected randomly), and the output will consist of separate results for each sub-landscape (point). Note, the actual window size may differ from the specified size for the reasons described above (see moving window). In addition, as described above, a border will automatically be included around every window and you also have the option of specifying the maximum percentage of the window comprised of border or nodata cells.

   Importantly, this option prevents the windows around the selected focal cells to overlap; thus, the sub-landscapes are non-overlapping. However, depending on the target number of points specified and the size and shape of the window specified, it may not be possible to meet the target number of windows. FRAGSTATS attempts to meet the target, but after a threshold number of failed attempts due to overlapping existing windows, FRAGSTATS terminates the process. Thus, in practice, you may not get the desired number of random sub-landscapes.

7. *Random points with overlap* – The second option for *partial sampling* of the landscape is 'random points with overlap' in which FRAGSTATS selects a user-specified number of focal cells at random and puts a window of specified size and shape around each point as the basis for defining sub-landscapes. If you select this option, then you must specify the level of heterogeneity (patch, class and/or landscape), the shape (round or square) and size (radius or length of side, in meters) of the window to be used, and the target number of focal cells (to be selected randomly), and the output will consist of separate results for each sub-landscape (point). Note, the actual window size may differ from the specified size for the reasons described above (see moving window). In addition, as described above, a border will automatically be included around every window and you also have the option of specifying the maximum percentage of the window comprised of border or nodata cells.

Importantly, this option prevents the windows around the selected focal cells to overlap; thus, the sub-landscapes are non-overlapping. However, depending on the target number of points specified and the size and shape of the window specified, it may not be possible to meet the target number of windows. FRAGSTATS attempts to meet the target, but after a threshold number of failed attempts due to overlapping existing windows, FRAGSTATS terminates the process. Thus, in practice, you may not get the desired number of random sub-landscapes.

Step 6. Selecting and Parameterizing Patch, Class, and Landscape Metrics

The next step is to select and parameterize the patch, class, and landscape metrics. Note, these options are only consequential if you select the respective levels in the **Analysis Parameters** dialog box (Fig. 5). The metrics are selected and parameterized (as needed) in the right pane of the model dialog (Fig. 8). Note, there is a separate set of tabbed dialogs for each level of metrics (patch, class, and landscape). Each dialog box consists of a series of tabbed pages. Each tabbed page represents a group of related metrics as discussed in the Background section, although the aggregation tab includes all of the aggregation, subdivision and isolation groups of metrics.

The selection of metrics is relatively straightforward. On each tabbed page select the desired individual metrics using the check boxes, or select all of the metrics using the **Select All** button. You can also **De-select All** or **Invert** your selection using the corresponding buttons. Each metric is discussed in detail in the FRAGSTATS Metrics section.

A number of metrics require you to provide additional parameters before they can be calculated. In most cases, this involves entering a number in a text box, while in other cases, this involves specifying a separate table. These special requirements are described below in association with the corresponding tabbed page.

- **Area-Edge** – If you select *Total Edge* (TE) or *Edge Density* (ED) on the **Area-Edge** tab at either the class or landscape level, you must also specify how you want to treat **boundary** and **background** edges (Fig. 1); specifically, what percentage of the landscape boundary and background class edges to treat as *true* edge and therefore included in the edge length calculations? Note, if a border is present, then only background edges are affected by this designation, since all other edges along the landscape boundary will be made explicit by the information in the border. If a border is absent, then all boundary and background edges are affected. See the Overview section for a more detailed discussion. There are three options to choose from by clicking on the select button **[...]**:

    - **None** – Do not count any boundary/background as edge (0%). This is the default.

    - **All** – Count all boundary/background as edge (100%).

    - **Partial** – Specify the percentage of boundary/background edge to treat as an edge (0-100%). For example, if you specify 50%, then half the total length of edge of involving the landscape boundary (if a border is absent) and any internal background will be included as edge in the affected metrics.

- **Core area** – If you select any of the core area metrics on the **Core area tab**, you must also either specify a **fixed edge depth** (in meters) or specify an **edge depth table** as described previously (see Specifying Common Tables).

- **Contrast** – If you select any of the contrast metrics on the **Contrast tab**, you must also specify an **edge contrast** table as described previously (see Specifying Common Tables).

- **Aggregation** – If you select *Proximity index* (PROX) or *Similarity index* (SIMI) on the **Aggregation tab** at either the class or landscape level, you must also specify a **search radius** (i.e., the distance [in meters] from a focal patch within which neighboring patches are evaluated). There is no default value, so if you fail to enter a distance, an error message will be written to the Activity log window upon execution and the run will fail. In addition, if you select the similarity index, you must also specify a **similarity weights table** as described previously (see Specifying Common Tables).

  Likewise, if you select the *Connectance index* (CONNECT) at either the class or landscape level, you must also specify a **threshold distance** (i.e., the distance [in meters] between patches below which they are deemed connected). There is no default value, so if you fail to enter a distance, an error message will be written to the Activity log window upon execution and the run will fail.

- **Diversity** – If you select *Relative patch richness* (RPR) on the **Diversity tab** at the landscape level, you must also specify the **maximum number of classes**. There is no default value, so if you fail to enter a distance, an error message will be written to the Activity log window upon execution and the run will fail.

Step 7. Executing FRAGSTATS

Now you are finally ready to execute FRAGSTATS. Click on the **Run** button on the toolbar or select **Run** from the Analysis drop-down menu. This will open up the Run dialog (Fig. 9) that will list the analysis type (referring to the sampling method selected), current file, number of metrics selected at each level, and prompt you to click on **Proceed** to execute or **Cancel** to cancel the run. The Current file will be blank until clicking on **Proceed**, after which it will list the current file being processed. Thus, if you are running a batch file, then it will list each input file in turn as it is being processed. After the run is executed, the Activity log will report that the run has ended. In addition, if you have automatically saved results, the Activity log will indicate that the results were saved to the specified location. For long runs, a

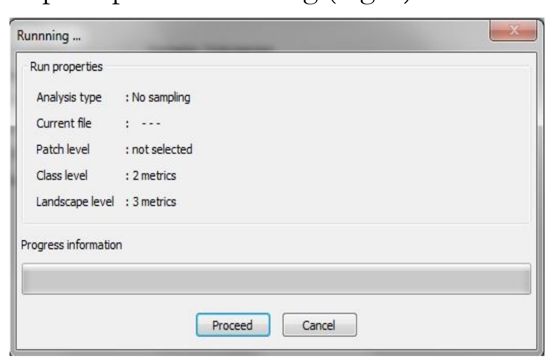

Figure 9. Run dialog to execute FRAGSTATS.

progress indicator will display the progress of the run, and the activity log will report on various stages of the run. For example, for batch processing the activity log will report on the stages of processing each input layer.

Step 8. Browsing and Saving the Results

The final step is to browse the output and, if desired, save it to a file (potentially several files). After the run has ended (as indicated in the Activity log), click on the **Results** button in the right pane of the model dialog (Fig. 10). In the corresponding dialog, the **Run list** includes a list of all the input layers analyzed in each run. For example, if the batch manager included two input layers, then after the execution the run list will include the results for the two input layers, and they will be listed with the prefix R-001 to indicate Run number one (Fig. 10). A second execution will list the results for each input layer, but with the prefix R-002, and so on for subsequent runs during the same session. For each input layer, there is a separate set of tabbed dialogs for each level of metrics: patch, class, and landscape. If you did not previously check the **Automatically save results** box and specify a basename for the output files (see Setting Analysis Parameters) prior to executing the run, then you can save the results to output files here.

Clicking on a particular input layer and a tab allows you to quickly view and evaluate the results of an analysis before actually saving it to a file(s). This can save you the time of opening the results in a separate text editor or importing the data to a spreadsheet before "seeing" the output. Note, the tabs will only contain data if the corresponding metrics were selected for the analysis. In addition, each time you execute a run within the same session, the results will be added to the results manager. The results of your current session can be managed with the following options:

- **Save ADJ file** – If you check the **Save ADJ file** box in the Run list manager, the cell adjacency file will be saved (basename.adj) when the corresponding run is saved (see Output files in the Overview for information on the adjacency file).

- **Save run as...** – If you click the **Save run as ...** button, you will be prompted to navigate to a destination folder and provide a basename for the output files (see Output files in the Overview for information on the output files corresponding to the patch, class and landscape metrics) associated with the corresponding run (i.e., the run associated with the highlighted input layer in the **Run list**). Note, the "basename" will be combined with the .patch, .class, and .land extensions for the corresponding output files, as well as the .adj extension for the adjacency matrix if the save ADJ file box is checked. If you attempt to save to a file name that already exists, you will be prompted as to whether you want to overwrite this file or not; appending the results to an existing file is not an option because there is no guarantee that the output file structure will be the same. If you wish to append the results of several runs with identical output formats, you will have to do so manually at your own risk. Importantly, saving a run involves saving the results for all of the input layers associated with the run of the highlighted layer to a single output file(s). Thus, if run #1 consists of five input layers, and any of the input layers are highlighted in the run list, then the results for each of the five input layers will be appended to a single output file for each level of metrics selected. For example, the basename.land file will contain the landscape-level metrics for all five input layers associated with run #1.

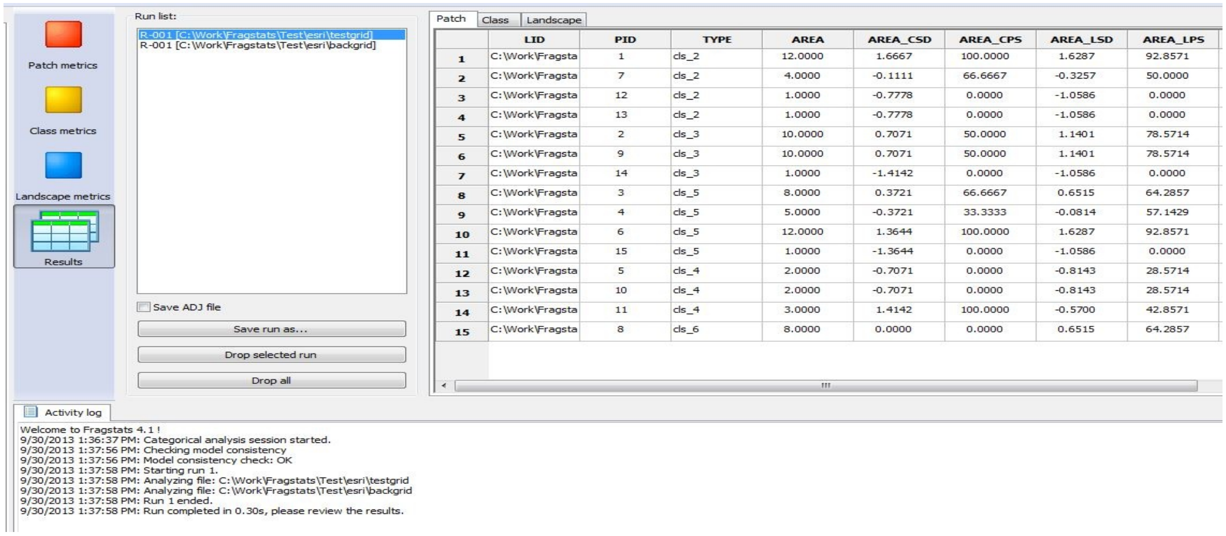

Figure 10. Results dialog depicting the layers analyzed and the corresponding patch, class and/or landscape metrics computed for each layer.

- **Drop selected run** – If you click the **Drop selected run** button, the results associated with the run number highlighted in the **Run list** will be dropped from the results. Note, the results for all of the layers associated with the run of the layer highlighted will be dropped, not just the results of the layer highlighted.

- **Drop all** – If you click the **Drop all** button, then all the runs in the **Run list** will be dropped from the results.

Step 9. Getting Help

The Help drop-down menu provides you with online help.

- **Help Content** – Allows you to access a familiar windows-based help interface with the standard content, index, and find options. The help files include information on "what's new", background on landscape pattern analysis, user guidelines, and details on the metrics.

- **About FRAGSTATS** – Lists the authors and the software release version.

Running via the Command Line

FRAGSTATS can be executed via a command line to allow you to run FRAGSTATS from within another program (e.g., R). The command line control is limited to specifying a FRAGSTATS model file (.fca). In essence, you can call FRAGSTATS, specify an existing model, and execute the model from a single command line. However, the model file must be created first via the Graphical User

Interface in the usual way–there are simply too many parameters to make full specification via the command line a practical alternative at this time. The syntax for this command line call is as follows (note, there is a required space before and after -m, -b and -o in the command line below):

```
frg -m model_name_here -b batch_file_name_here -o output_file_name_here
```

Here are some example valid command line calls:

```
frg -m test.fca
frg.exe -m test.fca
c:\foobar\frg -m test.fca
frg -m test.fca -b c:\foobar\batch_file.fbt
frg -m test.fca -o c:\foobar\basename
frg -m test.fca -b c:\foobar\batch_file.fbt -o c:\foobar\basename
```

There are several important considerations regarding the arguments in the command line:

- **frg [required]** – frg simply calls and executes the program. The .exe extension is optional (i.e., either frg or frg.exe will work) and it is NOT case sensitive. If the FRAGSTATS executable (frg.exe) is NOT in the current folder OR is NOT specified in the system's Path variable, then the full path to the executable is required, as in the third example given.

- **-m [required]** – This is a *required* switch to name a FRAGSTATS model file (.fca). The model file is a fully parameterized model created via the graphical user interface. This file specifies all required and user-selected parameters of the analysis. It should be parameterized completely according to the instructions given elsewhere for Running FRAGSTATS via the Graphical User Interface. Note, FRAGSTATS parameterization files are assigned the .fca extension and this should be included in the argument. If the model file does not exist or is improperly formatted, the execution will fail.

- **-b [optional]** – This is an optional switch to name a FRAGSTATS batch file (.fbt). The batch file lists the input layers and the corresponding grid attributes of each layer (see previous discussion). If you specify the -b switch, then you must provide a batch file. The batch file specified here will override whatever is specified in the model file. Thus, the model file can be created without specifying any input layers, if you intend on specifying a batch file here. Note, specifying a batch file here is identical to loading the same batch file in the model via the graphical user interface and not specifying the -b switch here. Importantly, if you do NOT specify the -b switch, then the input layers must be specified in the model file, or the execution will fail.

- **-o [optional]** – This is an *optional* switch to name an output file name (i.e., basename). The output file name is the basename for the output files corresponding to each level of metrics selected (basename.patch, basename.class, basename.land, and basename.adj). If you specify the -o switch, then you must provide an output file name with a complete path. Note, if you specify the basename of a file that already exists, FRAGSTATS will automatically rename the extension of the existing files to *.bk1. The next time there is a conflict, the files will be renamed *.bk2, and so on. Appending the results to an existing file is not an option because there is no guarantee that the output file structure will be the same. Importantly, if you do NOT specify the -o switch, then the output file (basename) must be specified and the **Automatically save results...** button checked in the model file, or the execution will fail.

FRAGSTATS METRICS

Overview

FRAGSTATS computes several statistics for each patch and class (patch type) in the landscape and for the landscape as a whole. At the class and landscape level, some of the metrics quantify landscape composition, while others quantify landscape configuration. Landscape composition and configuration can affect ecological processes independently and interactively (see Background). Thus, it is especially important to understand for each metric what aspect of landscape pattern is being quantified. In addition, many of the metrics are partially or completely redundant; that is, they quantify a similar or identical aspect of landscape pattern. In most cases, redundant metrics will be very highly or even perfectly correlated. For example, at the landscape level, *patch density* (PD) and *mean patch size* (MPS) will be perfectly correlated because they represent the same information. These redundant metrics are alternative ways of representing the same information; they are included in FRAGSTATS because the preferred form of representing a particular aspect of landscape pattern will differ among applications and users. It behooves the user to understand these redundancies, because in most applications only 1 of each set of redundant metrics should be employed. It is important to note that in a particular application, some metrics may be empirically redundant as well; not because they measure the same aspect of landscape pattern, but because for the particular landscapes under investigation, different aspects of landscape pattern are statistically correlated. The distinction between this form of redundancy and the former is important, because little can be learned by interpreting metrics that are inherently redundant, but much can be learned about landscapes by interpreting metrics that are empirically redundant.

Many of the patch indices have counterparts at the class and landscape levels. For example, many of the class indices (e.g., mean shape index) represent the same basic information as the corresponding patch indices (e.g., patch shape index), but instead of considering a single patch, they consider all patches of a particular type simultaneously. Likewise, many of the landscape indices are derived from patch or class characteristics. Consequently, many of the class and landscape indices are computed from patch and class statistics by summing or averaging over all patches or classes. Even though many of the class and landscape indices represent the same fundamental information, naturally the algorithms differ slightly. Class indices represent the spatial distribution and pattern within a landscape of a single patch type; whereas, landscape indices represent the spatial pattern of the entire landscape mosaic, considering all patch types simultaneously. Thus, even though many of the indices have counterparts at the class and landscape levels, their interpretations may be somewhat different. Most of the class indices can be interpreted as fragmentation indices because they measure the configuration of a particular patch type; whereas, most of the landscape indices can be interpreted more broadly as landscape heterogeneity indices because they measure the overall landscape pattern. Hence, it is important to interpret each index in a manner appropriate to its scale (patch, class, or landscape).

In the sections that follow, each metric computed in FRAGSTATS is described in detail. Metrics are grouped according to the aspect of landscape pattern measured (see Background), as follows:

- Area and edge metrics

- Shape metrics
- Core area metrics
- Contrast metrics
- Aggregation metrics
- Diversity metrics

Within each of these groups, metrics are further grouped into patch, class, and landscape metrics, as described below.

Patch Metrics

Patch metrics are computed for every patch in the landscape; the resulting patch output file contains a row (observation vector) for every patch, where the columns (fields) represent the individual metrics. The first three columns include header information about the patch:

- **Landscape ID**.--The first field in the patch output file is *Landscape ID* (LID). Landscape ID is set to the name of the input image obtained from the input file (see Run Parameters).

- **Patch ID**.--The second field in the patch output file is *Patch ID* (PID). If a Patch ID image is specified that contains unique ID's for each patch, FRAGSTATS reads the patch ID from the designated image. If an image is not specified, FRAGSTATS creates unique ID's for each patch and optionally produces an image that contains patch ID's that correspond to the FRAGSTATS output.

- **Patch Type**.--The third field in the patch output file is *Patch type* (TYPE). FRAGSTATS contains an option to name an ASCII file (class descriptors file) that contains character descriptors for each patch type. If the class descriptors option is not used, FRAGSTATS will write the numeric patch type codes to TYPE.

There are two basic types of metrics at the patch level: (1) indices of the spatial character and context of individual patches, and (2) measures of the deviation from class and landscape norms; that is, how much the computed value of each metric for a patch deviates from the class and landscape means. The deviation statistics are useful in identifying patches with extreme values on each metric. Because the deviation statistics are computed similarly for all patch metrics, they are described in common below:

Patch Deviation Statistics.--In addition to the standard patch metrics, FRAGSTATS computes several deviation statistics for each patch that measures how much it deviates from the class or landscape norm (i.e., how extreme an observation it is) for each metric. Specifically, for each patch and each patch metric, FRAGSTATS computes the following four measures of deviation:

Standard Deviations from the Class Mean

$$CSD = \frac{x_{ij} - \bar{x}_i}{s_i}$$	x_{ij} = value of a patch metric for patch ij. $\bar{x}_i$ = mean value of the corresponding patch metric for patch type (class) i. s_i = standard deviation of the corresponding patch metric for patch type (class) i.
Description	CSD equals the value of the metric (x) for the focal patch (ij) minus the mean of the metric across all patches in the focal class, divided by the class standard deviation (population formula).
Units	Same as the metric
Range	-∞ < metric < +∞ Although standard deviation has no theoretical limit, 66.5% of the observations (assuming a normal distribution) will be within ±1 standard deviations of the mean, 95% within ±2 standard deviations, and 99.7% within ±3 standard deviations.
Comments	The number of standard deviations from the class mean is obtained from a z-score transformation of the observed value using the mean and standard deviation derived from all patches in the focal class. This transformation results in a standardized metric that has zero mean and unit variance for the class. Any observation that is, say, more than 2.5 standard deviations from the class mean can be considered an extreme observation. This is a quick and easy way to identify patches with extreme values of a metric. However, it is necessary to assume an underlying normal distribution in order for standard deviations to have a direct interpretation regarding the percent of the distribution greater or smaller than the observed value. CSD can be computed for each patch metric and is reported in the patch output file as the metric name followed by _CSD. For example, the class standard deviation metric for the shape index (SHAPE) would be given the variable name: SHAPE_CSD.

Percentile of the Class Distribution	
$$CPS = \left(\frac{rank(x_{ij}) - 1}{n_i - 1}\right)(100)$$	x_{ij} = value of a patch metric for patch ij. n_i = number of patches of the corresponding patch type (class) i.
Description	CPS equals the percentile of the rank-ordered distribution of all patches in the focal class for the corresponding metric (x); that is, the percent of observations in rank order that are smaller than the observed value for the focal patch (ij).
Units	Percent

Range	0 ≤ metric ≤ 100 CPS = 0 if the observed patch metric is the lowest value for any patch in the class. Conversely, CPS = 100 if the observed patch metric is the highest value for any patch in the class.
Comments	The percentile of the class distribution is obtained by rank ordering observations from lowest to highest and computing the percentage of observations smaller than the observed value for the focal patch. In contrast to standard deviation, this deviation statistic makes no assumption about the underlying distribution; it simply quantifies the percent of the observed distribution that is smaller than the observed value for the focal patch under consideration.

Standard Deviations from the Landscape Mean	
$LSD = \frac{x_{ij} - \bar{x}}{s}$	x_{ij} = value of a patch metric for patch ij. $\bar{x}$ = mean value of the corresponding patch metric across all patches in the landscape. s = standard deviation of the corresponding patch metric for all patches in the landscape.
Description	LSD equals the value of the metric (x) for the focal patch (ij) minus the mean of the metric across all patches in the landscape divided by the landscape standard deviation (population formula).
Units	Same as the metric
Range	-∞ < metric < +∞ Although standard deviation has no theoretical limit, 66.5% of the observations (assuming a normal distribution) will be within ±1 standard deviations of the mean, 95% within ±2 standard deviations, and 99.7% within ±3 standard deviations.

Comments	The number of standard deviations from the landscape mean is obtained from a z-score transformation of the observed value using the mean and standard deviation derived from all patches in the landscape. This transformation results in a standardized metric that has zero mean and unit variance for the entire landscape. Any observation that is, say, more than 2.5 standard deviations from the landscape mean can be considered an extreme observation. This is a quick and easy way to identify patches with extreme values of a metric. However, it is necessary to assume an underlying normal distribution in order for standard deviations to have a direct interpretation regarding the percent of the distribution greater or smaller than the observed value. LSD can be computed for each patch metric and is reported in the patch output file as the metric name followed by a _LSD. For example, the landscape standard deviation metric for the shape index (SHAPE) would be given the variable name: SHAPE_LSD.

Percentile of the Landscape Distribution	
$LPS = \left(\frac{rank(x_{ij}) - 1}{N - 1} \right)(100)$	x_{ij} = value of a patch metric for patch ij. N = number of patches in the landscape.
Description	LPS equals the percentile of the rank ordered distribution of all patches in the landscape for the corresponding metric (x); that is, the percent of observations in rank order that are smaller than the observed value for the focal patch (ij).
Units	Percent
Range	$0 \leq metric \leq 100$ LPS = 0 if the observed patch metric is the lowest value for any patch in the landscape. Conversely, LPS = 100 if the observed patch metric is the highest value for any patch in the landscape.
Comments	The percentile of the landscape distribution is obtained by rank ordering observations from lowest to highest and computing the percentage of observations smaller than the observed value for the focal patch. In contrast to standard deviation, this deviation statistic makes no assumption about the underlying distribution; it simply quantifies the percent of the observed distribution that is smaller than the observed value for the focal patch under consideration.

Class Metrics

Class metrics are computed for every patch type or class in the landscape; the resulting class output file contains a row (observation vector) for every class, where the columns (fields) represent the individual metrics. The first two columns include header information about the class:

- **Landscape ID**.--The first field in the class output file is *Landscape ID* (LID). Landscape ID is set to the name of the input image obtained from the input layer.

- **Patch Type**.--The second field in the class output file is *Patch type* (TYPE). FRAGSTATS contains an option to name an ASCII file (class descriptors file) that contains character descriptors for each patch type. If the class descriptor option is not used, FRAGSTATS will write the numeric patch type codes to TYPE.

There are two basic types of metrics at the class level: (1) indices of the amount and spatial configuration of the class, and (2) distribution statistics that provide first- and second-order statistical summaries of the patch metrics for the focal class. The latter are used to summarize the mean, area-weighted mean, median, range, standard deviation, and coefficient of variation in the patch attributes across all patches in the focal class. Because the distribution statistics are computed similarly for all class metrics, they are described in common below:

Class Distribution Statistics.--Class metrics measure the aggregate properties of the patches belonging to a single class or patch type. Some class metrics go about this by characterizing the aggregate properties without distinction among the separate patches that comprise the class. These metrics are defined elsewhere. Another way to quantify the configuration of patches at the class level is to summarize the aggregate distribution of the patch metrics for all patches of the corresponding patch type. In other words, since the class represents an aggregation of patches of the same type, we can characterize the class by summarizing the patch metrics for the patches that comprise each class. There are many possible first- and second-order statistics that can be used to summarize the patch distribution. FRAGSTATS computes the following: (1) *Mean* (MN), (2) *Area-weighted mean* (AM), (3) *Median* (MD), (4) *Range* (RA), (5) *Standard deviation* (SD), and (6) *Coefficient of variation* (CV). FRAGSTATS computes these distribution statistics for all patch metrics at the class level. In the class output file, these metrics are labeled by concatenating the metric acronym with an underscore and the distribution statistic acronym. For example, *Patch area* (AREA) is summarized at the class level by each of the distribution statistics and reported in the class output file as follows: *Mean patch area* (AREA_MN), *Area-weighted mean patch area* (AREA_AM), *Median patch area* (AREA_MD), *Range in patch area* (AREA_RA), *Standard deviation in patch area* (AREA_SD), and *Coefficient of variation in patch area* (AREA_CV).

$MN = \dfrac{\sum_{j=1}^{n} x_{ij}}{n_i}$	MN (Mean) equals the sum, across all patches of the corresponding patch type, of the corresponding patch metric values, divided by the number of patches of the same type. MN is given in the same units as the corresponding patch metric.

$AM = \sum_{j=1}^{n} \left[x_{ij} \left(\frac{a_{ij}}{\sum_{j=1}^{n} a_{ij}} \right) \right]$	AM (area-weighted mean) equals the sum, across all patches of the corresponding patch type, of the corresponding patch metric value multiplied by the proportional abundance of the patch [i.e., patch area (m^2) divided by the sum of patch areas].
$MD = x_{50\%}$	MD (median) equals the value of the corresponding patch metric for the patch representing the midpoint of the rank order distribution of patch metric values for patches of the corresponding patch type.
$RA = x_{max} - x_{min}$	RA (range) equals the value of the corresponding patch metric for the largest observed value minus the smallest observed value (i.e., the difference between the maximum and minimum observed values) for patches of the corresponding patch type.
$SD = \sqrt{\frac{\sum_{j=1}^{n} \left[x_{ij} - \left(\frac{\sum_{j=1}^{n} x_{ij}}{n_i} \right) \right]^2}{n_i}}$	SD (standard deviation) equals the square root of the sum of the squared deviations of each patch metric value from the mean metric value of the corresponding patch type, divided by the number of patches of the same type; that is, the root mean squared error (deviation from the mean) in the corresponding patch metric. Note, this is the population standard deviation, not the sample standard deviation.
$CV = \frac{SD}{MN}(100)$	CV (coefficient of variation) equals the standard deviation divided by the mean, multiplied by 100 to convert to a percentage, for the corresponding patch metric.

Landscape Metrics

Landscape metrics are computed for entire patch mosaic; the resulting landscape output file contains a single row (observation vector) for the landscape, where the columns (fields) represent the individual metrics. The first column includes header information about the landscape:

(L1) Landscape ID.--The first field in the landscape output file is landscape ID (LID). Landscape ID is set to the name of the input image obtained from the input file.

Like class metrics, there are two basic types of metrics at the landscape level: (1) indices of the composition and spatial configuration of the landscape, and (2) distribution statistics that provide first- and second-order statistical summaries of the patch metrics for the entire landscape. The latter are used to summarize the mean, area-weighted mean, median, range, standard deviation, and coefficient of variation in the patch attributes across all patches in the landscape. Because the distribution statistics are computed similarly for all landscape metrics, they are described in common below:

Landscape Distribution Statistics.--Landscape metrics measure the aggregate properties of the entire patch mosaic. Some landscape metrics go about this by characterizing the aggregate properties without distinction among the separate patches that comprise the mosaic. These metrics are defined elsewhere. Another way to quantify the configuration of patches at the landscape level is to summarize the aggregate distribution of the patch metrics for all patches in the landscape. In other words, since the landscape represents an aggregation of patches, we can characterize the landscape by summarizing the patch metrics. There are many possible first- and second-order statistics that can be used to summarize the patch distribution. FRAGSTATS computes the following: (1) *Mean* (MN), (2) *Area-weighted mean* (AM), (3) *Median* (MD), (4) *Range* (RA), (5) *Standard deviation* (SD), and (6) *Coefficient of variation* (CV). FRAGSTATS computes these distribution statistics for all patch metrics at the landscape level. In the class output file, these metrics are labeled by concatenating the metric acronym with an underscore and the distribution statistic acronym. For example, *Patch area* (AREA) is summarized at the landscape level by each of the distribution statistics and reported in the class output file as follows: *Mean patch area* (AREA_MN), *Area-weighted mean patch area* (AREA_AM), *Median patch area* (AREA_MD), *Range in patch area* (AREA_RA), *Standard deviation in patch area* (AREA_SD), and *Coefficient of variation in patch area* (AREA_CV). Note, the acronyms for the distribution statistics are the same at the class and landscape levels, so they can only be distinguished by the output file they belong to (i.e., ".basename".class or "basename".land).

$MN = \frac{\sum_{i=1}^{m}\sum_{j=1}^{n} x_{ij}}{N}$	MN (Mean) equals the sum, across all patches in the landscape, of the corresponding patch metric values, divided by the total number of patches. MN is given in the same units as the corresponding patch metric.

$$AM = \sum_{i=1}^{m}\sum_{j=1}^{n}\left[x_{ij}\left(\frac{a_{ij}}{\sum_{i=1}^{m}\sum_{j=1}^{n}a_{ij}}\right)\right]$$	AMN (area-weighted mean) equals the sum, across all patches in the landscape, of the corresponding patch metric value multiplied by the proportional abundance of the patch [i.e., patch area (m^2) divided by the sum of patch areas]. Note, the proportional abundance of each patch is determined from the sum of patch areas rather than the total landscape area, because the latter may include internal background area not associated with any patch.
$$MD = x_{50\%}$$	MD (median) equals the value of the corresponding patch metric for the patch representing the midpoint of the rank order distribution of patch metric values based on all patches in the landscape.
$$RA = x_{max} - x_{min}$$	RA (range) equals the value of the corresponding patch metric for the largest observed value minus the smallest observed value (i.e., the difference between the maximum and minimum observed values) for all patches in the landscape.
$$SD = \sqrt{\frac{\sum_{i=1}^{m}\sum_{j=1}^{n}\left[x_{ij} - \left(\frac{\sum_{i=1}^{m}\sum_{j=1}^{n}x_{ij}}{N}\right)\right]^2}{N}}$$	SD (standard deviation) equals the square root of the sum of the squared deviations of each patch metric value from the mean metric value computed for all patches in the landscape, divided by the total number of patches; that is, the root mean squared error (deviation from the mean) in the corresponding patch metric. Note, this is the population standard deviation, not the sample standard deviation.
$$CV = \frac{SD}{MN}(100)$$	CV (coefficient of variation) equals the standard deviation divided by the mean, multiplied by 100 to convert to a percentage, for the corresponding patch metric.

General Comments

Not all groups of metrics (see previous list) have metrics at all levels. For example, diversity metrics only exist at the landscape level. Also note that the organizational hierarchy used here is opposite of that used in the FRAGSTATS graphical user interface (GUI). In the GUI, metrics are first grouped by level (patch, class, and landscape) and then further grouped by the aspect of landscape pattern measured. The GUI organization strives to be consistent with the way most users conduct a FRAGSTATS analysis. Often times, for example, users are only interested in class metrics. Here, however, the discussion of the metrics is facilitated by reversing the hierarchy and first grouping them according the aspect of pattern measured, then by the level of organization (patch, class, and landscape). In this manner, issues common to all metrics that relate to the same aspect of landscape pattern can be discussed once.

Following this convention, each metrics section begins with a brief introduction to the metrics in the group, followed by an overview of the various metrics computed by FRAGSTATS and a discussion of important limitations in their use and interpretation. Following this overview, each metric is defined, including a mathematical definition, measurement units, theoretical range in values, and any special considerations or limitations in the use of the metric. For each metric, the mathematical formula is described in narrative terms to facilitate interpretation of the formula. The acronym for the metric given on the left-hand side of the equation is the field name used in the ASCII output files. To facilitate interpretation of the algorithm, we intentionally separate from each equation any constants used to rescale the metric. For example, in many cases the right-hand side of the equation is multiplied by 100 to convert a proportion to a percentage, or multiplied or divided by 10,000 to convert m^2 to hectares. These conversion factors are separated out by parentheses even though they may be factored into the equation differently in the computational form of the algorithm.

Mean versus area-weighted mean

Metrics based on the mean patch characteristic, such as *Mean patch size* (AREA_MN) or *Mean patch shape index* (SHAPE_MN), provide a measure of central tendency in the corresponding patch characteristic across the entire landscape, but nevertheless describe the patch structure of the landscape as that of the average patch characteristic. Thus, each patch regardless of its size is considered equally (i.e., given equal weight) in describing the landscape structure. Consequently, metrics based on the mean patch characteristic offer a fundamentally *patch-centric* perspective of the landscape structure. They do not describe the conditions, for example, that an animal dropped at random on the landscape would experience, because that depends on the probability of landing in a particular patch, which is dependent on patch size.

Conversely, metrics based on the area-weighted mean patch characteristic, such as the *Area-weighted mean patch size* (AREA_AM) and *Area-weighted mean patch shape index* (SHAPE_AM), while still derived from patch characteristics, provide a *landscape-centric* perspective of landscape structure because they reflect the average conditions of a pixel chosen at random or the conditions that an animal dropped at random on the landscape would experience. This is in fact the basis for the subdivision metrics of Jaeger (2000) described later.

All patch metrics can be summarized at the class or landscape level using the mean and the area-weighted mean; the choice of formulation depends on the perspective sought: patch-centric or landscape-centric. **In most applications, the landscape-centric perspective is the one sought and thus the area-weighted mean is the proper formulation**. However, there are some special cases involving the isolation metrics (*Proximity index*, *Similarity index*, and *Euclidean nearest-neighbor distance*) where the area-weighted mean patch characteristic can provide misleading results. The isolation metrics describe the spatial context of individual patches, and they can be summarized at the class or landscape level to characterize the entire landscape. Consider the *Proximity index* (PROX). The *Proximity index* operates at the patch level. For each patch, the size and distance to all neighboring patches of the same type (within some specified search distance) are enumerated to provide an index of patch isolation. A patch with lots of other large patches in close proximity will have a large index value (i.e., low isolation). Both the *Mean* and *Area-weighted mean proximity index* can be calculated at the class and landscape levels. A potential problem in interpretation lies in cases involving widely varying patch sizes. Consider the special case involving 10 patches of the focal class, in which 9 of the 10 patches are equal in size and quite small (say 1 ha each). The ninth patch, however, is quite large (say 1,000 ha). Let's assume that all the small patches are close to the large patch (within the search distance). The proximity index for each of the 9 small patches will be quite large, because the single large patch will be enumerated in the index. The *Proximity index* for the single large patch will be quite small, because the only neighboring patches are quite small (1 ha each). Consequently, the *Mean proximity index* will be much larger than the *Area-weighted mean proximity index*, connoting very different levels of patch isolation. Which is correct? It is difficult to say. From a purely patch-based perspective, the mean would appear to capture the structure best, since the average "patch" is not very isolated. However, the average "organism" would be found in the single large patch, since it represents >99% of the focal habitat area, so it seems logical that the area-weighted mean would provide a better measure. In this case, the *Area-weighted mean proximity index* will be quite small, connoting high isolation, when in fact the single large patch represents the matrix of the landscape. In this case, it is not clear whether either the *Mean* or *Area-weighted mean proximity index* provides a useful measure of isolation. The important point here is that for some metrics, namely the isolation metrics, under some conditions, namely extreme patch size distributions, the mean and area-weighted mean can provide different and potentially misleading results.

Area and Edge Metrics

Background.--This group of metrics represents a loose collection of metrics that deal with the size of patches and the amount of edge created by these patches. Although these metrics could easily be subdivided into separate groups or assigned to other already recognized groups, there is enough similarity in the basic patterns assessed by these metrics to include them under one umbrella.

The area of each patch comprising a landscape mosaic is perhaps the single most important and useful piece of information contained in the landscape. Not only is this information the basis for many of the patch, class, and landscape indices, but patch area has a great deal of ecological utility in its own right. For example, there is considerable evidence that bird species richness and the occurrence and abundance of some species are strongly correlated with patch size (e.g., Robbins et al. 1989). Most species have minimum area requirements: the minimum area needed to meet all life history requirements. Some of these species require that their minimum area requirements be fulfilled in contiguous habitat patches; in other words, the individual habitat patch must be larger than the species minimum area requirement for them to occupy the patch. These species are sometimes referred to as "area-sensitive" species. Thus, patch size information alone could be used to model species richness, patch occupancy, and species distribution patterns in a landscape given the appropriate empirical relationships derived from field studies.

Although patch area per se may be extremely important ecologically, the extent of patch (or patches collectively) may be even more important. Connectivity is considered a "vital element of landscape structure" (Taylor et al., 1993), but it has eluded precise definition and has been difficult to quantify and implement in practice. In part, this is due to differences between the *continuity* or "structural connectedness" of patch types (or habitat) and the *connectivity* or "functional connectedness" of the landscape as perceived by an organism or ecological process. Continuity refers to the physical continuity of a patch type (or a habitat) across the landscape. Contiguous habitat is physically connected, but once subdivided, for example, as a result of habitat fragmentation, it becomes physically disconnected. Continuity can be evaluated by a measure of habitat extensiveness; i.e., the extent of the reach of a contiguous patch or collection of patches on average. The notion of continuity adopts an island biogeographic perspective because the focus is on the physical continuity of a single patch type. What constitutes connectivity or "functional connectedness" between patches, on the other hand, clearly depends on the organism or process of interest; patches that are connected for bird dispersal might not be connected for salamanders, seed dispersal, fire spread, or hydrologic flow. As With (1999) notes, "what ultimately influences the connectivity of the landscape from the organism's perspective is the scale and pattern of movement (scale at which the organism perceives the landscape) relative to the scale and pattern of patchiness (structure of the landscape); ...i.e., a species' gap-crossing or dispersal ability relative to the gap-size distribution on the landscape"(Dale et al. 1994, With and Crist 1995, Pearson et al. 1996, With et al. 1997). Functional connectedness, therefore, relates to the interaction of ecological flows (including organisms) with landscape pattern.

The amount of edge in a landscape is important to many ecological phenomena. In particular, a great deal of attention has been given to wildlife-edge relationships (Thomas et al. 1978 and 1979, Strelke and Dickson 1980, Morgan and Gates 1982, Logan et al. 1985). In landscape ecological investigations, much of the presumed importance of spatial pattern is related to edge effects. The forest edge effect, for example, results primarily from differences in wind and light intensity and quality reaching a forest patch that alter microclimate and disturbance rates (e.g., Gratkowski 1956, Ranney et al. 1981, Chen and Franklin 1990). These changes, in combination with changes in seed dispersal and herbivory, can influence vegetation composition and structure (Ranney et al. 1981). The proportion of a forest patch that is affected in this manner is dependent, therefore, upon patch shape and orientation, and by adjacent land cover. A large but convoluted patch, for example, could be entirely edge habitat. It is now widely accepted that edge effects must be viewed from an organism-centered perspective because edge effects influence organisms differently; some species have an affinity for edges, some are unaffected, and others are adversely affected.

Indeed, one of the most dramatic and well-studied consequences of habitat fragmentation is an increase in the proportional abundance of edge-influenced habitat. Early wildlife management efforts were focused on maximizing edge habitat because it was believed that most species favored habitat conditions created by edges and that the juxtaposition of different habitats would increase species diversity (Leopold 1933). Indeed this concept of edge as a positive influence guided land management practices for most of the twentieth century. Recent studies, however, have suggested that changes in microclimate, vegetation, invertebrate populations, predation, brood parasitism, and competition along forest edges (i.e., edge effects) has resulted in the population declines of several vertebrate species dependent upon forest interior conditions (e.g., Strelke and Dickson 1980, Whitcomb et al. 1981, Kroodsma 1982, Brittingham and Temple 1983, Wilcove 1985, Temple 1986, Noss 1988, Yahner and Scott 1988, Robbins et al. 1989). In fact, many of the adverse effects of forest fragmentation on organisms seem to be directly or indirectly related to these so-called edge effects. Forest interior species, therefore, may be sensitive to patch shape because for a given patch size, the more complex the shape, the larger the edge-to-interior ratio. Total class edge in a landscape, therefore, often is the most critical piece of information in the study of fragmentation, and many of the class indices directly or indirectly reflect the amount of class edge. Similarly, the total amount of edge in a landscape is directly related to the degree of spatial heterogeneity in that landscape. Note, edges have myriad ecological effects, as noted above, and may be addressed by simply quantifying the total length of edge (as in the edge metrics included here), or by quantifying the core area remaining after accounting for adverse penetrating edge effects (see core area metrics), or by quantifying the magnitude of contrast along edges due to differences between adjoining patch types (see contrast metrics).

Overall, the size and extent of patches and the edges associated with patch boundaries comprising a class or the entire landscape mosaic is one of the most basic aspects of landscape pattern that can affect myriad processes. For example, although there are myriad effects of habitat fragmentation on individual behavior, habitat use patterns, and intra- and inter-specific interactions, many of these effects are caused by a reduction in habitat area and continuity and an increase in the proportion of edge-influenced habitat. Briefly, as a species' habitat is lost from the landscape (without being fragmented), at some point there will be insufficient area of habitat to support a viable population, and with continued loss eventually there will be insufficient area of habitat to support even a single individual and the species will be extirpated from the landscape. This area relationship is expected to vary among species depending on their minimum area requirements. Moreover, the area threshold for occupancy may occur when total habitat area is still much greater than the individual's minimum area requirement. For example, an individual may not occupy available habitat unless there are other individuals of the same species occupying the same or nearby patches of habitat, or an individual's occupancy may be influenced by what other species are occupying the patch. Similarly, as habitat is lost and simultaneously fragmented into smaller and less extensive patches, at some point there will be insufficient contiguous area of suitable habitat within a home range size area to support an individual. Or the habitat may become too discontinuous, resulting in too much resistance to movement through nonhabitat to accumulate enough suitable habitat. This is the ultimate consequence of habitat loss and fragmentation–insufficient habitat quantity, quality and connectivity to support individuals and viable populations.

FRAGSTATS Metrics.--FRAGSTATS computes several simple statistics representing area, extent and perimeter (or edge) at the patch, class, and landscape levels. Area metrics quantify landscape composition, not landscape configuration. As noted above, the *area* (AREA) of each patch comprising a landscape mosaic is perhaps the single most important and useful piece of information contained in the landscape. However, the size of a patch may not be as important as the extensiveness of the patch for some organisms and processes. *Radius of gyration* (GYRATE) is a measure of patch extent; that is, how far across the landscape a patch extends its reach. All other things equal, the larger the patch, the larger the radius of gyration. Similarly, holding area constant, the more extensive the patch (i.e., elongated and less compact), the greater the radius of gyration. The radius of gyration can be considered a measure of the average distance an organism can move within a patch before encountering the patch boundary from a random starting point.

Class area (CA) and *percentage of landscape* (PLAND) are fundamental measures of landscape composition; specifically, how much of the landscape is comprised of a particular patch type. This is an important characteristic in a number of ecological applications. For example, an important by-product of habitat fragmentation is habitat loss. In the study of forest fragmentation, therefore, it is important to know how much of the target patch type (habitat) exists within the landscape. In addition, although many vertebrate species that specialize on a particular habitat have minimum area requirements (e.g., Robbins et al. 1989), not all species require that suitable habitat to be present in a single contiguous patch. For example, northern spotted owls have minimum area requirements for late-seral forest that varies geographically; yet, individual spotted owls use late-seral forest that may be distributed among many patches (Forsman et al. 1984). For this species, late-seral forest area might be a good index of habitat suitability within landscapes the size of spotted owl home ranges (Lehmkuhl and Raphael 1993). In addition to its direct interpretive value, class area (in absolute or relative terms) is used in the computations for many of the class and landscape metrics.

In addition to these primary metrics, FRAGSTATS also summarizes the distribution of patch area and extent (radius of gyration) across all patches at the class and landscape levels. For example, the distribution of patch area (AREA) is summarized by its mean and variability. These summary measures provide a way to characterize the distribution of area among patches at the class or landscape level. For example, progressive reduction in the size of habitat fragments is a key component of habitat fragmentation. Thus, a landscape with a smaller mean patch size for the target patch type than another landscape might be considered more fragmented. Similarly, within a single landscape, a patch type with a smaller mean patch size than another patch type might be considered more fragmented. Thus, mean patch size can serve as a habitat fragmentation index, although the limitations discussed below may reduce its utility in this respect. When aggregated at the class or landscape level, the *area-weighted mean patch radius of gyration* (GYRATE_AM) provides a measure of landscape continuity (also known as correlation length) that represents the average traversability of the landscape for an organism that is confined to remain within a single patch; specifically, it gives the average distance one can move from an random starting point and traveling in a random direction without leaving the patch.

Mean patch size (AREA_MN) at the class level is a function of the number of patches in the class and total class area. Importantly, although mean patch size is derived from the number of patches, it does not convey any information about how many patches are present. A mean patch size of 10 ha could represent 1 or 100 patches and the difference could have profound ecological implications. Furthermore, mean patch size represents the average condition. Variation in patch size may convey more useful information. For example, a mean patch size of 10 ha could represent a class with 5 10-ha patches or a class with 2-, 3-, 5-, 10-, and 30-ha patches, and this difference could be important ecologically. For these reasons, mean patch size is probably best interpreted in conjunction with total class area, patch density (or number of patches), and patch size variability. At the landscape level, mean patch size and patch density are both a function of number of patches and total landscape area. In contrast to the class level, these indices are completely redundant (assuming there is no internal background). Although both indices may be useful for "describing" 1 or more landscapes, they would never be used simultaneously in a statistical analysis of landscape structure.

In many ecological applications, second-order statistics, such as the variation in patch size, may convey more useful information than first-order statistics, such as mean patch size. Variability in patch size measures a key aspect of landscape heterogeneity that is not captured by mean patch size and other first-order statistics. For example, consider 2 landscapes with the same patch density and mean patch size, but with very different levels of variation in patch size. Greater variability indicates less uniformity in pattern either at the class level or landscape level and may reflect differences in underlying processes affecting the landscapes. Variability is a difficult thing to summarize in a single metric. FRAGSTATS computes three of the simplest measures of variability–range, standard deviation, and coefficient of variation.

Patch size standard deviation (AREA_SD) is a measure of absolute variation; it is a function of the mean patch size and the difference in patch size among patches. Thus, although patch size standard deviation conveys information about patch size variability, it is a difficult parameter to interpret without doing so in conjunction with mean patch size because the absolute variation is dependent on mean patch size. For example, two landscapes may have the same patch size standard deviation, e.g., 10 ha; yet one landscape may have a mean patch size of 10 ha, while the other may have a mean patch size of 100 ha. In this case, the interpretations of landscape pattern would be very different, even though absolute variation is the same. Specifically, the former landscape has greatly varying and smaller patch sizes, while the latter has more uniformly-sized and larger patches. For this reason, *patch size coefficient of variation* (AREA_CV) is generally preferable to standard deviation for comparing variability among landscapes. Patch size coefficient of variation measures relative variability about the mean (i.e., variability as a percentage of the mean), not absolute variability. Thus, it is not necessary to know mean patch size to interpret the coefficient of variation. Nevertheless, patch size coefficient of variation also can be misleading with regards to landscape structure in the absence of information on the number of patches or patch density and other structural characteristics. For example, two landscapes may have the same patch size coefficient of variation, e.g., 100%; yet one landscape may have 100 patches with a mean patch size of 10 ha, while the other may have 10 patches with a mean patch size of 100 ha. In this case, the interpretations of landscape structure could be very different, even though the coefficient of variation is the same. Ultimately, the choice of standard deviation or coefficient of variation will depend on whether absolute or relative variation is more meaningful in a particular application. Because these measures are not wholly redundant, it may be meaningful to interpret both measures in some applications.

It is important to keep in mind that both standard deviation and coefficient of variation assume a normal distribution about the mean. In a real landscape, the distribution of patch sizes may be highly irregular. It may be more informative to inspect the actual distribution itself, rather than relying on summary statistics such as these that make assumptions about the distribution and therefore can be misleading. Also, note that patch size standard deviation and coefficient of variation can equal 0 under 2 different conditions: (1) when there is only 1 patch in the landscape; and (2) when there is more than 1 patch, but they are all the same size. In both cases, there is no variability in patch size, yet the ecological interpretations could be different.

FRAGSTATS computes several statistics representing the amount of perimeter (or edge) at the patch, class, and landscape levels. Edge metrics usually are best considered as representing landscape configuration, even though they are not spatially explicit at all. At the patch level, edge is a function of patch *perimeter* (PERIM). At the class and landscape levels, *total edge* (TE) is an absolute measure of total edge length of a particular patch type (class level) or of all patch types (landscape level). In applications that involve comparing landscapes of varying size, this index may not be useful. *Edge density* (ED) standardizes edge to a per unit area basis that facilitates comparisons among landscapes of varying size. However, when comparing landscapes of identical size, total edge and edge density are completely redundant. Alternatively, the amount of edge present in a landscape can be compared to that expected for a landscape of the same size but with a simple geometric shape (square) and no internal edge. This is the basis for the *landscape shape index* (LSI) and its normalized version (nLSI) that are described in Aggregation metrics section.

Limitations.--Area metrics have limitations imposed by the scale of investigation. Minimum patch size and landscape extent set the lower and upper limits of these area metrics, respectively. These are critical limits to recognize because they establish the lower and upper limits of resolution for the analysis of landscape composition and configuration. Otherwise, area metrics have few limitations. All edge indices are affected by the resolution of the image. Generally, the finer the resolution (i.e., the greater the detail with which edges are delineated), the greater the edge length. At coarse resolutions, edges may appear as relatively straight lines; whereas, at finer resolutions, edges may appear as highly convoluted lines. Thus, values calculated for edge metrics should not be compared among images with different resolutions. In addition, patch perimeter and the length of edges will be biased upward in raster images because of the stair-step patch outline, and this will affect all edge indices. The magnitude of this bias will vary in relation to the grain or resolution of the image, and the consequences of this bias with regards to the use and interpretation of these indices must be weighed relative to the phenomenon under investigation.

Number	Metric (acronym)
Patch Metrics	
P1	Patch Area (AREA)

P2	Patch Perimeter (PERIM)
P3	Radius of Gyration (GYRATE)
Class Metrics	
C1	Total (Class) Area (CA)
C2	Percentage of Landscape (PLAND)
C3	Largest Patch Index (LPI)
C4	Total Edge (TE)
C5	Edge Density (ED)
C6-C11	Patch Area Distribution (AREA_MN, _AM, _MD, _RA, _SD, _CV)
C12-C17	Radius of Gyration Distribution (GYRATE_MN, _AM, _MD, _RA, _SD, _CV)
Landscape Metrics	
L1	Total Area (TA)
L2	Largest Patch Index (LPI)
L3	Total Edge (TE)
L4	Edge Density (ED)
L5-L10	Patch Area Distribution (AREA_MN, _AM, _MD, _RA, _SD, _CV)
L11-L16	Radius of Gyration Distribution (GYRATE_MN, _AM, _MD, _RA, _SD, _CV)

(P1) Area	
$AREA = a_{ij}\left(\frac{1}{10{,}000}\right)$	a_{ij} = area (m^2) of patch ij.
Description	AREA equals the area (m^2) of the patch, divided by 10,000 (to convert to hectares).
Units	Hectares
Range	AREA > 0, without limit. The range in AREA is limited by the grain and extent of the image; in a particular application, AREA may be further limited by the specification of a minimum patch size that is larger than the grain.

Comments	The *area* of each patch comprising a landscape mosaic is perhaps the single most important and useful piece of information contained in the landscape. Not only is this information the basis for many of the patch, class, and landscape indices, but patch area has a great deal of ecological utility in its own right. Note that the choice of the 4-neighbor or 8-neighbor rule for delineating patches will have an impact on this metric.

(P2) Perimeter	
$PERIM = p_{ij}$	p_{ij} = perimeter (m) of patch ij.
Description	PERIM equals the perimeter (m) of the patch, including any internal holes in the patch, regardless of whether the perimeter represents 'true' edge or not (e.g., the case when a patch is artificially bisected by the landscape boundary when a landscape border is present).
Units	Meters
Range	PERIM > 0, without limit.
Comments	Patch *perimeter* is another fundamental piece of information available about a landscape and is the basis for many class and landscape metrics. Specifically, the perimeter of a patch is treated as an edge, and the intensity and distribution of edges constitutes a major aspect of landscape pattern. In addition, the relationship between patch perimeter and patch area is the basis for most shape indices.

(P3) Radius of Gyration	
$GYRATE = \sum_{r=1}^{z} \frac{h_{ijr}}{z}$	h_{ijr} = distance (m) between cell ijr [located within patch ij] and the centroid of patch ij (the average location), based on cell center-to-cell center distance. z = number of cells in patch ij.
Description	GYRATE equals the mean distance (m) between each cell in the patch and the patch centroid.
Units	Meters
Range	GYRATE ≥ 0, without limit. GYRATE = 0 when the patch consists of a single cell and increases without limit as the patch increases in extent. GYRATE achieves its maximum value when the patch comprises the entire landscape.

Comments	*Radius of gyration* is a measure of patch extent; thus it is effected by both patch size and patch compaction. Note that the choice of the 4-neighbor or 8-neighbor rule for delineating patches will have an impact on this metric.

(C1) Total (Class) Area	
$$CA = \sum_{j=1}^{n} a_{ij} \left(\frac{1}{10,000} \right)$$	a_{ij} = area (m^2) of patch ij.
Description	CA equals the sum of the areas (m^2) of all patches of the corresponding patch type, divided by 10,000 (to convert to hectares); that is, total class area.
Units	Hectares
Range	CA > 0, without limit. CA approaches 0 as the patch type becomes increasing rare in the landscape. CA = TA when the entire landscape consists of a single patch type; that is, when the entire image is comprised of a single patch.
Comments	*Class area* is a measure of landscape composition; specifically, how much of the landscape is comprised of a particular patch type. In addition to its direct interpretive value, class area is used in the computations for many of the class and landscape metrics.

(C2) Percentage of Landscape	
$$PLAND = P_i = \frac{\sum_{j=1}^{n} a_{ij}}{A} (100)$$	P_i = proportion of the landscape occupied by patch type (class) i. a_{ij} = area (m^2) of patch ij. A = total landscape area (m^2).
Description	PLAND equals the sum of the areas (m^2) of all patches of the corresponding patch type, divided by total landscape area (m^2), multiplied by 100 (to convert to a percentage); in other words, PLAND equals the percentage the landscape comprised of the corresponding patch type. Note, total landscape area (A) includes any internal background present.
Units	Percent

Range	$0 < \text{PLAND} \leq 100$ PLAND approaches 0 when the corresponding patch type (class) becomes increasingly rare in the landscape. PLAND = 100 when the entire landscape consists of a single patch type; that is, when the entire image is comprised of a single patch.
Comments	*Percentage of landscape* quantifies the proportional abundance of each patch type in the landscape. Like total class area, it is a measure of landscape composition important in many ecological applications. However, because PLAND is a relative measure, it may be a more appropriate measure of landscape composition than class area for comparing among landscapes of varying sizes.

(C3) Largest Patch Index	
$$LPI = \frac{\max_{j=1}^{n}(a_{ij})}{A}(100)$$	a_{ij} = area (m^2) of patch ij. A = total landscape area (m^2).
Description	LPI equals the area (m^2) of the largest patch of the corresponding patch type divided by total landscape area (m^2), multiplied by 100 (to convert to a percentage); in other words, LPI equals the percentage of the landscape comprised by the largest patch. Note, total landscape area (A) includes any internal background present.
Units	Percent
Range	$0 < \text{LPI} \leq 100$ LPI approaches 0 when the largest patch of the corresponding patch type is increasingly small. LPI = 100 when the entire landscape consists of a single patch of the corresponding patch type; that is, when the largest patch comprises 100% of the landscape.
Comments	*Largest patch index* at the class level quantifies the percentage of total landscape area comprised by the largest patch. As such, it is a simple measure of dominance.

(C4) Total Edge	
$$TE = \sum_{k=1}^{m} e_{ik}$$	e_{ik} = total length (m) of edge in landscape involving patch type (class) i; includes landscape boundary and background segments involving patch type i.

Description	TE equals the sum of the lengths (m) of all edge segments involving the corresponding patch type. If a landscape border is present, TE includes landscape boundary segments involving the corresponding patch type and representing 'true' edge only (i.e., abutting patches of different classes). If a landscape border is absent, TE includes a user-specified proportion of landscape boundary segments involving the corresponding patch type. Regardless of whether a landscape border is present or not, TE includes a user-specified proportion of internal background edge segments involving the corresponding patch type.
Units	Meters
Range	TE ≥ 0, without limit. TE = 0 when there is no class edge in the landscape; that is, when the entire landscape and landscape border, if present, consists of the corresponding patch type and the user specifies that none of the landscape boundary and background edge be treated as edge.
Comments	*Total edge* at the class level is an absolute measure of total edge length of a particular patch type. In applications that involve comparing landscapes of varying size, this index may not be as useful as edge density (see below). However, when comparing landscapes of identical size, total edge and edge density are completely redundant.

(C5) Edge Density	
$$ED = \frac{\sum_{k=1}^{m} e_{ik}}{A}(10{,}000)$$	e_{ik} = total length (m) of edge in landscape involving patch type (class) i; includes landscape boundary and background segments involving patch type i. A = total landscape area (m^2).
Description	ED equals the sum of the lengths (m) of all edge segments involving the corresponding patch type, divided by the total landscape area (m^2), multiplied by 10,000 (to convert to hectares). If a landscape border is present, ED includes landscape boundary segments involving the corresponding patch type and representing 'true' edge only (i.e., abutting patches of different classes). If a landscape border is absent, ED includes a user-specified proportion of landscape boundary segments involving the corresponding patch type. Regardless of whether a landscape border is present or not, ED includes a user-specified proportion of internal background edge segments involving the corresponding patch type. Note, total landscape area (A) includes any internal background present.
Units	Meters per hectare

Range	ED ≥ 0, without limit. ED = 0 when there is no class edge in the landscape; that is, when the entire landscape and landscape border, if present, consists of the corresponding patch type and the user specifies that none of the landscape boundary and background edge be treated as edge.
Comments	*Edge density* at the class level has the same utility and limitations as Total Edge (see Total Edge description), except that edge density reports edge length on a per unit area basis that facilitates comparison among landscapes of varying size.

(L1) Total Area	
$$TA = A\left(\frac{1}{10{,}000}\right)$$	A = total landscape area (m^2).
Description	TA equals the total area (m^2) of the landscape, divided by 10,000 (to convert to hectares). Note, total landscape area (A) includes any internal background present.
Units	Hectares
Range	TA > 0, without limit.
Comments	*Total area* (TA) often does not have a great deal of interpretive value with regards to evaluating landscape pattern, but it is important because it defines the extent of the landscape. Moreover, total landscape area is used in the computations for many of the class and landscape metrics.

(L2) Largest Patch Index	
$$LPI = \frac{\max(a_{ij})}{A}(100)$$	a_{ij} = area (m^2) of patch ij. A = total landscape area (m^2).
Description	LPI equals the area (m^2) of the largest patch in the landscape divided by total landscape area (m^2), multiplied by 100 (to convert to a percentage); in other words, LPI equals the percent of the landscape that the largest patch comprises. Note, total landscape area (A) includes any internal background present.
Units	Percent
Range	0 < LPI ≤ 100 LPI approaches 0 when the largest patch in the landscape is increasingly small. LPI = 100 when the entire landscape consists of a single patch; that is, when the largest patch comprises 100% of the landscape.

Comments	*Largest patch index* quantifies the percentage of total landscape area comprised by the largest patch. As such, it is a simple measure of dominance.

(L3) Total Edge

$TE = E$	E = total length (m) of edge in landscape.

Description	TE equals the sum of the lengths (m) of all edge segments in the landscape. If a landscape border is present, TE includes landscape boundary segments representing 'true' edge only (i.e., abutting patches of different classes). If a landscape border is absent, TE includes a user-specified proportion of the landscape boundary. Regardless of whether a landscape border is present or not, TE includes a user-specified proportion of internal background edge.
Units	Meters
Range	TE ≥ 0, without limit. TE = 0 when there is no edge in the landscape; that is, when the entire landscape and landscape border, if present, consists of a single patch and the user specifies that none of the landscape boundary and background edge be treated as edge.
Comments	*Total edge* is an absolute measure of total edge length of a particular patch type. In applications that involve comparing landscapes of varying size, this index may not be as useful as edge density (see below). However, when comparing landscapes of identical size, total edge and edge density are completely redundant.

(L4) Edge Density

$ED = \frac{E}{A}(10,000)$	E = total length (m) of edge in landscape. A = total landscape area (m^2).

Description	ED equals the sum of the lengths (m) of all edge segments in the landscape, divided by the total landscape area (m^2), multiplied by 10,000 (to convert to hectares). If a landscape border is present, ED includes landscape boundary segments representing 'true' edge only (i.e., abutting patches of different classes). If a landscape border is absent, ED includes a user-specified proportion of the landscape boundary. Regardless of whether a landscape border is present or not, ED includes a user-specified proportion of internal background edge. Note, total landscape area (A) includes any internal background present.
Units	Meters per hectare

Range	ED $\geq$ 0, without limit. ED = 0 when there is no edge in the landscape; that is, when the entire landscape and landscape border, if present, consists of a single patch and the user specifies that none of the landscape boundary and background edge be treated as edge.
Comments	*Edge density* has the same utility and limitations as Total Edge (see Total Edge description), except that edge density reports edge length on a per unit area basis that facilitates comparison among landscapes of varying size.

Shape Metrics

<u>Background</u>.--The interaction of patch shape and size can influence a number of important ecological processes. Patch shape has been shown to influence inter-patch processes such as small mammal migration (Buechner 1989) and woody plant colonization (Hardt and Forman 1989), and may influence animal foraging strategies (Forman and Godron 1986). However, the primary significance of shape in determining the nature of patches in a landscape seems to be related to the 'edge effect' (see discussion of edge effects for Area and Edge Metrics).

Shape is a difficult parameter to quantify concisely in a metric for the reasons discussed below. Generally speaking, the shape of a geometric object, such as a patch, is a function of its morphology. Thus, one might expect shape metrics to discriminate among patch morphologies. While it is possible to quantitatively distinguish morphological patterns, as is done in the field of computer visions (e.g., face recognition), it is generally deemed unimportant to do so in landscape ecological applications. Instead, the emphasis is on geometric complexity and distinguishing among patches and landscapes on the basis of overall complexity rather than particular morphologies. Conseqently, the shape metrics described below all deal with overall geometric complexity and do not distinguish among distinct morphologies.

<u>FRAGSTATS Metrics</u>.--FRAGSTATS computes several metrics that quantify landscape configuration in terms of the complexity of patch shape at the patch, class, and landscape levels. Most of these shape metrics are based on perimeter-area relationships. Perhaps the simplest shape index is a straightforward *perimeter-area ratio* (PARA). A problem with this metric as a shape index is that it varies with the size of the patch. For example, holding shape constant, an increase in patch size will cause a decrease in the perimeter-area ratio. Patton (1975) proposed a diversity index based on shape for quantifying habitat edge for wildlife species and as a means for comparing alternative habitat improvement efforts (e.g., wildlife clearings). This *shape index* (SHAPE) measures the complexity of patch shape compared to a standard shape (square) of the same size, and therefore alleviates the size dependency problem of PARA. This shape index is widely applicable in landscape ecological research (Forman and Godron 1986).

Another other basic type of shape index based on perimeter-area relationships is the *fractal dimension index* (FRAC). In landscape ecological research, patch shapes are frequently characterized via the fractal dimension of the object (Krummel et al. 1987, Milne 1988, Turner and Ruscher 1988, Iverson 1989, Ripple et al. 1991). The appeal of fractal analysis is that it can be applied to spatial features over a wide variety of scales. Mandelbrot (1977, 1982) introduced the concept of fractal, a geometric form that exhibits structure at all spatial scales, and proposed a perimeter-area method to calculate the fractal dimension of natural planar shapes. The perimeter-area method quantifies the degree of complexity of the planar shapes. The degree of complexity of a polygon is characterized by the fractal dimension (D), such that the perimeter (P) of a patch is related to the area (A) of the same patch by $P \approx \sqrt{A^D}$ (i.e., $\log P \approx \frac{1}{2} D \log A$). For simple Euclidean shapes (e.g., circles and rectangles), $P \approx \sqrt{A}$ and $D = 1$ (the dimension of a line). As the polygons become more complex, the perimeter becomes increasingly plane-filling and $P \approx A$ with $D \rightarrow 2$. Although fractal analysis typically has not been used to characterize individual patches in landscape ecological research, we use this relationship to calculate the fractal dimension of each patch separately. Note that the value of the fractal dimension calculated in this manner is dependent upon patch size and/or the units used (Rogers 1993). Thus, varying the cell size of the input image will affect the patch fractal dimension. Therefore, caution should be exercised when using this fractal dimension index as a measure of patch shape complexity.

Fractal analysis usually is applied to the entire landscape mosaic using the perimeter-area relationship $A = k P^{2/D}$, where k is a constant (Burrough 1986). If sufficient data are available, the slope of the line obtained by regressing log(P) on log(A) is equal to 2/D (Burrough 1986). Note, fractal dimension computed in this manner is equal to 2 divided by the slope; D is not equal to the slope (Krummel et al. 1987) nor is it equal to 2 times the slope (e.g., O'Neill et al. 1988, Gustafson and Parker 1992). We refer to this index as the *perimeter-area fractal dimension* (PAFRAC) in FRAGSTATS. Because this index employs regression analysis, it is subject to spurious results when sample sizes are small. In landscapes with only a few patches, it is not unusual to get values that greatly exceed the theoretical limits of this index. Thus, this index is probably only useful if sample sizes are large (e.g., $n > 20$; although PAFRAC is computed in FRAGSTATS if $n \geq 10$). If insufficient data are available, an alternative to the regression approach is to calculate the *mean patch fractal dimension* (FRAC_MN) based on the fractal dimension of each patch, or the *area-weighted mean patch fractal dimension* (FRAC_AM) at the class and landscape levels by weighting patches according to their size, although these metrics do not have the same interpretation or utility as PAFRAC. In contrast to the fractal dimension of a single patch, which provides an index of shape complexity for that patch, the perimeter-area fractal dimension of a patch mosaic provides an index of patch shape complexity across a wide range of spatial scales (i.e., patch sizes). Specifically, it describes the power relationship between patch area and perimeter, and thus describes how patch perimeter increases per unit increase in patch area. If, for example, small and large patches alike have simple geometric shapes, then PAFRAC will be relatively low, indicating that patch perimeter increases relatively slowly as patch area increases. Conversely, if small and large patches have complex shapes, then PAFRAC will be much higher, indicating that patch perimeter increases more rapidly as patch area increases–reflecting a consistency of complex patch shapes across spatial scales. The fractal dimension of patch shapes, therefore, is suggestive of a common ecological process or anthropogenic influence affecting patches across a wide range of scales, and differences between landscapes can suggest differences in the underlying pattern-generating process (e.g., Krummel 1987).

An alternative method of assessing shape is based on ratio of patch area to the area of the smallest circumscribing circle, known as the *related circumscribing circle* (CIRCLE)(Baker and Cai 1992). The circumscribing circle provides a measure of overall patch elongation. A highly convoluted but narrow patch will have a low related circumscribing circle index due to the relative compactness of the patch, yet a narrow and elongated patch will have a high related circumscribing square index. This index may be particularly useful for distinguishing patches that are both linear (narrow) and elongated.

A final method of assessing patch shape is based on the spatial connectedness, or contiguity, of cells within a grid-cell patch to provide an index on patch boundary configuration and thus patch shape (LaGro 1991). *Contiguity index* (CONTIG) is quantified by convolving a 3x3 pixel template with a binary digital image in which the pixels within the patch of interest are assigned a value of 1 and the background pixels (all other patch types) are given a value of zero. A template value of 2 is assigned to quantify horizontal and vertical pixel relationships within the image and a value of 1 is assigned to quantify diagonal relationships. This combination of integer values weights orthogonally contiguous pixels more heavily than diagonally contiguous pixels, yet keeps computations relatively simple. The center pixel in the template is assigned a value of 1 to ensure that a single-pixel patch in the output image has a value of 1, rather than 0. The value of each pixel in the output image, computed when at the center of the moving template, is a function of the number and location of pixels, of the same class, within the nine cell image neighborhood. Specifically, the contiguity value for a pixel in the output image is the sum of the products, of each template value and the corresponding input image pixel value, within the nine cell neighborhood. Thus, large contiguous patches result in larger contiguity index values.

Limitations.--All shape indices based on perimeter-area relationships have important limitations. First, perimeter lengths are biased upward in raster images because of the stair-stepping pattern of line segments, and the magnitude of this bias varies in relation to the grain or resolution of the image. Thus, the computed perimeter-area ratio will be somewhat higher than it actually is in the real-world. Second, as an index of "shape", the perimeter-to-area ratio method is relatively insensitive to differences in patch morphology. Thus, although patches may possess very different shapes, they may have identical areas and perimeters. For this reason, shape indices based on perimeter-area ratios are not useful as measures of patch morphology; they are best considered as measures of overall shape complexity. Alternative indices of shape that are not based on perimeter-area rations are less troubled by these limitations. But these too, generally do not distinguish patch morphology, but instead emphasize one or more aspects of shape complexity (e.g., elongation).

Number	Metric (acronym)
Patch Metrics	
P1	Perimeter-Area Ratio (PARA)
P2	Shape Index (SHAPE)
P3	Fractal Dimension Index (FRAC)
P4	Related Circumscribing Circle (CIRCLE)
P5	Contiguity Index (CONTIG)
Class Metrics	
C1	Perimeter-Area Fractal Dimension (PAFRAC)
C2-C7	Perimeter-Area Ratio Distribution (PARA_MN, _AM, _MD, _RA, _SD, _CV)
C8-C13	Shape Index Distribution (SHAPE_MN, _AM, _MD, _RA, _SD, _CV)
C14-C19	Fractal Index Distribution (FRAC_MN, _AM, _MD, _RA, _SD, _CV)
C20-C25	Linearity Index Distribution (LINEAR_MN, _AM, _MD, _RA, _SD, _CV)
C26-C31	Related Circumscribing Square Distribution (SQUARE_MN, _AM, _MD, _RA, _SD, _CV)
C32-C37	Contiguity Index Distribution (CONTIG_MN, _AM, _MD, _RA, _SD, _CV)

Landscape Metrics	
L1	Perimeter-Area Fractal Dimension (PAFRAC)
L2-L7	Perimeter-Area Ratio Distribution (PARA_MN, _AM, _MD, _RA, _SD, _CV)
L8-L13	Shape Index Distribution (SHAPE_MN, _AM _MD, _RA, _SD, _CV)
L14-L19	Fractal Index Distribution (FRAC_MN, _AM, _MD, _RA, _SD, _CV)
L20-L25	Linearity Index Distribution (LINEAR_MN, _AM, _MD, _RA, _SD, _CV)
L26-L31	Related Circumscribing Square Distribution (SQUARE_MN, _AM, _MD, _RA, _SD, _CV)
L32-L37	Contiguity Index Distribution (CONTIG_MN, _AM, _MD, _RA, _SD, _CV)

(P1) Perimeter-Area Ratio

$$PARA = \frac{p_{ij}}{a_{ij}}$$

p_{ij} = perimeter (m) of patch ij.
a_{ij} = area (m^2) of patch ij.

Description	PARA equals the ratio of the patch perimeter (m) to area (m^2).
Units	None
Range	PARA > 0, without limit.
Comments	*Perimeter-area ratio* is a simple measure of shape complexity, but without standardization to a simple Euclidean shape (e.g., square). A problem with this metric as a shape index is that it varies with the size of the patch. For example, holding shape constant, an increase in patch size will cause a decrease in the perimeter-area ratio.

(P2) Shape Index

$$SHAPE = \frac{.25\ p_{ij}}{\sqrt{a_{ij}}}$$

p_{ij} = perimeter (m) of patch ij.
a_{ij} = area (m^2) of patch ij.

Description	SHAPE equals patch perimeter (m) divided by the square root of patch area (m^2), adjusted by a constant to adjust for a square standard.
Units	None
Range	SHAPE ≥ 1, without limit. SHAPE = 1 when the patch is square and increases without limit as patch shape becomes more irregular.

Comments	*Shape index* corrects for the size problem of the perimeter-area ratio index (see previous description) by adjusting for a square standard and, as a result, is the simplest and perhaps most straightforward measure of shape complexity.

(P3) Fractal Dimension Index	
$FRAC = \frac{2 \ln (.25\, p_{ij})}{\ln a_{ij}}$	p_{ij} = perimeter (m) of patch ij. a_{ij} = area (m^2) of patch ij.
Description	FRAC equals 2 times the logarithm of patch perimeter (m) divided by the logarithm of patch area (m^2); the perimeter is adjusted to correct for the raster bias in perimeter.
Units	None
Range	$1 \leq FRAC \leq 2$ A fractal dimension greater than 1 for a 2-dimensional patch indicates a departure from Euclidean geometry (i.e., an increase in shape complexity). FRAC approaches 1 for shapes with very simple perimeters such as squares, and approaches 2 for shapes with highly convoluted, plane-filling perimeters.
Comments	*Fractal dimension index* is appealing because it reflects shape complexity across a range of spatial scales (patch sizes). Thus, like the shape index (SHAPE), it overcomes one of the major limitations of the straight perimeter-area ratio as a measure of shape complexity.

(P4) Related Circumscribing Circle	
$SQUARE = 1 - \left[\frac{a_{ij}}{a_{ij}^{s}}\right]$	a_{ij} = area (m^2) of patch ij. a_{ij}^{s} = area (m^2) of smallest circumscribing circle around patch ij.
Description	CIRCLE equals 1 minus patch area (m^2) divided by the area (m^2) of the smallest circumscribing circle.
Units	None
Range	$0 \leq CIRCLE < 1$ CIRCLE = 0 for circular patches and approaches 1 for elongated, linear patches one cell wide.
Comments	*Related circumscribing circle* derives from Baker and Cai (1992). Note, this index is not influenced by patch size.

(P5) Contiguity Index	
$$CONTIG = \frac{\left[\frac{\sum_{r=1}^{z} c_{ijr}}{a_{ij}^{*}}\right] - 1}{v - 1}$$	c_{ijr} = contiguity value for pixel r in patch ij. v = sum of the values in a 3-by-3 cell template (13 in this case). a_{ij}^{*} = area of patch ij in terms of number of cells.
Description	CONTIG equals the average contiguity value (see discussion) for the cells in a patch (i.e., sum of the cell values divided by the total number of pixels in the patch) minus 1, divided by the sum of the template values (13 in this case) minus 1.
Units	None
Range	$0 \leq CONTIG \leq 1$ CONTIG equals 0 for a one-pixel patch and increases to a limit of 1 as patch contiguity, or connectedness, increases. Note, 1 is subtracted from both the numerator and denominator to confine the index to a range of 1.
Comments	*Contiguity index* assesses the spatial connectedness, or contiguity, of cells within a grid-cell patch to provide an index on patch boundary configuration and thus patch shape (LaGro 1991).

(C1) Perimeter-Area Fractal Dimension	
$$PAFRAC = \frac{\frac{2}{\left[n_i \sum_{j=1}^{n} (\ln p_{ij} \cdot \ln a_{ij})\right] - \left[\left(\sum_{j=1}^{n} \ln p_{ij}\right)\left(\sum_{j=1}^{n} \ln a_{ij}\right)\right]}}{\left(n_i \sum_{j=1}^{n} \ln p_{ij}^{2}\right) - \left(\sum_{j=1}^{n} \ln p_{ij}\right)^{2}}$$	a_{ij} = area (m^2) of patch ij. p_{ij} = perimeter (m) of patch ij. n_i = number of patches in the landscape of patch type (class) i.
Description	PAFRAC equals 2 divided by the slope of regression line obtained by regressing the logarithm of patch area (m^2) against the logarithm of patch perimeter (m). That is, 2 divided by the coefficient b_1 derived from a least squares regression fit to the following equation: $\ln(area) = b_0 + b_1 \cdot \ln(perim)$. Note, PAFRAC excludes any background patches.
Units	None

Range	$1 \le \text{PAFRAC} \le 2$ A fractal dimension greater than 1 for a 2-dimensional landscape mosaic indicates a departure from a Euclidean geometry (i.e., an increase in patch shape complexity). PAFRAC approaches 1 for shapes with very simple perimeters such as squares, and approaches 2 for shapes with highly convoluted, plane-filling perimeters. PAFRAC employs regression techniques and is subject to small sample problems. Specifically, PAFRAC may greatly exceed the theoretical range in values when the number of patches is small (e.g., <10), and its use should be avoided in such cases. In addition, PAFRAC requires patches to vary in size. Thus, PAFRAC is undefined and reported as "N/A" in the "basename".class file if all patches are the same size or there is < 10 patches.
Comments	*Perimeter-area fractal dimension* is appealing because it reflects shape complexity across a range of spatial scales (patch sizes). However, like its patch-level counterpart (FRACT), perimeter-area fractal dimension is only meaningful if the log-log relationship between perimeter and area is linear over the full range of patch sizes. If it is not (and this must be determined separately), then fractal dimension should be computed separately for the range of patch sizes over which it is constant. Note, because this index employs regression analysis, it is subject to spurious results when sample sizes are small. In landscapes with only a few patches, it is not unusual to get values that greatly exceed the theoretical limits of this index. Thus, this index is probably most useful if sample sizes are large (e.g., n ≥ 20), although FRAGSTATS computes the index for moderate sample sizes as well (i.e., n ≥10). In addition, it is important to realize that the perimeter-area fractal dimension computed in FRAGSTATS is based on the regression of log area on log perimeter; that is, $\ln(\text{area}) = b_0 + b_1 \cdot \ln(\text{perim})$. It is equally valid to compute fractal dimension by regressing log perimeter on log area; that is, $\ln(\text{perim}) = b_0 + b_1 \cdot \ln(\text{area})$, in which case the fractal dimension (D) is equal to 2 times the slope (b_1). These two approaches give slightly different answers and it is not clear that one is superior to the other. Both approaches are used in practice, so it behooves you to note the manner by which fractal dimension is computed when comparing among studies.

(L1) Perimeter-Area Fractal Dimension

$$\text{PAFRAC} = \frac{2}{\dfrac{\left[N \sum_{i=1}^{m} \sum_{j=1}^{n} (\ln p_{ij} \cdot \ln a_{ij})\right] - \left[\left(\sum_{i=1}^{m} \sum_{j=1}^{n} \ln p_{ij}\right)\left(\sum_{i=1}^{m} \sum_{j=1}^{n} \ln a_{ij}\right)\right]}{\left(N \sum_{i=1}^{m} \sum_{j=1}^{n} \ln p_{ij}^{2}\right) - \left(\sum_{i=1}^{m} \sum_{j=1}^{n} \ln p_{ij}\right)^{2}}}$$

a_{ij} = area (m^2) of patch ij.
p_{ij} = perimeter (m) of patch ij.
N = total number of patches in the landscape.

Description	PAFRAC equals 2 divided by the slope of regression line obtained by regressing the logarithm of patch area (m^2) against the logarithm of patch perimeter (m). That is, 2 divided by the coefficient b_1 derived from a least squares regression fit to the following equation: $\ln(area) = b_0 + b_1 \cdot \ln(perim)$. Note, PAFRAC excludes any background patches.
Units	None
Range	$1 \leq PAFRAC \leq 2$ A fractal dimension greater than 1 for a 2-dimensional landscape mosaic indicates a departure from a Euclidean geometry (i.e., an increase in patch shape complexity). PAFRAC approaches 1 for shapes with very simple perimeters such as squares, and approaches 2 for shapes with highly convoluted, plane-filling perimeters. PAFRAC employs regression techniques and is subject to small sample problems. Specifically, PAFRAC may greatly exceed the theoretical range in values when the number of patches is small (e.g., <10), and its use should be avoided in such cases. In addition, PAFRAC requires patches to vary in size. Thus, PAFRAC is undefined and reported as "N/A" in the "basename".land file if all patches are the same size or there is only 1 patch.
Comments	*Perimeter-area fractal dimension* at the landscape level is identical to the class level (see previous comments), except here all patches in the landscape are included in the regression of patch area against patch perimeter.

Core Area Metrics

Background.– Core area is defined as the area within a patch beyond some specified depth-of-edge influence (i.e., edge distance) or buffer width. Like patch shape, the primary significance of core area in determining the character and function of patches in a landscape appears to be related to the 'edge effect.' As discussed elsewhere (see Area and Edge Metrics), edge effects result from a combination of biotic and abiotic factors that alter environmental conditions along patch edges compared to patch interiors. The nature of the edge effect differs among organisms and ecological processes (Hansen and di Castri 1992). For example, some bird species are adversely affected by predation, competition, brood parasitism, and perhaps other factors along forest edges. Core area has been found to be a much better predictor of habitat quality than patch area for these forest interior specialists (Temple 1986). Unlike patch area, core area is affected by patch shape. Thus, while a patch may be large enough to support a given species, it still may not contain enough suitable core area to support the species. In some cases, it seems likely that edge effects would vary in relation to the type and nature of the edge (e.g., the degree of floristic and structural contrast and orientation). Thus, FRAGSTATS allows the user to specified an edge depth file that contains edge influence distances for every pairwise combination of patch types. In the absence of such information, the user can specify a single edge depth for all edge types.

In raster images, there are different ways to determine core area. FRAGSTATS employs a method involving the use of a variably-sized masked placed on cells on the perimeter of a patch, where the mask size varies depending the specified edge depth associated with the corresponding combination of patch types. Actually, the mask is placed over cells just outside the patch perimeter; referred to here as 'bounding' cells. Briefly, a mask is placed over each bounding cell. The mask itself is near circular in shape (as circular as you can get in the raster world) and sized according to the specified edge depth, as follows.

First, the size of the user-specified edge-depth (D) radius is used to determine the size of a square mask: $2 \times R + 1$, where R is equal to D rounded down to the nearest number of cell sizes. For example, if cell size is 30 and D = 50, then R = 1 and mask size = 2 * 1 + 1 = 3x3 cells. Note, the formula above ensures that each mask has a focal cell and is symmetrical in all directions so that it can be centered on a bounding cell for processing. A 4x4 mask would have no center cell and could no be superimposed centered on a bounding cell, making it useless. The effect is that all mask side sizes are made up of an odd number of cells (3x3, 5x5, 7x7, 9x9, ..., 101x101, etc).

Next, after the square mask is built, the distance is measured between the center of the focal cell (bounding cell) to the center of each of the others to determine if they are within the specified edge depth. If the center is in, the whole cell is in (=1), otherwise the cell is rejected (=0). The result is a final mask (cells = 1) that approximates a circular mask -- as well as can be done using rasters. The smaller the edge depth, the choppier the resulting mask. Conversely, the larger the edge depth, the better the circle will look.

Lastly, cells within the mask are eliminated from the 'core' of the patch. After all bounding cells are treated in this manner, the remaining cells not masked constitute the 'core' of the patch.

FRAGSTATS Metics.--FRAGSTATS computes several metrics based on core area at the patch, class, and landscape levels. Most of the indices dealing with number or density of patches, size of patches, and variability in patch size have corresponding core area indices computed in the same manner after eliminating the specified edge from all patches. For example, patch area, class area, total landscape area, and the percentage of landscape in each patch type all have counterparts computed after eliminating edge area defined by the specified edge depth; these are *core area* (CORE) at the patch level, *total core area* (TCA) at the class and landscape levels, and *core area percent of landscape* (CPLAND) at the class level. The latter index quantifies the core area in each patch type as a percentage of total landscape area. For organisms strongly associated with patch interiors, this index may provide a better measure of habitat availability than its counterpart, *percentage of landscape* (PLAND). In contrast to their counterparts, these core area indices integrate into a single measure the affects of patch area, patch shape, and edge effect distance. Therefore, although they quantify landscape composition, they are affected by landscape configuration. For this reason, these metrics at the class level may be very useful in the study of habitat loss and fragmentation.

From an organism-centered perspective, a single patch may actually contain several disjunct patches of suitable interior habitat, and it may be more appropriate to consider disjunct core areas as separate patches. For this reason, FRAGSTATS computes the *number of core areas* (NCORE) in each patch, as well as the number in each class and the landscape as a whole (NDCA). If core area is deemed more important than total area, then these indices may be more applicable than their counterparts, but they are subject to the same limitations as their counterparts (number of patches) because they are not standardized with respect to area. For this reason, number of core areas can be reported on a per unit area basis (*disjunct core area density*, DCAD) that has the same ecological applicability as its counterpart (patch density), except that all edge area is eliminated from consideration. Conversely, this information can be represented as mean core area (CORE_MN). Like their counterparts, note the difference between core area density and mean core area at the class level. Specifically, core area density is based on total landscape area; whereas, mean core area is based on total core area for the class. In contrast, at the landscape level, they are both based on total landscape area and are therefore completely redundant (at least if the landscape contains no background). Furthermore, mean core area can be defined in 2 ways. First, mean core area can be defined as the *mean core area per patch* (CORE_MN). Thus, patches with no core area are included in the average, and the total core area in a patch is considered together as 1 observation, regardless of whether the core area is contiguous or divided into 2 or more disjunct areas within the patch. Alternatively, mean core area can be defined as the *mean area per disjunct core* (DCORE_MN). The distinction between these 2 ways of defining mean core area should be noted.

FRAGSTATS also computes an index that quantifies core area as a percentage of total area. The *core area index* (CAI) at the patch level quantifies the percentage of the patch that is comprised of core area. Similarly, at the class and landscape levels *core area index area-weighted mean* (CAI_AM) quantifies core area for the entire class or landscape as a percentage of total class or landscape area, respectively. Note, that this is equivalent to the *total core area index* reported in FRAGSTATS 2.0. The core area index is basically an edge-to-interior ratio like many of the shape indices (see Shape Metrics), the main difference being that the core area index treats edge as an area of varying width and not as a line (perimeter) around each patch. In addition, the core area index is a relative measure; it does not reflect patch size, class area, or total landscape area; it merely quantifies the percentage of available area, regardless of whether it is 10 ha or 1,000 ha, comprised of core. This index does not confound area and configuration like the previous core area indices; rather, it isolates the configuration effect. For this reason, the core area index is probably best interpreted in conjunction with total area at the corresponding scale. For example, in conjunction with total class area, this index could serve as an effective fragmentation index for a particular class.

Limitations.--All core area indices are affected by the interaction of patch size, patch shape, and the specified edge depths. In particular, increasing edge depths or shape complexity, or decreasing patch size will decrease core area, and vice versa. On the one hand, this may be desirable as an integrative measure that has explicit functional relevance to the organism or process under consideration. On the other hand, there are potential pitfalls associated with integrative measures like core area. In particular, the confounding of patch area and configuration effects can complicate interpretation. For example, if the core area is small, it indicates that very little core area is available, but it does not discriminate between a small patch (area effect) and a large patch with a complex shape (configuration effect). In addition, core area is meaningful only if the specified depth-of-edge distance is meaningful to the phenomenon under investigation. Unfortunately, in many cases there is no empirical basis for specifying any particular depth-of-edge effect and so it must be chosen somewhat arbitrarily. The usefulness of core area as a metric is directly related to the arbitrariness in the specified edge depths, and this should be clearly understood when using these metrics.

Ultimately, the utility of core area metrics compared to their patch area counterparts depends on the resolution, minimum patch dimensions, and edge influence distance(s) employed. For example, given a landscape with a resolution of 1 m^2 and minimum patch dimensions of 100 x 100 m, if an edge influence distance of 1 m is specified, then core area and patch area will be nearly identical and core area will be relatively insensitive to differences in patch size and shape. In this case, core area offers little over its patch area counterpart.

Code	Metric (acronym)
Patch Metrics	
P1	Core Area (CORE)
P2	Number of Core Areas (NCA)
P3	Core Area Index (CAI)
Class Metrics	
C1	Total Core Area (TCA)
C2	Core Area Percentage of Landscape (CPLAND)
C3	Number of Disjunct Core Areas (NDCA)
C4	Disjunct Core Area Density (DCAD)
C5-C10	Core Area Distribution (CORE_MN, _AM, _MD, _RA, _SD, _CV)
C11-C16	Disjunct Core Area Distribution (DCORE_MN, _AM, _MD, _RA, _SD, _CV)
C17-C22	Core Area Index Distribution (CAI_MN, _AM, _MD, _RA, _SD, _CV)

Landscape Metrics	
L1	Total Core Area (TCA)
L2	Number of Disjunct Core Areas (NDCA)
L3	Disjunct Core Area Density (DCAD)
L4-L9	Core Area Distribution (CORE_MN, _AM, _MD, _RA, _SD, _CV)
L10-L15	Disjunct Core Area Distribution (DCORE_MN, _AM, _MD, _RA, _SD, _CV)
L16-L21	Core Area Index Distribution (CAI_MN, _AM, _MD, _RA, _SD, _CV)

(P1) Core Area	
$$CORE = a_{ij}^{c}\left(\frac{1}{10,000}\right)$$	a_{ij}^{c} = core area (m^2) of patch ij based on specified edge depths (m).
Description	CORE equals the area (m^2) within the patch that is further than the specified depth-of-edge distance from the patch perimeter, divided by 10,000 (to convert to hectares). Edge segments along the landscape boundary are treated like background (as specified in the edge depth file) unless a landscape border is present, in which case the boundary edge types are made explicit by the information in the border.
Units	Hectares
Range	CORE ≥ 0, without limit. CORE = 0 when every location within the patch is within the specified depth-of-edge distance from the patch perimeter. CORE approaches AREA as the specified depth-of-edge distance(s) decreases and as patch shape is simplified.
Comments	*Core area* represents the area in the patch greater than the specified depth-of-edge distance from the perimeter. Note, that a single depth-of-edge distance can be used for all edges or the user can specify a edge depth file that provides unique distances for each pairwise combination of patch types.

(P2) Number of Core Areas	
$$NCORE = n_{ij}^{c}$$	n_{ij}^{c} = number of disjunct core areas in patch ij based on specified edge depths (m).
Description	NCORE equals the number of disjunct core areas contained within the patch boundary.

Units	None
Range	NCORE ≥ 0, without limit. NCORE = 0 when CORE = 0 (i.e., every location within the patch is within the specified depth-of-edge distance from the patch perimeter). NCORE > 1 when, because of shape, the patch contains disjunct core areas.
Comments	A disjunct core is a spatially contiguous (and therefore distinct) core area (see Core Area description). Depending on the size and shape of the patch and the specified depth-of-edge distance(s), a single patch may actually contain several disjunct core areas. From an organism- or process-centered perspective, it may be more appropriate to consider disjunct core areas as separate patches.

(P3) Core Area Index	
$CAI = \frac{a_{ij}^{c}}{a_{ij}} (100)$	a_{ij}^{c} = core area (m^2) of patch ij based on specified edge depths (m). a_{ij} = area (m^2) of patch ij.
Description	CAI equals the patch core area (m^2) divided by total patch area (m^2), multiplied by 100 (to convert to a percentage); in other words, CAI equals the percentage of a patch that is core area.
Units	Percent
Range	0 ≤ CAI < 100 CAI = 0 when CORE = 0 (i.e., every location within the patch is within the specified depth-of-edge distance(s) from the patch perimeter); that is, when the patch contains no core area. CAI approaches 100 when the patch, because of size, shape, and edge width, contains mostly core area.
Comments	*Core area index* is a relative index that quantifies core area as a percentage of patch area (i.e., the percentage of the patch that is comprised of core area).

(C1) Total Core Area	
$TCA = \sum_{j=1}^{n} a_{ij}^{c} \left(\frac{1}{10{,}000} \right)$	a_{ij}^{c} = core area (m^2) of patch ij based on specified edge depths (m).
Description	TCA equals the sum of the core areas of each patch (m^2) of the corresponding patch type, divided by 10,000 (to convert to hectares).
Units	Hectares

Range	TCA ≥ 0, without limit. TCA = 0 when every location within each patch of the corresponding patch type is within the specified depth-of-edge distance(s) from the patch perimeters. TCA approaches total class area (CA) as the specified depth-of-edge distance(s) decreases and as patch shapes are simplified.
Comments	*Total core area* is defined the same as core area (CORE) at the patch level (see Core Area), but here core area is aggregated (summed) over all patches of the corresponding patch type.

(C2) Core Area Percentage of Landscape	
$$CPLAND = \frac{\sum_{j=1}^{n} a_{ij}^{c}}{A}(100)$$	a_{ij}^{c} = core area (m^2) of patch ij based on specified edge depths (m). A = total landscape area (m^2).
Description	CPLAND equals the sum of the core areas of each patch (m^2) of the corresponding patch type, divided by total landscape area (m^2), multiplied by 100 (to convert to a percentage); in other words, CPLAND equals the percentage the landscape comprised of core area of the corresponding patch type. Note, total landscape area (A) includes any internal background present.
Units	Percent
Range	0 ≤ CPLAND < 100 CPLAND approaches 0 when core area of the corresponding patch type (class) becomes increasingly rare in the landscape, because of increasing smaller patches and/or more convoluted patch shapes. CPLAND approaches 100 when the entire landscape consists of a single patch type (i.e., when the entire image is comprised of a single patch) and the specified depth-of-edge distance(s) approaches zero.
Comments	*Core area percentage of landscape* is defined the same as core area (CORE) at the patch level (see Core Area), but here core area is aggregated (summed) over all patches of the corresponding patch type and computed as a percentage of the total landscape area, which facilitates comparison among landscape of varying size.

(C3) Number of Disjunct Core Areas	
$$NDCA = \sum_{j=1}^{n} n_{ij}^{c}$$	n_{ij}^{c} = number of disjunct core areas in patch ij based on specified edge depths (m).

Description	NDCA equals the sum of the number of disjunct core areas contained within each patch of the corresponding patch type; that is, the number of disjunct core areas contained within the landscape.
Units	None
Range	NDCA ≥ 0, without limit. NDCA = 0 when TCA = 0 (i.e., every location within patches of the corresponding patch type are within the specified depth-of-edge distance(s) from the patch perimeters). NDCA > 1 when, due to patch shape complexity, a patch contains more than 1 core area.
Comments	*Number of disjunct core areas* is defined the same at the patch level (see Number of Core Areas), but here it is aggregated (summed) over all patches of the corresponding patch type. Number of disjunct core areas is an alternative to the number of patches when it makes sense to treat the core areas as functionally distinct patches.

(C4) Disjunct Core Area Density

$$DCAD = \frac{\sum_{j=1}^{n} n_{ij}^{c}}{A}(10{,}000)(100)$$

n_{ij}^{c} =	number of disjunct core areas in patch ij based on specified edge depths (m).
A =	total landscape area (m^2).

Description	DCAD equals the sum of number of disjunct core areas contained within each patch of the corresponding patch type, divided by total landscape area (m^2), multiplied by 10,000 and 100 (to convert to 100 hectares). Note, total landscape area (A) includes any internal background present.
Units	Number per 100 hectares
Range	DCAD ≥ 0, without limit. DCAD = 0 when TCA = 0 (i.e., every location within patches of the corresponding patch type are within the specified depth-of-edge distance(s) from the patch perimeters); in other words, when there are no core areas.
Comments	*Disjunct core area density*, like its counterpart, patch density (PD),expresses number of disjunct core areas on a per unit area basis that facilitates comparisons among landscapes of varying size. Of course, if total core area is held constant, then disjunct core area density and number of disjunct core areas convey the same information.

(L1) Total Core Area

$$TCA = \sum_{i=1}^{m} \sum_{j=1}^{n} a_{ij}^{c} \left(\frac{1}{10{,}000} \right)$$	a_{ij}^{c} = core area (m^2) of patch ij based on specified edge depths (m).
Description	TCA equals the sum of the core areas of each patch (m^2), divided by 10,000 (to convert to hectares).
Units	Hectares
Range	TCA ≥ 0, without limit. TCA = 0 when every location within every patch is within the specified depth-of-edge distance(s) from the patch perimeters. TCA approaches total landscape area as the specified depth-of-edge distance(s) decreases and as patch shapes are simplified.
Comments	*Total core area* is defined the same as core area (CORE) at the patch level (see Core Area), but here core area is aggregated (summed) over all patches.

(L2) Number of Disjunct Core Areas	
$$NDCA = \sum_{i=j}^{m} \sum_{j=1}^{n} n_{ij}^{c}$$	n_{ij}^{c} = number of disjunct core areas in patch ij based on specified edge depths (m).
Description	NDCA equals the sum of the number of disjunct core areas contained within each patch in the landscape; that is, the number of disjunct core areas contained within the landscape.
Units	None
Range	NDCA ≥ 0, without limit. NCA = 0 when TCA = 0 (i.e., every location within every patch is within the specified depth-of-edge distance(s) from the patch perimeters); in other words, when there are no core areas. NDCA > 1 when, due to patch size and shape, at least one core area exists.
Comments	*Number of disjunct core areas* is defined the same at the patch level (see Number of Core Areas), but here it is aggregated (summed) over all patches. Number of disjunct core areas is an alternative to the number of patches when it makes sense to treat the core areas as functionally distinct patches.

(L3) Disjunct Core Area Density

$$DCAD = \frac{\sum_{i=1}^{m}\sum_{j=1}^{n} n_{ij}^{c}}{A}(10{,}000)(100)$$	n_{ij}^{c} = number of disjunct core areas in patch ij based on specified edge depths (m). A = total landscape area (m^2).
Description	DCAD equals the sum of number of disjunct core areas contained within each patch, divided by total landscape area (m^2), multiplied by 10,000 and 100 (to convert to 100 hectares). Note, total landscape area (A) includes any internal background present.
Units	Number per 100 hectares
Range	DCAD ≥ 0, without limit. DCAD = 0 when TCA = 0 (i.e., every location within every patch is within the specified depth-of-edge distance(s) from the patch perimeters); in other words, when there are no core areas. DCAD > 1 when, due to patch size and shape, at least one core area exists.
Comments	*Disjunct core area density*, like its counterpart, patch density (PD),expresses number of disjunct core areas on a per unit area basis that facilitates comparisons among landscapes of varying size. Of course, if total core area is held constant, then disjunct core area density and number of disjunct core areas convey the same information.

Contrast Metrics

Background.--Contrast refers to the magnitude of difference between adjacent patch types with respect to one or more ecological attributes at a given scale that are relevant to the organism or process under consideration. The contrast between a patch and its neighborhood can influence a number of important ecological processes (Forman and Godron 1986). The 'edge effects' described elsewhere (see Area and Edge Metrics), for example, are influenced by the degree of contrast between patches. Microclimatic changes (e.g., wind, light intensity and quality, etc.) are likely to extend farther into a patch along an edge with high structural contrast than along an edge with low structural contrast (Ranney et al. 1981). Similarly, the adverse affects of brown-headed cowbird nest parasitism on some forest-dwelling neotropical migratory bird species are likely to be greatest along high-contrast forest edges (e.g., between mature forest patches and grassland), because cowbirds prefer to forage in early-seral habitats and parasitize nests in late-seral habitats (Brittingham and Temple 1983). In addition, patch isolation may be a function of the contrast between a patch and its ecological neighborhood. In particular, the degree of contrast between a habitat patch and the surrounding landscape may influence dispersal patterns and survival, and thus indirectly affect the degree of patch isolation. Similarly, an organism's ability to use the resources in adjacent patches, as in the process of landscape supplementation (Dunning et al. 1992), may depend on the nature of the boundary between the patches. The boundary between patches can function as a barrier to movement, a differentially-permeable membrane that facilitates some ecological flows but impedes others, or as a semipermeable membrane that partially impairs flows (Wiens et al. 1985, Hansen and di Castri 1992). The contrast along an edge may influence its function in this regard. For example, high-contrast edges may prohibit or inhibit some organisms from seeking supplementary resources in surrounding patches. Conversely, some species (e.g., great horned owl, *Bubo virginianus*) seem to prefer the juxtaposition of patch types with high contrast, as in the process of landscape complementation (Dunning et al. 1992).

Clearly, edge contrast can assume a variety of meanings for different ecological processes. Therefore, contrast can be defined in a variety of ways, but it always reflects the magnitude of difference between patches with respect to one or more ecological attributes at a given scale that are important to the phenomenon under investigation (Kotliar and Wiens 1990, Wiens et al. 1985). Similar to Romme (1982), FRAGSTATS employs weights to represent the magnitude of edge contrast between adjacent patch types; weights must range between 0 (no contrast) and 1 (maximum contrast). Under most circumstances, it is probably not valid to assume that all edges function similarly. Often there will not be a strong empirical basis for establishing a weighting scheme, but a reasoned guess based on a theoretical understanding of the phenomenon is probably better than assuming all edges are alike. For example, from an avian habitat use standpoint, we might weight edges somewhat subjectively according to the degree of structural and floristic contrast between adjacent patches, because a number of studies have shown these features to be important to many bird species (Thomas et al. 1978 and 1979, Logan et al. 1985).

FRAGSTATS Metrics.–FRAGSTATS computes several indices based on edge contrast at the patch, class, and landscape levels. At the patch level, the *edge contrast index* (ECON) measures the degree of contrast between a patch and its immediate neighborhood. Each segment of the patch perimeter is weighted by the degree of contrast with the adjacent patch. Weights must range between 0 (no contrast) and 1 (maximum contrast). Total patch perimeter is reduced proportionate to the degree of contrast in the perimeter and reported as a percentage of the total perimeter. Thus, a patch with a 10% edge contrast index has very little contrast with its neighborhood; it has the equivalent of 10% of its perimeter in maximum-contrast edge. Conversely, a patch with a 90% edge contrast index has high contrast with its neighborhood. Note that this index is a relative measure. Given any amount of edge, it measures the degree of contrast in that edge. In other words, high values of ECON mean that the edge present, regardless of whether it is 10 m or 1,000 m, is of high contrast, and vice versa. At the class and landscape levels, FRAGSTATS computes a *total edge contrast index* (TECI). Like its patch-level counterpart, this index quantifies edge contrast as a percentage of maximum possible. However, this index ignores patch distinctions; it quantifies edge contrast for the landscape as a whole. FRAGSTATS also computes distribution statistics for the edge contrast index at the class and landscape levels. The *mean edge contrast index* (ECON_MN), for example, quantifies the average edge contrast for patches of a particular patch type (class level) or for all patches in the landscape.

These edge contrast indices are relative measures. Given any amount or density of edge, they measure the degree of contrast in that edge. High values of these indices mean that the edge present, regardless of whether it is 10 m or 1,000 m, is of high contrast, and vice versa. For this reason, these indices are probably best interpreted in conjunction with total edge or edge density. Because of this, FRAGSTATS also computes an index that incorporates both edge density and edge contrast in a single index. *Contrast-weighted edge density* (CWED) standardizes edge to a per unit area basis that facilitates comparison among landscapes of varying size. Unlike edge density, however, this index reduces the length of each edge segment proportionate to the degree of contrast. Thus, 100 m/ha of maximum-contrast edge (i.e., weight = 1) is unaffected; but 100 m/ha of edge with a contrast weight of 0.2 is reduced by 80% to 20 m/ha of contrast-weighted edge. This index measures the equivalent maximum-contrast edge density. For example, an edge density of 100 means that there are 100 meters of edge per hectare in the landscape. A contrast-weighted edge density of 80 for the same landscape means that there are an equivalent of 80 meters of maximum-contrast edge per hectare in the landscape. A landscape with 100 m/ha of edge and an average contrast weight of 0.8 would have twice the contrast-weighted edge density (80 m/ha) as a landscape with only 50 m/ha of edge but with the same average contrast weight (40 m/ha). Thus, both edge density and edge contrast are reflected in this index. For many ecological phenomena, edge types function differently. Consequently, comparing total edge density among landscapes may be misleading because of differences in edge types. This contrast-weighted edge density index attempts to quantify edge from the perspective of its functional significance. Thus, landscapes with the same contrast-weighted edge density are presumed to have the same total magnitude of edge effects from a functional perspective.

All edge contrast indices consider landscape boundary and background segments even if they have an edge contrast weight of zero. In the absence of a landscape border, the landscape boundary is assigned as background edge and treated according to the background contrast weight specified in the contrast weight file. In the presence of a landscape border, all landscape boundary edges are made explicit by the information present in the border and are assigned the appropriate contrast weight given in the contrast weight file. Regardless of whether a border is present or not, all background edges, both internal (positively valued) and external (negatively valued), are assigned the background contrast weight specified in the contrast weight file. Assigning a meaningful contrast weight to the boundary and background presents a special challenge because, in practice, background (and the boundary, in the absence of a border) often represents area for which nothing is known. Thus, it can be difficult to assign a single contrast weight that applies equally well to all background/boundary edges. A landscape border is often included to avoid this problem, because all boundary edges are made explicit; however, even a border doesn't eliminate the problem of assigning a weight to background if it exists. The potential severity of the boundary/background problem depends on the size and heterogeneity of the landscape and the extent of background edge. Larger and more heterogeneous landscapes without little or no background will have proportionately less total edge located along the boundary and/or background.

Limitations.–Edge contrast indices are limited by the considerations discussed elsewhere for metrics based on total edge length (see Area and Edge Metrics). These indices are only calculated if an edge contrast weight file is specified. More importantly, the usefulness of these indices is directly related to the meaningfulness of the weighting scheme used to quantify edge contrast. Clearly, edge contrast can assume a variety of meanings for different ecological processes. Therefore, contrast can be defined in a variety of ways, but it always reflects the magnitude of difference between patches with respect to one or more ecological attributes at a given scale that are important to the phenomenon under investigation. Under most circumstances, it is probably not valid to assume that all edges function similarly. Often there will not be a strong empirical basis for establishing a weighting scheme, but a reasoned guess based on a theoretical understanding of the phenomenon is probably better than assuming all edges are alike. For example, from an avian habitat use standpoint, we might weight edges somewhat subjectively according to the degree of structural and floristic contrast between adjacent patches, because a number of studies have shown these features to be important to many bird species. Careful consideration should be given to devising weights that reflect any empirical and theoretical knowledge and understanding of the phenomenon under consideration. If the weighting scheme does not accurately represent the phenomenon under investigation, then the results will be spurious.

Code	**Metric (acronym)**
Patch Metrics	
P1	Edge Contrast Index (ECON)
Class Metrics	
C1	Contrast-Weighted Edge Density (CWED)
C2	Total Edge Contrast Index (TECI)
C3-C8	Edge Contrast Index Distribution (ECON_MN, _AM, _MD, _RA, _SD, _CV)
Landscape Metrics	
L1	Contrast-Weighted Edge Density (CWED)
L2	Total Edge Contrast Index (TECI)
L3-L8	Edge Contrast Index Distribution (ECON_MN, _AM, _MD, _RA, _SD, _CV)

(P1) Edge Contrast Index	
$$ECON = \frac{\sum_{k=1}^{m} (p_{ijk} \cdot d_{ik})}{p_{ij}} (100)$$	p_{ijk} = length (m) of edge of patch ij adjacent to patch type (class) k. d_{ik} = dissimilarity (edge contrast weight) between patch types i and k. p_{ij} = length (m) of perimeter of patch ij.
Description	ECON equals the sum of the patch perimeter segment lengths (m) multiplied by their corresponding contrast weights, divided by total patch perimeter (m), multiplied by 100 (to convert to a percentage). Edge segments along the landscape boundary are treated like background (as specified in the edge contrast weight file) unless a landscape border is present, in which case the boundary edge types are made explicit by the information in the border.
Units	Percent
Range	$0 \leq ECON \leq 100$ ECON = 0 if the landscape consists of only 1 patch and the landscape boundary consists of all background (i.e., in the absence of a border) and is give a zero-contrast weight (d = 0). Also, ECON = 0 when all of the patch perimeter segments involve patch type adjacencies that have been given a zero-contrast weight in the edge contrast weight file. ECON = 100 when the entire patch perimeter is maximum-contrast edge (d = 1). ECON < 100 when a portion of the patch perimeter is less than maximum-contrast edge (d < 1).
Comments	*Edge Contrast Index* is founded on the notion that all edges are not created equal. To account for this, the notion of edge "contrast" was created. This index is a relative measure of the amount of contrast along the patch perimeter.

(C1) Contrast-Weighted Edge Density	
$$CWED = \frac{\sum_{k=1}^{m} (e_{ik} \cdot d_{ik})}{A} (10,000)$$	e_{ik} = total length (m) of edge in landscape between patch types (classes) i and k; includes landscape boundary segments involving patch type i. d_{ik} = dissimilarity (edge contrast weight) between patch types i and k. A = total landscape area (m^2).

Description	CWED equals the sum of the lengths (m) of each edge segment involving the corresponding patch type multiplied by the corresponding contrast weight, divided by the total landscape area (m^2), multiplied by 10,000 (to convert to hectares). Edge segments along the landscape boundary are treated like background (as specified in the edge contrast weight file) unless a landscape border is present, in which case the boundary edge types are made explicit by the information in the border. Note, total landscape area (A) includes any internal background present.
Units	Meters per hectare
Range	CWED ≥ 0, without limit. CWED = 0 when there is no class edge in the landscape; that is, when the entire landscape and landscape border, if present, consists of the corresponding patch type and the user specifies that background edge be given a zero-contrast weight (d = 0). CWED increases as the amount of class edge in the landscape increases and/or as the contrast in edges involving the corresponding patch type increase (i.e., contrast weight approaches 1).
Description	*Contrast-weighted edge density* standardizes edge to a per unit area basis that facilitates comparison among landscapes of varying size

(C2) Total Edge Contrast Index

$$TECI = \frac{\sum_{k=1}^{m} (e_{ik} \cdot d_{ik})}{\sum_{k=1}^{m} e^{*}_{ik}} (100)$$	e_{ik} = total length (m) of edge in landscape between patch types (classes) i and k; includes landscape boundary segments involving patch type i. e^{*}_{ik} = total length (m) of edge in landscape between patch types (classes) i and k; includes the entire landscape boundary and all background edge segments, regardless of whether they represent edge or not. d_{ik} = dissimilarity (edge contrast weight) between patch types i and k.
Description	TECI equals the sum of the lengths (m) of each edge segment involving the corresponding patch type multiplied by the corresponding contrast weight, divided by the sum of the lengths (m) of all edge segments involving the same type, multiplied by 100 (to convert to a percentage). Edge segments along the landscape boundary are treated like background (as specified in the edge contrast weight file) unless a landscape border is present, in which case the boundary edge types are made explicit by the information in the border.
Units	Percent

Range	0 ≤ TECI ≤ 100 TECI = 0 when there is no class edge in the landscape; that is, when the entire landscape and landscape border, if present, consists of the corresponding patch type and the user specifies that background edge be given a zero-contrast weight (d = 0). TECI approaches 0 as the contrast in edges involving the corresponding patch type lesson (i.e., contrast weight approaches 0). TECI = 100 when all class edge is maximum contrast (d = 1).
Description	*Total edge contrast index* is similar to the edge contrast index at the patch level, only here it is applied to all edges of the corresponding patch type

(L1) Contrast-Weighted Edge Density

$$CWED = \frac{\sum_{i=1}^{m} \sum_{k=i+1}^{m} (e_{ik} \cdot d_{ik})}{A} (10{,}000)$$

e_{ik} = total length (m) of edge in landscape between patch types (classes) i and k; includes landscape boundary segments involving patch type i.
d_{ik} = dissimilarity (edge contrast weight) between patch types i and k.
A = total landscape area (m^2).

Description	CWED equals the sum of the lengths (m) of each edge segment in the landscape multiplied by the corresponding contrast weight, divided by the total landscape area (m^2), multiplied by 10,000 (to convert to hectares). Edge segments along the landscape boundary are treated like background (as specified in the edge contrast weight file) unless a landscape border is present, in which case the boundary edge types are made explicit by the information in the border. Note, total landscape area (A) includes any internal background present.
Units	Meters per hectare
Range	CWED ≥ 0, without limit. CWED = 0 when there is no edge in the landscape; that is, when the entire landscape and landscape border, if present, consists of the corresponding patch type and the user specifies that background edge be given a zero-contrast weight (d = 0). CWED increases as the amount of edge in the landscape increases and/or as the contrast in edges increase (i.e., contrast weight approaches 1).
Description	*Contrast-weighted edge density* standardizes edge to a per unit area basis that facilitates comparison among landscapes of varying size

(L2) Total Edge Contrast Index

$$\text{TECI} = \frac{\sum_{i=1}^{m}\sum_{k=i+1}^{m}(e_{ik} \cdot d_{ik})}{E^*}(100)$$	e_{ik} = total length (m) of edge in landscape between patch types (classes) i and k; includes landscape boundary segments involving patch type i. E^* = total length (m) of edge in landscape; includes entire landscape boundary and background edge segments regardless of whether they represent edge or not. d_{ik} = dissimilarity (edge contrast weight) between patch types i and k.
Description	TECI equals the sum of the lengths (m) of each edge segment in the landscape multiplied by the corresponding contrast weight, divided by the total length (m) of edge in the landscape, multiplied by 100 (to convert to a percentage). Edge segments along the landscape boundary are treated like background (as specified in the edge contrast weight file) unless a landscape border is present, in which case the boundary edge types are made explicit by the information in the border.
Units	Percent
Range	$0 \leq \text{TECI} \leq 100$ TECI = 0 when there is no edge in the landscape; that is, when the entire landscape and landscape border, if present, consists of a single patch or the user specifies that all edge types be given a zero-contrast weight (d = 0). TECI approaches 0 as the contrast in edges lesson (i.e., contrast weight approaches 0). TECI = 100 when all edge is maximum contrast (d = 1).
Description	*Total edge contrast index* is similar to the edge contrast index at the patch level, only here it is applied to all edges across the landscape.

Aggregation Metrics

Background.–Aggregation refers to the tendency of patch types to be spatially aggregated; that is, to occur in large, aggregated or "contagious" distributions. This property is also often referred to as landscape *texture*. We use the term "aggregation" as an umbrella term to describe several closely related concepts: 1) dispersion, 2) interspersion, 3) subdivision, and 4) isolation. Each of these concepts relates to the broader concept of aggregation, but is distinct from the others in subtle but important ways, as follows.

Dispersion and Interspersion.–Many of the aggregation metrics deal explicitly with the spatial properties of dispersion and interspersion, and thus it is important to distinguish these two distinct components. *Dispersion* refers to the spatial distribution of a patch type (class) without explicit reference to any other patch types. Dispersion deals with how spread out or dispersed a patch type is, whereby the greater the dispersion, the greater the disaggregation of the class or landscape. *Interspersion*, on the other hand, refers to the spatial intermixing of different patch types (classes) without explicit reference to the dispersion of any patch type. Interspersion deals solely with how often each patch type is adjacent to each other patch type and not by the size, contiguity or dispersion of patches. Dispersion and interspersion are both aspects of landscape texture; they both deal with the adjacency of patch types, but do so in a different manner. Dispersion reflects the spatial distribution of a particular patch type and is based on how often cells of a patch type are adjacent to cells of the same patch type, whereas interspersion reflects the intermixing of patch types and is based on how often cells along the perimeter of patches are adjacent to other patch types. These two spatial properties are often highly confounded in real landscapes; as patch types become more dispersed they also tend to be more well interspersed among other patch types. Thus, an aggregated landscape tends to exhibit low dispersion and interspersion, whereas a disaggregated landscape tends to exhibit high dispersion and interspersion. Nevertheless, these two components can be measured independently or jointly, as described below.

Subdivision.–Subdivision is closely related to the concept of dispersion; both refer to the aggregation of patch types, but subdivision deals explicitly with the degree to which patch types are broken up (i.e., subdivided) into separate patches (i.e., fragments). Whereas dispersion deals with the aggregation or disaggregation of cells of the same patch type and is based on cell adjacencies independent of patch membership, subdivision deals explicitly with the subdivision of patch types into disjunct patches. Thus, two distributions can have identical levels of dispersion (e.g., if there are no like cell adjacencies, as in the case of a checkboard-like distribution), but they can have very different levels of subdivision. Of course, these two components of aggregation are often highly confounded in real landscapes; as patch types become more dispersed they also tend be more subdivided.

The subdivision of a particular habitat type may affect a variety of ecological processes, depending on the landscape context. For example, the number or density of patches may determine the number of subpopulations in a spatially-dispersed population, or metapopulation, for species exclusively associated with that habitat type. The number of subpopulations could influence the dynamics and persistence of the metapopulation (Gilpin and Hanski 1991). The number or density of patches also can alter the stability of species interactions and opportunities for coexistence in both predator-prey and competitive systems (Kareiva 1990). The number or density of patches in a landscape mosaic (pooled across patch types) can have the same ecological applicability, but more often serves as a general index of spatial heterogeneity of the entire landscape mosaic. A landscape with a greater number or density of patches has a finer grain; that is, the spatial heterogeneity occurs at a finer resolution. Although the number or density of patches in a class or in the landscape may be fundamentally important to a number of ecological processes, often it does not have any interpretive value by itself because it conveys no information about the area or distribution of patches. Number or density of patches is probably most valuable, however, as the basis for computing other, more interpretable, metrics, but is often use in combination with other metrics to characterize subdivision.

Isolation.--Isolation is closely related to the concept of subdivision; both refer to the subdivision per se of patch types, but isolation deals explicitly with the degree to which patches are spatially isolated from each other, whereas subdivision doesn't address the distance between patches, only that they are disjunct. Thus, two distributions can have identical levels of subdivision (e.g., identical patch size distributions), but they can have very different levels of isolation, for example if the patches are farther apart in one landscape compared to the other. Of course, these two components of aggregation are often highly confounded in real landscapes; as patch types become more subdivided they also tend be more isolated, but this isn't always the case. Consider the case when large contiguous patches get subdivided by roads; the level of patch subdivision goes up but the patches may or may not be more isolated from each other as a result.

The texture of a landscape is a fundamental aspect of landscape pattern and is important in many ecological processes. Interspersion is presumed to affect the quality of habitat for many species that require different patch types to meet different life history requisites, as in the process of landscape complementation (Dunning et al. 1992). Indeed, the notion of habitat interspersion has had a preeminent role in wildlife management during the past century. Wildlife management efforts are often focused on maximizing habitat interspersion because it is believed that the juxtaposition of different habitats will increase species diversity (Leopold 1933).

The disaggregation of a patch type of course plays a crucial role in the process of habitat loss and fragmentation. Specifically, habitat loss and fragmentation generally involves the disaggregation of contiguous habitat into more dispersed habitat and/or disjunct (i.e., subdivided) and more isolated patches. As habitat loss and fragmentation proceeds, habitat becomes disaggregated and eventually ecological function is impaired (Saunders et al.1991). Specifically, the subdivision and isolation of populations caused by this habitat loss and fragmentation can lead to reduced dispersal success and patch colonization rates which may result in a decline in the persistence of individual populations and an enhanced probability of regional extinction for entire populations across the landscape (e.g., Lande 1987; With and King 1999a,b; With 1999). In addition, the disaggregation of patch types may affect the propagation of disturbances across a landscape (Franklin and Forman 1987). Specifically, a patch type that is highly disaggregated and/or subdivided may be more resistant to the propagation of some disturbances (e.g., disease, fire, etc.), and thus more likely to persist in a landscape than a patch type that is highly aggregated and/or contiguous. Conversely, highly disaggregated and/or subdivided patch types may suffer higher rates of disturbance for some disturbance types (e.g. windthrow) than more aggregated and/or contiguous distributions.

Isolation of habitat patches is a critical factor in the dynamics of spatially structured populations. For example, there has been a proliferation of mathematical models on population dynamics and species interactions in spatially subdivided populations (Kareiva 1990), and results suggest that the dynamics of local plant and animal populations in a patch are influenced by their proximity to other subpopulations of the same or competing species. Patch isolation plays a critical role in island biogeographic theory (MacArthur and Wilson 1967) and metapopulation theory (Levins 1970, Gilpin and Hanski 1991). The role of patch isolation (e.g., as measured by interpatch distance) in metapopulations has had a preeminent role in conservation efforts for endangered species (e.g., Lamberson et al. 1992, McKelvey et al. 1992).

Isolation is particularly important in the context of habitat loss and fragmentation. Several authors have claimed, for example, that patch isolation explains why fragmented habitats often contain fewer bird species than contiguous habitats (Moore and Hooper 1975, Forman et al. 1976, Helliwell 1976, Whitcomb et al. 1981, Hayden et al. 1985, Dickman 1987). Specifically, as habitat is lost and fragmented, residual habitat patches become more isolated from each other in space and time. One of the more immediate consequence of this is the disruption of movement patterns and the resulting isolation of individuals and local populations. This has important metapopulation consequences. As habitat is fragmented, it is broken up into remnants that are isolated to varying degrees. Because remnant habitat patches are relatively small and therefore support fewer individuals, there will be fewer local (within patch) opportunities for intra-specific interactions. This may not present a problem for individuals (and the persistence of the population) if movement among patches is largely unimpeded by intervening habitats in the matrix and connectivity across the landscape can be maintained. However, if movement among habitat patches is significantly impeded or prevented, then individuals (and local populations) in remnant habitat patches may become functionally isolated. The degree of isolation for any fragmented habitat distribution will vary among species depending on how they perceive and interact with landscape patterns (Dale et al. 1994, With and Crist 1995, Pearson et al. 1996, With et al. 1997, With 1999); less vagile species with very restrictive habitat requirements and limited gap-crossing ability will likely be most sensitive to isolation effects.

Habitat patches can become functionally isolated in several ways. First, the patch edge may act as a filter or barrier that impedes or prevents movement, thereby disrupting emigration and dispersal from the patch (Wiens et al. 1985). Some evidence for this exists for small mammals (e.g., Wegner and Merriam 1979, Chasko and Gates 1982, Bendell and Gates 1987, Yahner 1986), but the data are scarce for other vertebrates. Thus, subdivision per se can lead to increased isolation. Whether edges themselves can limit movement presumably depends on what species are trying to cross the edge and on the structure of the edge habitat (Kremsater and Bunnell 1999). Second, the distance from remnant habitat patches to other neighboring habitat patches may influence the likelihood of successful movement of individuals among habitat patches. Again, the distance at which movement rates significantly decline will vary among species depending on how they scale the environment. In general, larger organisms can travel longer distances. Therefore, a 100 m-wide agricultural field may be a complete barrier to dispersal for small organisms such as invertebrates (e.g., Mader 1984), yet be quite permeable for larger and more vagile organisms such as birds. Lastly, the composition and structure of the intervening landscape mosaic may determine the permeability of the landscape to movements. Note that under an island biogeographic perspective, habitat patches exist in a uniform sea that is hostile to both survival and dispersal. In this case, the matrix is presumed to contain no meaningful structure and isolation is influenced largely by the distance among favorable habitat patches. However, under a landscape mosaic perspective, habitat patches are bounded by other patches that may be more or less similar (as opposed to highly contrasting and hostile) and connectivity is assessed by the extent to which movement is facilitated or impeded through different habitat types across the landscape. Each habitat may differ in its "viscosity" or resistance to movement, facilitating movement through certain elements of the landscape and impeding it in others. Again, the degree to which a given landscape structure facilitates or impedes movement will vary among organisms. Regardless of how habitat patches become isolated, whether it be due to properties of the edges themselves, the distance between patches, or properties of the intervening matrix, the end result is the same–fewer individual movements among habitat patches.

FRAGSTATS Metrics.–There are several different approaches for measuring aggregation. One popular index that subsumes both dispersion and interspersion is the *contagion index* (CONTAG) based on the probability of finding a cell of type i next to a cell of type j. This index was proposed first by O'Neill et al. (1988) and subsequently it has been widely used (Turner and Ruscher 1988, Turner 1989, Turner et al. 1989, Turner 1990a and b, Graham et al. 1991, Gustafson and Parker 1992). Li and Reynolds (1993) showed that the original formula was incorrect; they introduced 2 forms of an alternative contagion index that corrects this error and has improved performance. FRAGSTATS computes one of the contagion indices proposed by Li and Reynolds (1993). This contagion index is based on raster "cell" adjacencies, not "patch" adjacencies, and consists of the sum, over patch types, of the product of 2 probabilities: (1) the probability that a randomly chosen cell belongs to patch type i (estimated by the proportional abundance of patch type i), and (2) the conditional probability that given a cell is of patch type i, one of its neighboring cells belongs to patch type j (estimated by the proportional abundance of patch type i adjacencies involving patch type j). The product of these probabilities equals the probability that 2 randomly chosen adjacent cells belong to patch type i and j. This contagion index is appealing because of the straightforward and intuitive interpretation of this probability.

The contagion index has been widely used in landscape ecology because it seems to be an effective summary of overall clumpiness on categorical maps (Turner 1989). In addition, in many landscapes, it is highly correlated with indices of patch type diversity and dominance (Ritters et al. 1995) and thus may be an effective surrogate for those important components of pattern (O'Neill et al. 1996). Contagion measures both patch type interspersion (i.e., the intermixing of units of different patch types) as well as patch dispersion (i.e., the spatial distribution of a patch type) at the landscape level. All other things being equal, a landscape in which the patch types are well interspersed will have lower contagion than a landscape in which patch types are poorly interspersed. Contagion measures the extent to which patch types are aggregated or clumped (i.e., dispersion); higher values of contagion may result from landscapes with a few large, contiguous patches, whereas lower values generally characterize landscapes with many small and dispersed patches. Thus, holding interspersion constant, a landscape in which the patch types are aggregated into larger, contiguous patches will have greater contagion than a landscape in which the patch types are fragmented into many small patches. Contagion measures dispersion in addition to patch type interspersion because cells, not patches, are evaluated for adjacency. Landscapes consisting of large, contiguous patches have a majority of internal cells with like adjacencies. In this case, contagion is high because the proportion of total cell adjacencies comprised of like adjacencies is very large and the distribution of adjacencies among edge types is very uneven.

Unfortunately, as alluded to above, there are alternative procedures for computing contagion, and this has contributed to some confusion over the interpretation of published contagion values (see Ritters et al. 1996 for a discussion). Briefly, to calculate contagion, the adjacency of patch types is first summarized in an *adjacency* or *co-occurrence* matrix, which shows the frequency with which different pairs of patch types (including like adjacencies between the same patch type) appear side-by-side on the map (note, FRAGSTATS includes only the 4 orthogonal neighbors, not diagonal neighbors, regardless of the choice of neighbor rules for defining patches). Although this would seem to be a simple task, it is the source of differences among procedures for calculating contagion. The difference arises out of the option to count each immediately-adjacent pixel pair once or twice. In the *single-count* method, each pixel adjacency is counted once and the order of pixels is not preserved; whereas, in the *double-count* method, each pixel adjacency is counted twice and the order of pixels is preserved. Ritters et al. (1996) discuss the merits of both approaches. FRAGSTATS adopts the *double-count* method in which pixel order is preserved, with two exceptions. If a landscape border is present, the adjacencies along the landscape boundary (i.e., those between cells *inside* the landscape and those in the border) are only counted once, and they are tallied for the cells inside the landscape. For example, an adjacency on the landscape boundary between class 2 (inside the landscape) and class -3 (in the landscape border) is recorded as a 2-3 adjacency in the adjacency matrix, not a 3-2. Thus, if a landscape border is present, the adjacency matrix includes double-counts for all internal cell adjacencies and single-counts for all adjacencies on the landscape boundary not involving background. In effect, this gives double the weight to the internal adjacencies than those on the boundary, although the effect will be trivial in most landscapes because the boundary edges will represent a relative minor proportion of the total adjacencies. Similarly, all adjacencies involving background (both internal, i.e., inside the landscape, and external, i.e., on the landscape boundary) are counted only once, and they are tallied for the non-background cells. Essentially, each non-background cell inside the landscape (i.e., positively valued cell) is visited and the four cell sides are evaluated and tallied in the adjacency matrix. Since background cells and all cells in the landscape border, if present, are not visited per se, the edges involving these cells only get tallied once in association with the non-background cell inside the landscape.

McGarigal and Marks (1995) introduced the *interspersion and juxtaposition index* (IJI) that isolates the interspersion aspect of aggregation; it increases in value as patches tend to be more evenly interspersed in a "salt and pepper" mixture. Unlike the previous contagion index that is based on raster *cell* adjacencies, this index is based on *patch* adjacencies; only the patch perimeters are considered in determining the total length of each unique edge type. Each patch is evaluated for adjacency with all other patch types; like adjacencies are not possible because a patch can never be adjacent to a patch of the same type. Because this index is a measure of *patch* adjacency and not *cell* adjacency, the interpretation is somewhat different than the contagion index. The interspersion index measures the extent to which patch types are interspersed (not necessarily dispersed); higher values result from landscapes in which the patch types are well interspersed (i.e., equally adjacent to each other), whereas lower values characterize landscapes in which the patch types are poorly interspersed (i.e., disproportionate distribution of patch type adjacencies). The interspersion and juxtaposition index is not directly affected by the number, size, contiguity, or dispersion of patches per se, as is the contagion index. Consequently, a landscape containing 4 large patches, each a different patch type, and a landscape of the same extent containing 100 small patches of 4 patch types will have the same index value if the patch types are equally interspersed (or adjacent to each other based on the proportion of total edge length in each edge type); whereas, the value of contagion would be quite different. Like the contagion index, the interspersion and juxtaposition index is a relative index that represents the observed level of interspersion as a percentage of the maximum possible given the total number of patch types.

It is important to note the differences between the contagion index and the interspersion and juxtaposition index. Contagion is affected by both interspersion and dispersion. The interspersion and juxtaposition index, in contrast, is affected only by patch type interspersion and not necessarily by the size, contiguity, or dispersion of patches. Thus, although often indirectly affected by dispersion, the interspersion and juxtaposition index directly measures patch type interspersion, whereas contagion measures a combination of both patch type interspersion and dispersion. In addition, contagion and interspersion are typically inversely related to each other. Higher contagion generally corresponds to lower interspersion and vice versa. Finally, in contrast to the interspersion and juxtaposition index, the contagion index is strongly affected by the grain size or resolution of the image. Given a particular patch mosaic, a smaller grain size will result in greater contagion because of the proportional increase in like adjacencies from internal cells. The interspersion and juxtaposition index is not affected in this manner because it considers only patch edges. This scale effect should be carefully considered when attempting to compare results from different studies.

FRAGSTATS computes a suite of metrics from the cell adjacency matrix that isolate the dispersion aspect of aggregation. FRAGSTATS computes the *percentage of like adjacencies* (PLADJ), which is computed as the sum of the diagonal elements (i.e., like adjacencies) of the adjacency matrix divided by the total number of adjacencies. A landscape containing greater aggregation of patch types (e.g., larger patches with compact shapes) will contain a higher proportion of like adjacencies than a landscape containing disaggregated patch types (e.g., smaller patches and more complex shapes). In contrast to the contagion index, this metric measures only patch type dispersion, not interspersion, and is unaffected by the method used to summarize adjacencies. At the class level, this metric is computed as the percentage of like adjacencies of the focal class. A highly contagious (aggregated) patch type will contain a higher percentage of like adjacencies. Conversely, a highly fragmented (disaggregated) patch type will contain proportionately fewer like adjacencies. As such, this index provides an effective measure of class-specific aggregation that isolates the dispersion (as opposed to interspersion) component of aggregation. However, this index requires careful interpretation because it varies in relation to the proportion of the landscape comprised of the focal class (P_i). It has been shown that PLADJ for class i will equal P_i for a completely random map (Gardner and O'Neill 1991). If the focal class is more dispersed than is expected of a random distribution (i.e., overdispersed), then PLADJ $< P_i$. If the focal class is more contagiously distributed, then PLADJ $> P_i$. Thus, although PLADJ provides an absolute measure of aggregation of the focal class, it is difficult to interpret as a measure of contagion without adjusting for P_i.

FRAGSTATS computes two indices based on PLADJ that adjust for P_i in different ways. The *aggregation index* (AI) is computed as a percentage based on the ratio of the observed number of like adjacencies ($e_{i,i}$), based on the single-count method, to the maximum possible number of like adjacencies (max_$e_{i,i}$) given P_i (He et al. 2000). Note, the single-count method of tallying adjacencies is employed to be consistent with the published algorithm. The maximum number of like adjacencies is achieved when the class is clumped into a single compact patch, which does not have to be a square. The trick here is in determining the maximum value of $e_{i,i}$ for any P_i,. He et al. (2000) provide the formula for computing max_$_{ei,i}$. The index ranges from 0 when there is no like adjacencies (i.e., when the class is maximally dissagregated) to 1 when $e_{i,i}$ reaches the maximum (i.e., when the class is maximally aggregated). However, AI is partially confounded with P_i because the minimum value of the index varies with P_i when $P_i > 0.5$; specifically, the minimum value > 0 when $P_i > 0.5$ and asymptotically approaches 1 as $P_i \rightarrow 1$. Thus, AI does not account for the expected value under a spatially random distribution when $P_i > 0.5$; e.g., AI could equal 0.8 and yet the distribution could be more disaggregated than expected under a random distribution if $P_i > 0.8$. Thus, caution must be exercised in interpreting this metric. The *clumpiness index* (CLUMPY) is a class-level only metric computed such that it ranges from -1 when the patch type is maximally disaggregated to 1 when the patch type is maximally clumped. It returns a value of zero for a random distribution, regardless of P_i. Values less than zero indicate greater dispersion (or disaggregation) than expected under a spatially random distribution, and values greater than zero indicate greater contagion. Hence, this index provides a measure of class-specific aggregation that effectively isolates the configuration component from the area component and, as such, provides an effective index of fragmentation of the focal class that is not confounded by changes in class area.

FRAGSTATS computes a few metrics based on the number of unlike cell adjacencies (i.e., edges or patch perimeters). As the proportion of like cell adjacencies increases, the number of unlike cell adjacencies decreases. Unlike cell adjacencies represent the edges between patch types. Thus, there is an inverse relationship between the proportion of like cell adjacencies (the basis for PLADJ, AI and CLUMPY) and the length of edge. The *Landscape shape index* (LSI) index measures the perimeter-to-area ratio for the landscape as a whole. This index is identical to the habitat diversity index proposed by Patton (1975), except that we apply the index at the class level as well. LSI is identical to the shape index at the patch level (SHAPE), except that it treats the entire landscape as if it were one patch and any patch edges (or class edges) as though they belong to the perimeter. Like the shape index, it can be interpreted as a measure of the overall geometric complexity of the landscape or of a focal class; however, it can also be interpreted as a measure of landscape disaggregation – the greater the value of LSI, the more dispersed are the patch types. The landscape boundary must be included as edge in the calculation in order to use a square standard for comparison. Unfortunately, this may not be meaningful in cases where the landscape boundary does not represent true edge and/or the actual shape of the landscape is of no particular interest. In this case, the total amount of true edge, or some other index based on edge, would probably be more meaningful. If the landscape boundary represents true edge or the shape of the landscape is particularly important, then LSI can be a useful index, especially when comparing among landscapes of varying sizes. At the class level, the landscape shape index suffers from confounding with the extent of the class, similar to PLADJ and AI, but the confounding is nonlinear making interpretation even more difficult. Part of the difficulty lies in the fact that the minimum and maximum length of edge varies with the proportion of the landscape comprised of the focal patch, P_i. The *normalized Landscape shape index* (nLSI) isolates the aggregation effect from the landscape composition effect by attempting to scale the index between the theoretical minimum and maximum values for any given level of P_i, but it can be biased when P_i is quite large (e.g., $P_i >> .5$) and when the landscape shape is not rectangular. Nevertheless, nLSI, like CLUMPY, provides a more useful index of dispersion that isolates the configuration component from the composition component. FRAGSTATS also computes the *patch cohesion index* (COHESION) proposed by Schumaker (1996) to quantify the connectivity of habitat as perceived by organisms dispersing in binary landscapes. COHESION is computed from the information contained in patch area and perimeter; briefly, it is proportional to the area-weighted mean perimeter-area ratio divided by the area-weighted mean patch shape index (i.e., standardized perimeter-area ratio). COHESION is similar to the perimeter-to-area ratio metric (PARA, see Shape metrics) and thus is also confounded with P_i, like PLADJ, AI, and LSI, but it is invariant to changes in the cell size and is bounded 0-1, which makes it easier to interpret and robust to changes in the grain. It is well known that, on random binary maps, patches gradually coalesce as the proportion of habitat cells increases, forming a large, highly connected patch (termed a percolating cluster) that spans that lattice at a critical proportion (pc) that varies with the neighbor rule used to delineate patches (Staufer 1985, Gardner et al. 1987). Patch cohesion has the interesting property of increasing monotonically until an asymptote is reached near the critical proportion.

FRAGSTATS computes a suite of metrics that focus on the subdivision aspect of aggregation. The simplest measure of subdivision is the *number of patches* (NP) or *patch density* (PD). However, these simple measures of subdivision and other measures of aggregation have been criticized for their insensitivity and inconsistent behavior across a wide range of subdivision patterns. Jaeger (2000) discussed the limitations of these metrics for evaluating habitat fragmentation and concluded that most of these metrics do not behave in a consistent and logical manner across all phases of the fragmentation process. He introduced a suite of metrics derived from the cumulative distribution of patch sizes that provide alternative and more explicit measures of subdivision. 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 measure the graininess of the landscape; i.e., the tendency of the landscape to exhibit a fine- versus coarse-grain texture. FRAGSTATS computes three of the subdivision metrics proposed by Jaeger (2000). All of these metrics are based on the notion that two animals, placed randomly in different areas somewhere in a region, will have a certain likelihood of being in the same undissected area (i.e., the same patch), which is a function of the degree of subdivision of the landscape. The *landscape division index* (DIVISION) is based on the degree of coherence (C), which is defined as the probability that two animals placed in different areas somewhere in the region of investigation might find each other. Degree of coherence is based on the cumulative patch area distribution and is represented graphically as the area above the cumulative area distribution curve. Degree of coherence represents the probability that two animals, which have been able to move throughout the whole region before the landscape was subdivided, will be found in the same patch after the subdivision is in place. The degree of landscape division is simply the complement of coherence and is defined as the probability that two randomly chosen places in the landscape are not situated in the same undissected patch. Graphically, the degree of landscape division is equal to the area below the cumulative area distribution curve.

The *splitting index* (SPLIT) is defined as the number of patches one gets when dividing the total landscape into patches of equal size in such a way that this new configuration leads to the same degree of landscape division as obtained for the observed cumulative area distribution. The splitting index can be interpreted to be the "effective mesh number" of a patch mosaic with a constant patch size dividing the landscape into S patches, where S is the splitting index. The *effective mesh size* (MESH) simply denotes the size of the patches when the landscape is divided into S areas (each of the same size) with the same degree of landscape division as obtained for the observed cumulative area distribution. Thus, all three subdivision metrics are easily computed from the cumulative patch area distribution. These measures have the particular advantage over other conventional measures of subdivision (e.g., mean patch size, patch density) in that they are insensitive to the omission or addition of very small patches. In practice, this makes the results more reproducible as investigators do not always use the same lower limit of patch size. Jaeger (2000) argues that the most important and advantageous feature of these new measures is that effective mesh size is 'area-proportionately additive'; that is, it characterizes the subdivision of a landscape independently of its size. In fact, these three measures are closely related to the area-weighted mean patch size (AREA_AM) discussed previously, and under certain circumstances are perfectly redundant. The distinctions are discussed below for each metric.

FRAGSTATS computes several metrics that focus on the isolation aspect of aggregation. Unfortunately, because of the many factors that influence the functional isolation of a patch, it is a difficult thing to capture in a single measure. In the context of habitat fragmentation, for example, isolation can be measured as the time since the habitat was physically subdivided, but this is fraught with practical difficulties, because rarely do we have accurate historical data from which to determine when each patch was isolated. Moreover, given that fragmentation is an ongoing process, it can be difficult to objectively determine at what point the habitat becomes subdivided, since this is largely a function of scale. Isolation can be measured in the spatial dimension in several ways, depending on how one views the concept of isolation. The simplest measures discussed below are based on Euclidean distance between nearest neighbors (McGarigal and Marks 1995) or the cumulative area of neighboring habitat patches weighted by nearest neighbor distance within some ecological neighborhood (Gustafson and Parker 1992). These measures adopt an island biogeographic perspective, as they treat the landscape as a binary mosaic consisting of habitat patches and uniform matrix. Thus, the context of a patch is defined by the proximity and area of neighboring habitat patches; the role of the matrix is ignored. However, these measures can be modified to take into account other habitat types in the so-called matrix and their affects on the insularity of the focal habitat. For example, simple Euclidean distance can be modified to account for functional differences among organisms. The functional distance between patches clearly depends on how each organism scales and interacts with landscape patterns (With 1999); in other words, the same gap between patches may not be perceived as a relevant disconnection for some organisms, but may be an impassable barrier for others.

FRAGSTATS computes three isolation metrics that adopt an island biogeographic perspective on patch isolation. *Euclidean nearest neighbor distance* (ENN) is perhaps the simplest measure of patch isolation. Here, nearest neighbor distance is defined using simple Euclidean geometry as the shortest straight-line distance between the focal patch and its nearest neighbor of the same class, based on the distance between the cell centers of the two closest cells from the respective patches. At the class and landscape levels, FRAGSTATS computes the mean in ENN (ENN_MN). At the class level, ENN_MN can only be computed if there are at least two patches of the corresponding type. At the landscape level, ENN_MN considers only patches that have neighbors. Thus, there could be 10 patches in the landscape, but eight of them might belong to separate patch types and therefore have no neighbor within the landscape. In this case, ENN_MN would be based on the distance between the two patches of the same type. These two patches could be close together or far apart. In either case, the mean nearest-neighbor distance for this landscape may not characterize the entire landscape very well. For this reason, these metrics should be interpreted carefully when landscapes contain rare patch types. In addition to these first-order statistics, the variability in ENN provides a measure patch dispersion. Specifically, a small standard deviation (SD)in ENN (ENN_SD) relative to the mean implies a fairly uniform or regular distribution of patches across landscapes, whereas a large SD relative to the mean implies a more irregular or uneven distribution of patches. The distribution of patches may reflect underlying natural processes or human-caused disturbance patterns. In absolute terms, the magnitude of ENN_SD is a function of the mean nearest-neighbor distance and variation in nearest-neighbor distance among patches. Thus, while SD does convey information about nearest neighbor variability, it is a difficult parameter to interpret without doing so in conjunction with the mean nearest-neighbor distance. For example, two landscapes may have the same ENN_SD, e.g., 100 m; yet one landscape may have a mean nearest-neighbor distance of 100 m, while the other may have a mean nearest-neighbor distance of 1,000 m. In this case, the interpretations of landscape pattern would be very different, even though the absolute variation is the same. Specifically, the former landscape has a more irregular but concentrated pattern of patches, while the latter has a more regular but dispersed pattern of patches. For these reasons, coefficient of variation (CV) often is preferable to SD for comparing variability among landscapes. Coefficient of variation measures relative variability about the mean (i.e., variability as a percentage of the mean), not absolute variability, and is akin to the familiar indices of dispersion in point patterns based on the variance to mean ratio in nearest neighbor distance (e.g., Clark and Evans 1954). Thus, it is not necessary to know the mean nearest-neighbor distance to interpret this metric. Even so, ENN_CV can be misleading with regards to landscape structure without also knowing the number of patches or patch density and other structural characteristics. For example, two landscapes may have the same ENN_CV, e.g., 100%; yet one landscape may have 100 patches with a mean nearest-neighbor distance of 100 m, while the other may have 10 patches with a mean nearest-neighbor distance of 1,000 m. In this case, the interpretations of overall landscape pattern could be very different, even though ENN_CV is the same; although the identical CV's indicate that both landscapes have the same regularity or uniformity in patch distribution. Finally, both SD and CV assume a normal distribution about the mean. In a real landscape, nearest-neighbor distribution may be highly irregular. In this case, it may be more informative to inspect the actual distribution itself (e.g., plot a histogram of the nearest neighbor distances for the corresponding patches), rather than relying on summary statistics such as SD and CV that make assumptions about the distribution and therefore can be misleading.

FRAGSTATS also computes the *connectance index* (CONNECT) as the proportion of functional joinings among all patches, where each pair of patches is either connected or not based on some criterion. FRAGSTATS computes connectance using a threshold distance specified by the user and reports it as a percentage of the maximum possible connectance given the number of patches. The threshold distance in FRAGSTATS is based on Euclidean distance, but it could be based on some other measure of functional distance, such as the least cost path distance.

Even though nearest-neighbor distance is often used to evaluate patch isolation, it is important to recognize that the single nearest patch may not fully represent the ecological neighborhood of the focal patch. For example, a neighboring patch 100 m away that is 1 ha is size may not be as important to the effective isolation of the focal patch as a neighboring patch 200 m away, but 1000 ha in size. To overcome this limitation, the *proximity index* (PROX) was developed by Gustafson and Parker (1992)[see also Gustafson and Parker 1994, Gustafson et al. 1994, Whitcomb et al. 1981]. This index considers the size and proximity of all patches whose edges are within a specified search radius of the focal patch. The index is computed as the sum, over all patches of the corresponding patch type whose edges are within the search radius of the focal patch, of each patch size divided by the square of its distance from the focal patch. Note that FRAGSTATS uses the distance between the focal patch and each of the other patches within the search radius, similar to the isolation index of Whitcomb et al. (1981), rather than the nearest-neighbor distance of each patch within the search radius (which could be to a patch other than the focal patch), as in Gustafson and Parker (1992).

The proximity index quantifies the spatial context of a (habitat) patch in relation to its neighbors of the same class; specifically, the index distinguishes sparse distributions of small habitat patches from configurations where the habitat forms a complex cluster of larger patches. All other things being equal, a patch located in a neighborhood (defined by the search radius) containing more of the corresponding patch type than another patch will have a larger index value. Similarly, all other things being equal, a patch located in a neighborhood in which the corresponding patch type is distributed in larger, more contiguous, and/or closer patches than another patch will have a larger index value. Thus, the proximity index measures both the degree of patch isolation and the degree of fragmentation of the corresponding patch type within the specified neighborhood of the focal patch.

FRAGSTATS computes a single isolation metric that adopts a landscape mosaic perspective on patch isolation. The *similarity index* (SIMI) is a modification of the proximity index, the difference being that similarity considers the size and proximity of all patches, regardless of class, whose edges are within a specified search radius of the focal patch. SIMI quantifies the spatial context of a (habitat) patch in relation to its neighbors of the same or similar class; specifically, the index distinguishes sparse distributions of small and insular habitat patches from configurations where the habitat forms a complex cluster of larger, hospitable (i.e., similar) patches. All other things being equal, a patch located in a neighborhood (defined by the search radius) deemed more similar (i.e., containing greater area in patches with high similarity) than another patch will have a larger index value. Similarly, all other things being equal, a patch located in a neighborhood in which the similar patches are distributed in larger, more contiguous, and/or closer patches than another patch will have a larger index value. Essentially, the similarity index performs much the same way as the proximity index, but instead of focusing on only a single patch type (i.e., island biogeographic perspective), it considers all patch types in the mosaic (i.e., landscape mosaic perspective). Thus, the similarity index is a more comprehensive measure of patch isolation than the proximity index for organisms and processes that perceive and respond to patch types differentially.

Limitations.–All measures based on the adjacency matrix (i.e., the number of adjacencies between each pair of patch types) that include like-adjacencies (i.e., PLADJ, AI, CLUMPY, and CONTAG) are strongly affected by the grain size or resolution of the image. Given a particular patch mosaic, a smaller grain size will result in a proportional increase in like adjacencies. Given this scale dependency, these metrics are best used if the scale is held constant. Note, IJI, LSI, nLSI, and COHESION are not affected by resolution directly because only patch edges are considered. In addition, there are alternative ways to consider cell adjacencies. Adjacencies may include only the 4 cells sharing a side with the focal cell, or they may include the diagonal neighbors as well. FRAGSTATS uses the *4-neighbor* approach for the purpose of calculating these metrics. Further, there are at least two basic approaches for counting cell adjacencies, referred to as the single count and double count methods. As noted above, FRAGSTATS adopts the *double count* method in which pixel order is preserved. In this method, all non-background cells inside the landscape (i.e., positively-valued cells) are visited and the four sides of each cell are tallied in the adjacency matrix. As a result, all cell sides involving non-background classes inside the landscape are tallied twice (hence the term double count), but all cell sides involving background or landscape border (i.e., negatively-valued cells) are only counted once, as those cells are themselves not visited.

There are significant limitations associated with the use of isolation metrics that must be understood before they are used. The most important limitation of these particular metrics is that nearest-neighbor distances 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 processes under consideration and the landscape is an "open" system relative to that organism or process, then nearest-neighbor results can be misleading. For example, consider a small subpopulation of a bird species occupying a patch near the boundary of a somewhat arbitrarily defined (from a bird's perspective) landscape. The nearest neighbor within the landscape boundary might be quite far away, yet in reality the closest patch might be very close, but just outside the designated landscape boundary. The magnitude of this problem is a function of scale. Increasing the size of the landscape relative to the scale at which the organism under investigation perceives and responds to the environment will decrease the severity of this problem.

Similarly, the proximity and similarity indices involve a search window around the focal patch. Thus, these metrics may be biased low for patches located within the search radius distance from the landscape boundary because a portion of the search area will be outside the area under consideration. The magnitude is of this problem is also a function of scale. Increasing the size of the landscape relative to the average patch size and/or decreasing the search radius will decrease the severity of this problem at the class and landscape levels. However, at the patch level, regardless of scale, individual patches located within the search radius of the boundary will have biased indices. In addition, these indices evaluate the landscape context of patches at a specific scale of analysis defined by the size of the search radius. Therefore, these indices are only meaningful if the specified search radius has some ecological relevance to the phenomenon under consideration. Otherwise, the results will be arbitrary and therefore meaningless.

Lastly, the similarity index is a functional metric in that it requires additional parameterization, in this case, similarity coefficients that are unique to the ecological phenomenon under consideration. Consequently, as with any functional metric, its meaning depends entirely on the meaningfulness of the similarity coefficients applied. If these are arbitrary assignments or based on weak observational data, results will be arbitrary and therefore meaningless.

Code	Metric (acronym)
Patch Metrics	
P1	Euclidean Nearest Neighbor Distance (ENN)
P2	Proximity Index (PROX)
P3	Similarity Index (SIMI)
Class Metrics	
C1	Interspersion & Juxtaposition Index (IJI)
C2	Percentage of Like Adjacencies (PLADJ)
C3	Aggregation Index (AI)
C4	Clumpiness Index (CLUMPY)
C5	Landscape Shape Index (LSI)

C6	Normalized Landscape Shape Index (nLSI)
C7	Patch Cohesion Index (COHESION)
C8	Number of Patches (NP)
C9	Patch Density (PD)
C10	Landscape Division Index (DIVISION)
C11	Splitting Index (SPLIT)
C12	Effective Mesh Size (MESH)
C13-18	Euclidean Nearest Neighbor Distance Distribution (ENN_MN, _AM, _MD, _RA, _SD, _CV)
C19-24	Proximity Index Distribution (PROX_MN, _AM, _MD, _RA, _SD, _CV)
C25-30	Similarity Index Distribution (SIMI_MN, _AM, _MD, _RA, _SD, _CV)
C31	Connectance (CONNECT)
Landscape Metrics	
L1	Contagion (CONTAG)
L2	Interspersion & Juxtaposition Index (IJI)
L3	Percentage of Like Adjacencies (PLADJ)
L4	Aggregation Index (AI)
L5	Landscape Shape Index (LSI)
L6	Patch Cohesion Index (COHESION)
L7	Number of Patches (NP)
L8	Patch Density (PD)
L9	Landscape Division Index (DIVISION)
L10	Splitting Index (SPLIT)
L11	Effective Mesh Size (MESH)
L12-17	Euclidean Nearest Neighbor Distance Distribution (ENN_MN, _AM, _MD, _RA, _SD, _CV)
L18-23	Proximity Index Distribution (PROX_MN, _AM, _MD, _RA, _SD, _CV)
L24-29	Similarity Index Distribution (SIMI_MN, _AM, _MD, _RA, _SD, _CV)
L30	Connectance (CONNECT)

(P1) Euclidean Nearest-Neighbor Distance	
$ENN = h_{ij}$	h_{ij} = distance (m) from patch ij to nearest neighboring patch of the same type (class), based on patch edge-to-edge distance, computed from cell center to cell center.
Description	ENN equals the distance (m) to the nearest neighboring patch of the same type, based on shortest edge-to-edge distance. Note that the edge-to-edge distances are from cell center to cell center.
Units	Meters
Range	ENN > 0, without limit. ENN approaches 0 as the distance to the nearest neighbor decreases. The minimum ENN is constrained by the cell size, and is equal to twice the cell size when the 8-neighbor patch rule is used or the distance between diagonal neighbors when the 4-neighbor rule is used. The upper limit is constrained by the extent of the landscape. ENN is undefined and reported as "N/A" in the “basename”.patch file if the patch has no neighbors (i.e., no other patches of the same class).
Comments	*Euclidean nearest-neighbor distance* is perhaps the simplest measure of patch context and has been used extensively to quantify patch isolation. Here, nearest neighbor distance is defined using simple Euclidean geometry as the shortest straight-line distance between the focal patch and its nearest neighbor of the same class.

(P2) Proximity Index	
$PROX = \sum_{s=1}^{n} \frac{a_{ijs}}{h_{ijs}^2}$	a_{ijs} = area (m^2) of patch ijs within specified neighborhood (m) of patch ij. h_{ijs} = distance (m) between patch ijs and patch ijs, based on patch edge-to-edge distance, computed from cell center to cell center.
Description	PROX equals the sum of patch area (m^2) divided by the nearest edge-to-edge distance squared (m^2) between the patch and the focal patch of all patches of the corresponding patch type whose edges are within a specified distance (m) of the focal patch. Note, when the search buffer extends beyond the landscape boundary, only patches contained within the landscape are considered in the computations. In addition, note that the edge-to-edge distances are from cell center to cell center.
Units	None

Range	PROX ≥ 0. PROX = 0 if a patch has no neighbors of the same patch type within the specified search radius. PROX increases as the neighborhood (defined by the specified search radius) is increasingly occupied by patches of the same type and as those patches become closer and more contiguous (or less fragmented) in distribution. The upper limit of PROX is affected by the search radius and the minimum distance between patches.
Comments	*Proximity index* was developed by Gustafson and Parker (1992) and considers the size and proximity of all patches whose edges are within a specified search radius of the focal patch. Note that FRAGSTATS uses the distance between the focal patch and each of the other patches within the search radius, similar to the isolation index of Whitcomb et al. (1981), rather than the nearest-neighbor distance of each patch within the search radius (which could be to a patch other than the focal patch), as in Gustafson and Parker (1992). The index is dimensionless (i.e., has no units) and therefore the absolute value of the index has little interpretive value; instead it is used as a comparative index.

(P3) Similarity Index	
$$SIMI = \sum_{s=1}^{n} \frac{a_{ijs} \cdot d_{ik}}{h_{ijs}^2}$$	a_{ijs} = area (m^2) of patch ijs within specified neighborhood (m) of patch ij. d_{ik} = similarity between patch types i and k. h_{ijs} = distance (m) between patch ijs and patch ijs, based on patch edge-to-edge distance, computed from cell center to cell center.
Description	SIMI equals the sum, over all neighboring patches with edges within a specified distance (m) of the focal patch, of neighboring patch area (m^2) times a similarity coefficient between the focal patch type and the class of the neighboring patch (0-1), divided by the nearest edge-to-edge distance squared (m^2) between the focal patch and the neighboring patch. Note, when the search buffer extends beyond the landscape boundary, only patches contained within the landscape are considered in the computations. In addition, note that the edge-to-edge distances are from cell center to cell center.
Units	None

Range	SIMI ≥ 0 SIMI = 0 if all the patches within the specified neighborhood have a zero similarity coefficient. SIMI increases as the neighborhood (defined by the specified search radius) is increasingly occupied by patches with greater similarity coefficients and as those similar patches become closer and more contiguous and less fragmented in distribution. The upper limit of SIMI is affected by the search radius and minimum distance between patches.
Comments	*Similarity index* is a modification of the proximity index (see Proximity Index description), the difference being that similarity considers the size and proximity of all patches, regardless of class, whose edges are within a specified search radius of the focal patch. Like the proximity index, this index is dimensionless (i.e., has no units) and therefore the absolute value of the index has little interpretive value; instead it is used as a comparative index.

(C1) Interspersion and Juxtaposition Index

$$IJI = \frac{-\sum_{k=1}^{m}\left[\left(\frac{e_{ik}}{\sum_{k=1}^{m} e_{ik}}\right)\ln\left(\frac{e_{ik}}{\sum_{k=1}^{m} e_{ik}}\right)\right]}{\ln(m-1)}(100)$$

e_{ik} = total length (m) of edge in landscape between patch types (classes) i and k.

m = number of patch types (classes) present in the landscape, including the landscape border, if present.

Description	IJI equals minus the sum of the length (m) of each unique edge type involving the corresponding patch type divided by the total length (m) of edge (m) involving the same type, multiplied by the logarithm of the same quantity, summed over each unique edge type; divided by the logarithm of the number of patch types minus 1; multiplied by 100 (to convert to a percentage). In other words, the observed interspersion over the maximum possible interspersion for the given number of patch types. Note, IJI considers all patch types present on an image, including any present in the landscape border, if present. All background edge segments are ignored, as are landscape boundary segments if a border is not provided, because adjacency information for these edge segments is not available and the intermixing of the focal class with background is assumed to be irrelevant.
Units	Percent

Range	0 < IJI ≤ 100 IJI approaches 0 when the corresponding patch type is adjacent to only 1 other patch type and the number of patch types increases. IJI = 100 when the corresponding patch type is equally adjacent to all other patch types (i.e., maximally interspersed and juxtaposed to other patch types). IJI is undefined and reported as "N/A" in the "basename".class file if the number of patch types is less than 3.
Comments	*Interspersion and juxtaposition index* is based on *patch* adjacencies, not *cell* adjacencies like the contagion index. As such, it does not provide a measure of class aggregation like the contagion index, but rather isolates the interspersion or intermixing of patch types.

(C2) Percentage of Like Adjacencies	
$$PLADJ = \left(\frac{g_{ii}}{\sum_{k=1}^{m} g_{ik}} \right)(100)$$	g_{ii} = number of like adjacencies (joins) between pixels of patch type (class) i based on the *double-count* method. g_{ik} = number of adjacencies (joins) between pixels of patch types (classes) i and k based on the *double-count* method.
Description	PLADJ equals the number of like adjacencies involving the focal class, divided by the total number of cell adjacencies involving the focal class; multiplied by 100 (to convert to a percentage). In other words, the percentage of cell adjacencies involving the corresponding patch type that are like adjacencies. All background edge segments are included in the sum of all adjacencies involving the focal class, including landscape boundary segments if a border is not provided. Cell adjacencies are tallied using the *double-count* method in which pixel order is preserved, at least for all internal adjacencies (i.e., involving cells on the inside of the landscape). If a landscape border is present, adjacencies on the landscape boundary are counted only once, as are all adjacencies with background.
Units	Percent

Range	$0 \leq \text{PLADJ} \leq 100$ PLADJ equals 0 when the corresponding patch type is maximally disaggregated (i.e., every cell is a different patch) and there are no like adjacencies. This occurs when the class is subdivided into one cell patches. Note, this condition can only be achieved when the proportion of the landscape comprised of the focal class (P_i) is ≤ 0.5. When $P_i = 0.5$, this occurs only when the class is distributed as a perfect checkerboard. When $P_i > 0.5$, the checkerboard begins to fill in and there will exist like adjacencies. PLADJ increases as the corresponding patch type becomes increasingly aggregated such that the proportion of like adjacencies increases. PLADJ = 100 when the landscape consists of single patch and all adjacencies are between the same class, and the landscape contains a border comprised entirely of the same class. If the landscape consists of single patch but does not contain a border, PLADJ will be less than 100 due to the background edge segments in the tally of adjacencies involving the focal class. Finally, PLADJ is undefined and reported as "N/A" in the "basename".class file if the class consists of a single cell.
Comments	*Percentage of like adjacencies* is calculated from the adjacency matrix, which shows the frequency with which different pairs of patch types (including like adjacencies between the same patch type) appear side-by-side on the map. PLADJ measures the degree of aggregation of the focal patch type. Thus, it is a measure of class-specific contagion. Regardless of how much of the landscape is comprised of the focal class (P_i), this index will be minimum if the patch type is maximally dispersed (or disaggregated), and it will be maximum if the patch type is maximally contagious. However, this index does not account for the fact that the percentage of like adjacencies for a random distribution equals P_i. If the percentage of like adjacencies is less than P_i, then the patch type is more dispersed than expected of a random landscape. Conversely, if the percentage of like adjacencies is greater than P_i, then the patch type is contagiously distributed. Note, this metric measures only dispersion and not interspersion, and thus may be a useful index of fragmentation of the focal class when interpreted in conjunction with P_i.

(C3) Aggregation Index		
$$AI = \left[\frac{g_{ii}}{\max \to g_{ii}} \right] (100)$$	g_{ii} =	number of like adjacencies (joins) between pixels of patch type (class) i based on the *single-count* method.
	max-g_{ii} =	maximum number of like adjacencies (joins) between pixels of patch type (class) i (see below) based on the *single-count* method.

Description	AI equals the number of like adjacencies involving the corresponding class, divided by the maximum possible number of like adjacencies involving the corresponding class, which is achieved when the class is maximally clumped into a single, compact patch; multiplied by 100 (to convert to a percentage). If A_i is the area of class i (in terms of number of cells) and n is the side of a largest integer square smaller than A_i, and $m = A_i - n^2$, then the largest number of shared edges for class i, max-g_{ii} will take one of the three forms: max-g_{ii} = 2n(n-1) , when m = 0, or max-g_{ii} = 2n(n-1) + 2m -1, when m ≤ n, or max-g_{ii} = 2n(n-1) + 2m -2, when m > n. Note, because of the design of the metric, like adjacencies are tallied using the *single-count* method, and all landscape boundary edge segments are ignored, even if a border is provided.
Units	Percent
Range	0 ≤ AI ≤ 100 Given any P_i , AI equals 0 when the focal patch type is maximally disaggregated (i.e., when there are no like adjacencies); AI increases as the focal patch type is increasingly aggregated and equals 100 when the patch type is maximally aggregated into a single, compact patch. AI is undefined and reported as "N/A" in the "basename".class file if the class consists of a single cell.
Comments	*Aggregation index* is calculated from an adjacency matrix, which shows the frequency with which different pairs of patch types (including like adjacencies between the same patch type) appear side-by-side on the map. Aggregation index takes into account only the like adjacencies involving the focal class, not adjacencies with other patch types. In addition, in contrast to all of the other metrics based on adjacencies, the aggregation index is based on like adjacencies tallied using the *single-count* method, in which each cell side is counted only once. Consequently, the tallies given in the "basename".adj output file are not correct for this metric. Further, because of the design of the metric, landscape boundary edge segments are ignored, even if a border is provided FRAGSTATS handles this case by distinguishing between internal like adjacencies (i.e., like adjacencies involving cells *inside* the landscape) and external like adjacencies (i.e., like adjacencies between cells *inside* the landscape and those in the border). Only internal like adjacencies are used in the calculation of this metric; a landscape border has no affect on this metric. The aggregation index is scaled to account for the maximum possible number of like adjacencies given any P_i. The maximum aggregation is achieved when the patch type consists of a single, compact patch, which is not necessarily a square patch.

(C4) Clumpiness Index	
$$Given\ G_i = \left(\frac{g_{ii}}{\sum_{k=1}^{m} g_{ik}} \right)$$ $$CLUMPY = \begin{bmatrix} \frac{G_i - P_i}{1 - P_i} \ for\ G_i \geq P_i \\ g \\ \frac{G_i - P_i}{1 - P_i} \ for\ G_i < P_i;\ P_i \geq .5 \\ \frac{P_i - G_i}{-P_i} \ for\ G_i < P_i;\ P_i < .5 \end{bmatrix}$$	g_{ii} = number of like adjacencies (joins) between pixels of patch type (class) i based on the *double-count* method. g_{ik} = number of adjacencies (joins) between pixels of patch types (classes) i and k based on the *double-count* method. P_i = proportion of the landscape occupied by patch type (class) i.

Description	CLUMPY equals the proportional deviation of the proportion of like adjacencies involving the corresponding class from that expected under a spatially random distribution. If the proportion of like adjacencies (G_i) is greater than or equal to the proportion of the landscape comprised of the focal class (P_i), then CLUMPY equals G_i minus P_i, divided by 1 minus P_i. Likewise, if $G_i < P_i$, and $P_i \geq 0.5$, then CLUMPY equals G_i minus P_i, divided by 1 minus P_i. However, if $G_i < P_i$, and $P_i <$ 0.5, then CLUMPY equals P_i minus G_i, divided by negative P_i. Note, all background edge segments are included in the sum of all adjacencies involving the focal class, including landscape boundary segments if a border is not provided. Cell adjacencies are tallied using the *double-count* method in which pixel order is preserved, at least for all internal adjacencies (i.e., involving cells on the inside of the landscape). If a landscape border is present, adjacencies on the landscape boundary are counted only once, as are all adjacencies with background. Note, P_i is based on the total landscape area (A) including any internal background present.
Units	Percent
Range	$-1 \leq$ CLUMPY ≤ 1 Given any P_i , CLUMPY equals -1 when the focal patch type is maximally disaggregated; CLUMPY equals 0 when the focal patch type is distributed randomly, and approaches 1 when the patch type is maximally aggregated. Note, CLUMPY equals 1 only when the landscape consists of a single patch and includes a border comprised of the focal class.

Comments	*Clumpiness index* is calculated from the adjacency matrix, which shows the frequency with which different pairs of patch types (including like adjacencies between the same patch type) appear side-by-side on the map. Clumpiness is scaled to account for the fact that the proportion of like adjacencies (G_i) will equal P_i for a completely random distribution (see previous discussion). The formula is contingent upon G_i and P_i because the minimum value of G_i has two forms which depend on P_i. Specifically, when $P_i \leq 0.5$, $G_i = 0$ when the class is maximally disaggregated (i.e., subdivided into one cell patches) and approaches 1 when the class is maximally clumped. However, when $P_i \geq 0.5$, $G_i = 2P_i - 1$ when the class is maximally disaggregated and approaches 1 when the class is maximally clumped. Note, when $G_i > P_i$, the formula given above assumes a maximum value of $G_i = 1$ (i.e., maximum clumping). This is not strictly true. In fact, the maximum value of G_i asymptotically approaches 1 as P_i increases to 1. At very small P_i, the maximum value of G_i is somewhat less. However, the bias is only nontrivial when the focal class consists of only a few cells. As the number of cells increases, the bias rapidly decreases and becomes trivial. Hence, when $G_i > P_i$ CLUMPY is slightly biased low. That is, the computed degree of clumping is slightly less than the actual degree of clumping, but again, the difference is trivial under most conditions. This approach of assuming that a maximum value of $G_i = 1$ is necessary because it is impossible to calculate the true maximum value of G_i, taking into account potential like adjacencies of perimeter cell surfaces of the focal class when maximally clumped into a single compact patch. Recall that FRAGSTATS allows for the existence of a landscape border, which may consist of cells of the same class as the neighboring patches inside the landscape proper (a situation virtually guaranteed to occur in a moving window analysis). Unfortunately, there is no way to calculate the expected number of perimeter cell surfaces adjacent to the landscape boundary given any P_i–this depends on the exact configuration and positioning of the focal class when maximally clumped. Note, the maximum like adjacencies computed for the aggregation index does not include perimeter cell surfaces. Thus, calculating maximum G_i based on this approach will always underestimate the true value. The use of 1 as the maximum G_i guarantees a theoretical maximum (upper limit) value of 1 for CLUMPY.

(C5) Landscape Shape Index	
$$LSI = \frac{.25\sum_{k=1}^{m} e_{ik}^{*}}{\sqrt{A}}$$	e^{*}_{ik} = total length (m) of edge in landscape between patch types (classes) i and k; includes the entire landscape boundary and some or all background edge segments involving class i. A = total landscape area (m^2).

Description	LSI equals .25 (adjustment for raster format) times the sum of the entire landscape boundary (regardless of whether it represents 'true' edge or not, or how the user specifies how to handle boundary/background) and all edge segments (m) within the landscape boundary involving the corresponding patch type, including some or all of those bordering background (based on user specifications), divided by the square root of the total landscape area (m^2). Note, total landscape area (A) includes any internal background present.
Units	None
Range	LSI ≥ 1, without limit. LSI = 1 when the landscape consists of a single square patch of the corresponding type; LSI increases without limit as landscape shape becomes more irregular and/or as the length of edge within the landscape of the corresponding patch type increases.
Comments	*Landscape shape index* provides a standardized measure of total edge or edge density that adjusts for the size of the landscape. Because it is standardized, it has a direct interpretation, in contrast to total edge, for example, that is only meaningful relative to the size of the landscape.

(C6) normalized Landscape Shape Index	
$$nLSI = \frac{e_i - \min e_i}{\max e_i - \min e_i}$$	e_i = total length of edge (or perimeter) of class i in terms of number of cell surfaces; includes all landscape boundary and background edge segments involving class i. min e_i = minimum total length of edge (or perimeter) of class i in terms of number of cell surfaces (see below). max e_i = maximum total length of edge (or perimeter) of class i in terms of number of cell surfaces (see below).

Description	nLSI equals the total length of edge (or perimeter) involving the corresponding class, given in number of cell surfaces, minus the minimum length of class edge (or perimeter) possible for a maximally aggregated class, also given in number of cell surfaces, which is achieved when the class is maximally clumped into a single, compact patch, divided by the maximum minus the minimum length of class edge. If a_i is the area of class i (in terms of number of cells)[note, this is equivalent to the sum of patch areas across all patches of class i] and n is the side of the largest integer square smaller than a_i (denoted) and $m = a_i - n^2$, then the minimum edge or perimeter of class i, min-e_i, will take one of the three forms (Milne 1991, Bogaert et al. 2000): min-$e_i = 4n$, when $m = 0$, or min-$e_i = 4n + 2$, when $n^2 < a_i \leq n(1+n)$, or min-$e_i = 4n + 4$, when $a_i > n(1+n)$. If A is the landscape area, including all internal background (in terms of number of cells), B = number of cells on the boundary (perimeter) of the landscape, Z = total length of landscape boundary (perimeter) given in number of cell surfaces, and P_i = proportion of the landscape comprised of the corresponding class, then the maximum edge or perimeter of class i, max-e_i, will take one of the three forms: max-$e_i = 4a_i$, when $P_i \leq 0.5$, or max-$e_i = 3A - 2a_i$, when A is even; $0.5 < P_i \leq (0.5A + 0.5B)/A$, or max-$e_i = 3A - 2a_i + 3$, when A is odd; $0.5 < P_i \leq (0.5A + 0.5B)/A$, or max-$e_i = Z + 4(A - a_i)$, when $P_i > (0.5A + 0.5B)/A$ Note, the formula for max-e_i recognizes the fact that as P_i increases beyond 0.5, the maximum total length of edge is achieved when the cells of the focal class fill in first along the boundary of the landscape. Unfortunately, the formulas given above for $P_i > 0.5$ are only an approximation for this effect. An analytical solution is not possible given the infinite number of landscape shapes possible. In addition, the formula for min-e_i assumes that the maximally aggregated class is a single square or almost square patch. However, if the landscape shape is highly irregular, then as the proportional class area P_i approaches 1, the shape of the landscape will constrain the minimum class edge possible (i.e., the actual min-e_i << the theoretical min-e_i) and nLSI will biased high (i.e., the class will appear to be relatively less aggregated than it actually is). However, for square or rectangular landscapes, or classes with $P_i << 1$, there is either no bias or it is trivial.
Units	None

Range	$0 \le nLSI \le 1$ nLSI = 0 when the landscape consists of a single square or maximally compact (i.e., almost square) patch of the corresponding type; LSI increases as the patch type becomes increasingly disaggregated and is 1 when the patch type is maximally disaggregated (i.e., a checkerboard when $P_i \le 0.5$). Note, nLSI is undefined and reported as N/A in the output files whenever max-e_i = min-e_i, which exists when the class consists either of a single cell, comprises all but 1 cell, or comprises the entire landscape, because it is impossible to distinguish between clumped, random and dispersed distributions in these cases.
Comments	*Normalized Landscape shape index* is the normalized version of the landscape shape index (LSI) and, as such, provides a simple measure of class aggregation or clumpiness. The normalization essentially rescales LSI to the minimum and maximum values possible for any class area. When the patch type is relatively rare (say $P_i < 0.1$) or relative dominant (say $P_i > 0.5$), the range between the minimum and maximum total edge (or perimeter) is relatively small; whereas when the patch type is intermediate in abundance (say $P_i = 0.5$), the range is quite large. nLSI essentially measures the degree of aggregation given this variable range. Note, just as LSI and the Aggregation Index (AI) are closely related, the normalized versions of these metrics are related, in fact perfectly so. For this reason, the normalized version of AI is not computed since it is completely redundant with nLSI. In addition, given the considerations given above regarding the computational method that assumes a square or almost square shape for a maximally compact class and the bias this creates if the landscape is highly irregular and the percentage of the landscape comprised of the focal class is high, it is advisable to avoid using this metric under these conditions of bias. Also, for these reasons, this metric is not available in the Moving Window analysis mode when a circular window shape is selected.

(C7) Patch Cohesion Index	
$$\text{COHESION} = \left[1 - \frac{\sum_{j=1}^{n} p_{ij}^{*}}{\sum_{j=1}^{n} p_{ij}^{*}\sqrt{a_{ij}^{*}}}\right] \cdot \left[1 - \frac{1}{\sqrt{Z}}\right]^{-1} \cdot (100)$$	p_{ij}^{*} = perimeter of patch ij in terms of number of cell surfaces. a_{ij}^{*} = area of patch ij in terms of number of cells. Z = total number of cells in the landscape.
Description	COHESION equals 1 minus the sum of patch perimeter (in terms of number of cell surfaces) divided by the sum of patch perimeter times the square root of patch area (in terms of number of cells) for patches of the corresponding patch type, divided by 1 minus 1 over the square root of the total number of cells in the landscape, multiplied by 100 to convert to a percentage. Note, total landscape area (Z) excludes any internal background present.

Units	None
Range	0 < COHESION < 100 COHESION approaches 0 as the proportion of the landscape comprised of the focal class decreases and becomes increasingly subdivided and less physically connected. COHESION increases monotonically as the proportion of the landscape comprised of the focal class increases until an asymptote is reached near the percolation threshold (see background discussion). COHESION is given as 0 if the landscape consists of a single non-background cell.
Comments	*Patch cohesion index* measures the physical connectedness of the corresponding patch type. Below the percolation threshold, patch cohesion is sensitive to the aggregation of the focal class. Patch cohesion increases as the patch type becomes more clumped or aggregated in its distribution; hence, more physically connected. Above the percolation threshold, patch cohesion does not appear to be sensitive to patch configuration (Gustafson 1998).

(C8) Number of Patches	
$NP = n_i$	n_i = number of patches in the landscape of patch type (class) i.
Description	NP equals the number of patches of the corresponding patch type (class).
Units	None
Range	NP ≥ 1, without limit. NP = 1 when the landscape contains only 1 patch of the corresponding patch type; that is, when the class consists of a single patch.
Comments	*Number of patches* of a particular patch type is a simple measure of the extent of subdivision or fragmentation of the patch type. Although the number of patches in a class may be fundamentally important to a number of ecological processes, often it has limited interpretive value by itself because it conveys no information about area, distribution, or density of patches. Of course, if total landscape area and class area are held constant, then number of patches conveys the same information as patch density or mean patch size and may be a useful index to interpret. Number of patches is probably most valuable, however, as the basis for computing other, more interpretable, metrics. Note that the choice of the 4-neighbor or 8-neighbor rule for delineating patches will have an impact on this metric.

(C9) Patch Density

$PD = \frac{n_i}{A}(10{,}000)(100)$		n_i = number of patches in the landscape of patch type (class) i. A = total landscape area (m^2).
Description	PD equals the number of patches of the corresponding patch type divided by total landscape area (m^2), multiplied by 10,000 and 100 (to convert to 100 hectares). Note, total landscape area (A) includes any internal background present.	
Units	Number per 100 hectares	
Range	PD > 0, constrained by cell size. PD is ultimately constrained by the grain size of the raster image, because the maximum PD is attained when every cell is a separate patch. Therefore, ultimately cell size will determine the maximum number of patches per unit area. However, the maximum density of patches of a single class is attained when every other cell is of that focal class (i.e., in a checker board manner; because adjacent cells of the same class would be in the same patch).	
Comments	*Patch density* is a limited, but fundamental, aspect of landscape pattern. Patch density has the same basic utility as number of patches as an index, except that it expresses number of patches on a per unit area basis that facilitates comparisons among landscapes of varying size. Of course, if total landscape area is held constant, then patch density and number of patches convey the same information. Like number of patches, patch density often has limited interpretive value by itself because it conveys no information about the sizes and spatial distribution of patches. Note that the choice of the 4-neighbor or 8-neighbor rule for delineating patches will have an impact on this metric.	

(C10) Landscape Division Index		
$DIVISION = \left[1 - \sum_{j=1}^{n}\left(\frac{a_{ij}}{A}\right)^2\right]$		a_{ij} = area (m^2) of patch ij. A = total landscape area (m^2).
Description	DIVISION equals 1 minus the sum of patch area (m^2) divided by total landscape area (m^2), quantity squared, summed across all patches of the corresponding patch type. Note, total landscape area (A) includes any internal background present.	
Units	Proportion	

Range	0 ≤ DIVISION < 1 DIVISION = 0 when the landscape consists of single patch. DIVISION approaches 1 when the focal patch type consists of single, small patch one cell in area. As the proportion of the landscape comprised of the focal patch type decreases and as those patches decrease in size, DIVISION approaches 1.
Comments	*Division* is based on the cumulative patch area distribution and is interpreted as the probability that two randomly chosen pixels in the landscape are not situated in the same patch of the corresponding patch type. Note, the similarity with Simpson's diversity index, only here the sum is across the proportional area of each patch in the focal class, rather than the proportional area of each patch 'type' in the landscape. Note, DIVISION is redundant with effective mesh size (MESH) below, i.e., they are perfectly, but inversely, correlated, but both metrics are included because of differences in units and interpretation. DIVISION is interpreted as a probability, whereas MESH is given as an area.

(C11) Splitting Index	
$$\text{SPLIT} = \frac{A^2}{\sum_{j=1}^{n} a_{ij}^2}$$	a_{ij} = area (m^2) of patch ij. A = total landscape area (m^2).
Description	SPLIT equals the total landscape area (m^2) squared divided by the sum of patch area (m^2) squared, summed across all patches of the corresponding patch type. Note, total landscape area (A) includes any internal background present.
Units	None
Range	1 ≤ SPLIT ≤ number of cells in the landscape area squared SPLIT = 1 when the landscape consists of single patch. SPLIT increases as the focal patch type is increasingly reduced in area and subdivided into smaller patches. The upper limit of SPLIT is constrained by the ratio of landscape area to cell size and is achieved when the corresponding patch type consists of a single one pixel patch.
Comments	*Split* is based on the cumulative patch area distribution and is interpreted as the effective mesh number, or number of patches with a constant patch size when the corresponding patch type is subdivided into S patches, where S is the value of the splitting index.

(C12) Effective Mesh Size

$$MESH = \frac{\sum_{j=1}^{n} a_{ij}^2}{A}\left(\frac{1}{10{,}000}\right)$$	a_{ij} = area (m^2) of patch ij. A = total landscape area (m^2).

Description	MESH equals the sum of patch area squared, summed across all patches of the corresponding patch type, divided by the total landscape area (m^2), divided by 10,000 (to convert to hectares). Note, total landscape area (A) includes any internal background present.
Units	Hectares
Range	ratio of cell size to landscape area ≤ MESH ≤ total landscape area (A) The lower limit of MESH is constrained by the ratio of cell size to landscape area and is achieved when the corresponding patch type consists of a single one pixel patch. MESH is maximum when the landscape consists of a single patch.
Comments	*Mesh* is based on the cumulative patch area distribution and is interpreted as the size of the patches when the corresponding patch type is subdivided into S patches, where S is the value of the splitting index. Note, MESH is redundant with DIVISION above, i.e., they are perfectly, but inversely, correlated, but both metrics are included because of differences in units and interpretation. DIVISION is interpreted as a probability, whereas MESH is given as an area. In addition, note the similarity between MESH and area-weight mean patch size (AREA_AM). Conceptually, these two metrics are closely related, but computationally they are quite different at the class level. Specifically, AREA_AM gives the area-weight mean patch size of patches of the corresponding class, where the proportional area of each patch is based on total class area (i.e., the total area of patches of the corresponding patch type). MESH, on the other hand, also gives the area-weighted mean patch size of patches of the corresponding patch size, but the proportional area of each patch is based on the total landscape area, not the class area. In this way, MESH takes into account the patch size distribution of the corresponding class as well as the total landscape area comprised of that class. Thus, holding the patch size distribution (of the corresponding class) constant, as the landscape extent increases (and the percent of the landscape comprised of this class decreases), MESH for the corresponding class will decrease. Hence, AREA_AM provides an absolute measure of patch structure, whereas MESH provides a relative measure of patch structure.

(C31) Connectance Index

$$\text{CONNECT} = \left[\frac{\sum_{j \neq k}^{n} c_{ijk}}{\frac{n_i (n_i - 1)}{2}} \right] (100)$$	c_{ijk} = joining between patch j and k (0 = unjoined, 1 = joined) of the corresponding patch type (i), based on a user specified threshold distance. n_i = number of patches in the landscape of the corresponding patch type (class).
Description	CONNECT equals the number of functional joinings between all patches of the corresponding patch type (sum of c_{ijk} where c_{ijk} = 0 if patch j and k are not within the specified distance of each other and c_{ijk} = 1 if patch j and k are within the specified distance), divided by the total number of possible joinings between all patches of the corresponding patch type, multiplied by 100 to convert to a percentage.
Units	Percent
Range	0 ≤ CONNECT ≤ 100 CONNECT = 0 when either the focal class consists of a single patch or none of the patches of the focal class are "connected" (i.e., within the user-specified threshold distance of another patch of the same type). CONNECT = 100 when every patch of the focal class is "connected."
Comments	*Connectance* is defined on the number of functional joinings between patches of the corresponding patch type, where each pair of patches is either connected or not based on a user-specified distance criterion. Connectance is reported as a percentage of the maximum possible connectance given the number of patches. Note, connectance can be based on either Euclidean distance or functional distance, as described elsewhere (see Isolation/Proximity Metrics).

(L1) Contagion Index

$$\text{CONTAG} = \left[1 + \frac{\sum_{i=1}^{m}\sum_{k=1}^{m}\left[P_i \cdot \frac{g_{ik}}{\sum_{k=1}^{m} g_{ik}} \right] \cdot \left[\ln \left(P_i \cdot \frac{g_{ik}}{\sum_{k=1}^{m} g_{ik}} \right) \right]}{2\ln(m)} \right] (100)$$

P_i = proportion of the landscape occupied by patch type (class) i.
g_{ik} = number of adjacencies (joins) between pixels of patch types (classes) i and k based on the *double-count* method.
m = number of patch types (classes) present in the landscape, including the landscape border if present.

Description	CONTAG equals minus the sum of the proportional abundance of each patch type multiplied by the proportion of adjacencies between cells of that patch type and another patch type, multiplied by the logarithm of the same quantity, summed over each unique adjacency type and each patch type; divided by 2 times the logarithm of the number of patch types; multiplied by 100 (to convert to a percentage). In other words, the observed contagion over the maximum possible contagion for the given number of patch types. Note, CONTAG considers all patch types present on an image, including any present in the landscape border, if present, and considers like adjacencies (i.e., cells of a patch type adjacent to cells of the same type). All background edge segments are ignored, as are landscape boundary segments if a border is not provided, because adjacency information for these edge segments is not available and the intermixing of the classes with background is assumed to be irrelevant. Cell adjacencies are tallied using the *double-count* method in which pixel order is preserved, at least for all internal adjacencies (i.e., involving cells on the inside of the landscape). If a landscape border is present, adjacencies on the landscape boundary are counted only once as are all adjacencies with background. Note, P_i is based on the total landscape area (A) excluding any internal background present.
Units	Percent
Range	$0 < CONTAG \leq 100$ CONTAG approaches 0 when the patch types are maximally disaggregated (i.e., every cell is a different patch type) and interspersed (equal proportions of all pairwise adjacencies). CONTAG = 100 when all patch types are maximally aggregated. CONTAG is undefined and reported as "N/A" in the "basename".land file if the number of patch types is less than 2, or all classes consist of one cell patches adjacent to only background.
Comments	*Contagion* is inversely related to edge density. When edge density is very low, for example, when a single class occupies a very large percentage of the landscape, contagion is high, and vice versa. In addition, note that contagion is affected by both the dispersion and interspersion of patch types. Low levels of patch type dispersion (i.e., high proportion of like adjacencies) and low levels of patch type interspersion (i.e., inequitable distribution of pairwise adjacencies results in high contagion, and vice versa.

(L2) Interspersion and Juxtaposition Index

$$IJI = \frac{-\sum_{i=1}^{m}\sum_{k=i+1}^{m}\left[\left(\frac{e_{ik}}{E}\right)\cdot\ln\left(\frac{e_{ik}}{E}\right)\right]}{\ln(0.5[m(m-1)])}(100)$$	e_{ik} = total length (m) of edge in landscape between patch types (classes) i and k. E = total length (m) of edge in landscape, excluding background. m = number of patch types (classes) present in the landscape, including the landscape border, if present.

Description	IJI equals minus the sum of the length (m) of each unique edge type divided by the total landscape edge (m), multiplied by the logarithm of the same quantity, summed over each unique edge type; divided by the logarithm of the number of patch types times the number of patch types minus 1 divided by 2; multiplied by 100 (to convert to a percentage). In other words, the observed interspersion over the maximum possible interspersion for the given number of patch types. Note, IJI considers all patch types present on an image, including any present in the landscape border, if present. All background edge segments are ignored, as are landscape boundary segments if a border is not provided, because adjacency information for these edge segments is not available and the intermixing of classes with background is assumed to be irrelevant.
Units	Percent
Range	$0 < IJI \leq 100$ IJI approaches 0 when the distribution of adjacencies among unique patch types becomes increasingly uneven. IJI = 100 when all patch types are equally adjacent to all other patch types (i.e., maximum interspersion and juxtaposition). IJI is undefined and reported as "N/A" in the "basename".land file if the number of patch types is less than 3.
Comments	*Interspersion and juxtaposition index* is based on patch adjacencies, not cell adjacencies like the contagion index. As such, it does not provide a measure of class aggregation like the contagion index, but rather isolates the interspersion or intermixing of patch types.

(L3) Percentage of Like Adjacencies	
$$PLADJ = \left(\frac{\sum_{i=1}^{m}(g_{ii})}{\sum_{i=1}^{m}\sum_{k=1}^{m}(g_{ik})}\right)(100)$$	g_{ii} = number of like adjacencies (joins) between pixels of patch type (class) i based on the *double-count* method . g_{ik} = number of adjacencies (joins) between pixels of patch types (classes) i and k based on the *double-count* method.

Description	PLADJ equals sum of the number of like adjacencies for each patch type, divided by the total number of cell adjacencies in the landscape; multiplied by 100 (to convert to a percentage). In other words, the proportion of cell adjacencies involving the same class. PLADJ considers all patch types present on an image, including any present in the landscape border, if present. All background edge segments are included in the denominator, including landscape boundary segments if a border is not provided. Cell adjacencies are tallied using the *double-count* method in which pixel order is preserved, at least for all internal adjacencies (i.e., involving cells on the inside of the landscape). If a landscape border is present, adjacencies on the landscape boundary are counted only once, as are all adjacencies with background.
Units	Percent
Range	$0 \leq \text{PLADJ} \leq 100$ PLADJ equals 0 when the patch types are maximally disaggregated (i.e., every cell is a different patch type) and there are no like adjacencies. PLADJ = 100 when all patch types are maximally aggregated (i.e., when the landscape consists of single patch and all adjacencies are between the same class), and the landscape contains a border comprised entirely of the same class. If the landscape consists of single patch but does not contain a border, PLADJ will be less than 100 due to the background edge segments along the boundary included in the tally of all adjacencies. PLADJ is undefined and reported as "N/A" in the "basename".land file if the landscape consists of a single non-background cell.
Comments	*Percentage of like adjacencies* is calculated from the adjacency matrix, which shows the frequency with which different pairs of patch types (including like adjacencies between the same patch type) appear side-by-side on the map. PLADJ measures the degree of aggregation of patch types. Thus, a landscape containing larger patches with simple shapes will contain a higher percentage of like adjacencies than a landscape with smaller patches and more complex shapes. In contrast to the contagion index at the landscape level, this metric measures only dispersion and not interspersion. Note, regardless of how much of the landscape is comprised of each class, this index will be minimum if all patch types are maximally dispersed (or disaggregated), and it will be maximum if all patch types are maximally contagious.

(L4) Aggregation Index

$$AI = \left[\sum_{i=1}^{m} \left(\frac{g_{ii}}{max \to g_{ii}} \right) P_i \right] (100)$$	g_{ii} = number of like adjacencies (joins) between pixels of patch type (class) i based on the *single-count* method. max-g_{ii} = maximum number of like adjacencies (joins) between pixels of patch type (class) i (see below) based on the *single-count* method. P_i = proportion of landscape comprised of patch type (class) i.
Description	AI equals the number of like adjacencies involving the corresponding class, divided by the maximum possible number of like adjacencies involving the corresponding class, which is achieved when the class is maximally clumped into a single, compact patch, multiplied the proportion of the landscape comprised of the corresponding class, summed over all classes and multiplied by 100 (to convert to a percentage). If A_i is the area of class i (in terms of number of cells) and n is the side of a largest integer square smaller than A_i, and m = A_i - n^2, then the largest number of shared edges for class i, max-g_{ii} will take one of the three forms: max-g_{ii} = 2n(n-1), when m = 0, max-g_{ii} = 2n(n-1) + 2m -1, when m ≤ n, or max-g_{ii} = 2n(n-1) + 2m -2, when m > n. Note, because of the design of the metric, like adjacencies are tallied using the *single-count* method, and all landscape boundary edge segments are ignored, even if a border is provided. Also, P_i is based on the total landscape area (A) excluding any background present.
Units	Percent
Range	0 ≤ AI ≤ 100 Given any P_i , AI equals 0 when the patch types are maximally disaggregated (i.e., when there are no like adjacencies); AI increases as the landscape is increasingly aggregated and equals 100 when the landscape consists of a single patch. AI is undefined and reported as "N/A" in the "basename".land file if each class consists of a single cell (and hence is undefined).
Comments	*Aggregation index* is calculated from an adjacency matrix at the class level (see class-level AI comments). At landscape level, the index is computed simply as an area-weighted mean class aggregation index, where each class is weighted by its proportional area in the landscape. The index is scaled to account for the maximum possible number of like adjacencies given any landscape composition.

(L5) Landscape Shape Index		
$$LSI = \frac{.25\ E^*}{\sqrt{A}}$$	E^* =	total length (m) of edge in landscape; includes the entire landscape boundary and some or all background edge segments.
	A =	total landscape area (m^2).

Description	LSI equals .25 (adjustment for raster format) times the sum of the entire landscape boundary (regardless of whether it represents 'true' edge or not, or how the user specifies how to handle boundary/background) and all edge segments (m) within the landscape boundary, including some or all of those bordering background (based on user specifications), divided by the square root of the total landscape area (m^2). Note, total landscape area (A) includes any internal background present.
Units	None
Range	LSI ≥ 1, without limit. LSI = 1 when the landscape consists of a single square patch; LSI increases without limit as landscape shape becomes more irregular and/or as the length of edge within the landscape increases.
Comments	*Landscape shape index* provides a standardized measure of total edge or edge density that adjusts for the size of the landscape. Because it is standardized, it has a direct interpretation, in contrast to total edge, for example, that is only meaningful relative to the size of the landscape.

(L6) Patch Cohesion Index		
$$COHESION = \left[1 - \frac{\sum_{i=1}^{m}\sum_{j=1}^{n} p_{ij}^*}{\sum_{i=1}^{m}\sum_{j=1}^{n} p_{ij}^*\sqrt{a_{ij}^*}}\right] \cdot \left[1 - \frac{1}{\sqrt{Z}}\right]^{-1} \cdot (100)$$	p_{ij}^* =	perimeter of patch ij in terms of number of cell surfaces.
	a_{ij}^* =	area of patch ij in terms of number of cells.
	Z =	total number of cells in the landscape.

Description	COHESION equals 1 minus the sum of patch perimeter (in terms of number of cells) divided by the sum of patch perimeter times the square root of patch area (in terms of number of cells) for all patches in the landscape, divided by 1 minus 1 over the square root of the total number of cells in the landscape, multiplied by 100 to convert to a percentage. Note, total landscape area (Z) excludes any internal background present.
Units	None
Range	The behavior of this metric at the landscape level has not yet been evaluated.

Comments	*Patch cohesion index* at the class level measures the physical connectedness of the corresponding patch type. However, at the landscape level, the behavior of this metric has not yet been evaluated.

(L7) Number of Patches	
$NP = N$	N = total number of patches in the landscape.
Description	NP equals the number of patches in the landscape. Note, NP does not include any internal background patches (i.e., within the landscape boundary) or any patches at all in the landscape border, if present.
Units	None
Range	NP ≥ 1, without limit. NP = 1 when the landscape contains only 1 patch.
Comments	*Number of patches* often has limited interpretive value by itself because it conveys no information about area, distribution, or density of patches. Of course, if total landscape area is held constant, then number of patches conveys the same information as patch density or mean patch size and may be a useful index to interpret. Number of patches is probably most valuable, however, as the basis for computing other, more interpretable, metrics. Note that the choice of the 4-neighbor or 8-neighbor rule for delineating patches will have an impact on this metric.

(L8) Patch Density	
$PD = \frac{N}{A}(10{,}000)(100)$	N = total number of patches in the landscape. A = total landscape area (m^2).
Description	PD equals the number of patches in the landscape, divided by total landscape area (m^2), multiplied by 10,000 and 100 (to convert to 100 hectares). Note, PD does not include background patches or patches in the landscape border, if present. However, total landscape area (A) includes any internal background present.
Units	Number per 100 hectares
Range	PD > 0, constrained by cell size. PD is ultimately constrained by the grain size of the raster image, because the maximum PD is attained when every cell is a separate patch.

Comments	*Patch density* is a limited, but fundamental, aspect of landscape pattern. Patch density has the same basic utility as number of patches as an index, except that it expresses number of patches on a per unit area basis that facilitates comparisons among landscapes of varying size. Of course, if total landscape area is held constant, then patch density and number of patches convey the same information. Like number of patches, patch density often has limited interpretive value by itself because it conveys no information about the sizes and spatial distribution of patches. Note that the choice of the 4-neighbor or 8-neighbor rule for delineating patches will have an impact on this metric.

(L9) Landscape Division Index	
$DIVISION = \left[1 - \sum_{i=1}^{m}\sum_{j=1}^{n}\left(\frac{a_{ij}}{A}\right)^2\right]$	a_{ij} = area (m^2) of patch ij. A = total landscape area (m^2).
Description	DIVISION equals 1 minus the sum of patch area (m^2) divided by total landscape area (m^2), quantity squared, summed across all patches in the landscape. Note, total landscape area (A) includes any internal background present.
Units	Proportion
Range	$0 \leq DIVISION < 1$ DIVISION = 0 when the landscape consists of single patch. DIVISION is achieves its maximum value when the landscape is maximally subdivided; that is, when every cell is a separate patch.
Comments	*Division* is based on the cumulative patch area distribution and is interpreted as the probability that two randomly chosen pixels in the landscape are not situated in the same patch. Note, the similarity with Simpson's diversity index, only here the sum is across the proportional area of each patch, rather than the proportional area of each patch type in the landscape. Note, DIVISION is redundant with effective mesh size (MESH) below, i.e., they are perfectly, but inversely, correlated, but both metrics are included because of differences in units and interpretation. DIVISION is interpreted as a probability, whereas MESH is given as an area. In addition, as described below (see MESH), DIVISION is perfectly redundant with area-weighted mean patch size (AREA_AM) when there is no background.

(L10) Splitting Index

$$\text{SPLIT} = \frac{A^2}{\sum_{i=1}^{m}\sum_{j=1}^{n} a_{ij}^2}$$	a_{ij} = area (m^2) of patch ij. A = total landscape area (m^2).
Description	SPLIT equals the total landscape area (m^2) squared divided by the sum of patch area (m^2) squared, summed across all patches in the landscape. Note, total landscape area (A) includes any internal background present.
Units	None
Range	1 ≤ SPLIT ≤ number of cells in the landscape squared SPLIT = 1 when the landscape consists of single patch. SPLIT increases as the landscape is increasingly subdivided into smaller patches and achieves its maximum value when the landscape is maximally subdivided; that is, when every cell is a separate patch.
Comments	*Split* is based on the cumulative patch area distribution and is interpreted as the effective mesh number, or number of patches with a constant patch size when the landscape is subdivided into S patches, where S is the value of the splitting index.

(L11) Effective Mesh Size	
$$\text{MESH} = \frac{\sum_{i=1}^{m}\sum_{j=1}^{n} a_{ij}^2}{A}$$	a_{ij} = area (m^2) of patch ij. A = total landscape area (m^2).
Description	MESH equals 1 divided by the total landscape area (m^2) multiplied by the sum of patch area (m^2) squared, summed across all patches in the landscape. Note, total landscape area (A) includes any internal background present.
Units	Hectares
Range	cell size ≤ MESH ≤ total landscape area (A) The lower limit of MESH is constrained by the cell size and is achieved when the landscape is maximally subdivided; that is, when every cell is a separate patch. MESH is maximum when the landscape consists of a single patch.

Comments	*Mesh* is based on the cumulative patch area distribution and is interpreted as the size of the patches when the landscape is subdivided into S patches, where S is the value of the splitting index. Note, MESH is redundant with DIVISION above, i.e., they are perfectly, but inversely, correlated, but both metrics are included because of differences in units and interpretation. DIVISION is interpreted as a probability, whereas MESH is given as an area. In addition, note the similarity between MESH and area-weight mean patch size (AREA_AM). Conceptually and computationally, these two metrics are almost identical at the landscape level, and under most circumstances will return identical values. Specifically, AREA_AM gives the area-weight mean patch size, where the proportional area of each patch is based on total landscape area *excluding* any background (i.e., background is excluded from the total landscape area). MESH also gives the area-weighted mean patch size, but the proportional area of each patch is based on the total landscape area *including* any background. Background is included in the so-called 'pedestal' of Jaeger (2000). Thus, if there is no internal background, these metrics will return identical values. If there is internal background, these metrics will return different values, and the magnitude of the difference will depend on the proportional extent of background. In the latter case, the choice of metrics depends on how you want to consider background.

(L30) Connectance Index

$$\text{CONNECT} = \left[\frac{\sum_{i=1}^{m} \sum_{j \neq k}^{n} c_{ijk}}{\sum_{i=1}^{m} \left(\frac{n_i \, (n_i - 1)}{2} \right)} \right] (100)$$

c_{ijk} = joining between patch j and k (0 = unjoined, 1 = joined) of the same patch type, based on a user-specified threshold distance.

n_i = number of patches in the landscape of each patch type (i).

Description	CONNECT equals the number of functional joinings between all patches of the same patch type (sum of c_{ijk} where c_{ijk} = 0 if patch j and k are not within the specified distance of each other and c_{ijk} = 1 if patch j and k are within the specified distance), divided by the total number of possible joinings between all patches of the same type, multiplied by 100 to convert to a percentage.
Units	Percent
Range	0 ≤ CONNECT ≤ 100 CONNECT = 0 when either the landscape consists of a single patch, or all classes consist of a single patch, or none of the patches in the landscape are "connected" (i.e., within the user-specified threshold distance of another patch of the same type). CONNECT = 100 when every patch in the landscape is "connected."

Comments	*Connectance* is defined on the number of functional joinings between patches of the same type, where each pair of patches is either connected or not based on a user-specified distance criterion. Connectance is reported as a percentage of the maximum possible connectance given the number of patches. Note, connectance can be based on either Euclidean distance or functional distance.

Diversity Metrics

Background.–Diversity measures have been used extensively in a variety of ecological applications. They originally gained popularity as measures of plant and animal species diversity. There has been a proliferation of diversity indices and we will make no attempt to review them here. FRAGSTATS computes 3 diversity indices. These diversity measures are influenced by 2 components--richness and evenness. Richness refers to the number of patch types present; evenness refers to the distribution of area among different types. Richness and evenness are generally referred to as the compositional and structural components of diversity, respectively. Some indices (e.g., Shannon's diversity index) are more sensitive to richness than evenness. Thus, rare patch types have a disproportionately large influence on the magnitude of the index. Other indices (e.g., Simpson's diversity index) are relatively less sensitive to richness and thus place more weight on the common patch types. These diversity indices have been applied by landscape ecologists to measure one aspect of landscape structure--landscape composition (e.g., Romme 1982, O'Neill et al. 1988, Turner 1990a).

FRAGSTATS Metrics.–FRAGSTATS computes several statistics that quantify diversity at the landscape level. These metrics quantify landscape composition at the landscape level; they are not affected by the spatial configuration of patches. The most popular diversity index is *Shannon's diversity index* (SHDI) based on information theory (Shannon and Weaver 1949). The value of this index represents the amount of "information" per individual (or patch, in this case). Information is a somewhat abstract mathematical concept that we will not attempt to define. The absolute magnitude of Shannon's diversity index is not particularly meaningful; therefore, it is used as a relative index for comparing different landscapes or the same landscape at different times. *Simpson's diversity index* (SIDI) is another popular diversity measure that is not based on information theory (Simpson 1949). Simpson's index is less sensitive to the presence of rare types and has an interpretation that is much more intuitive than Shannon's index. Specifically, the value of Simpson's index represents the probability that any two cells selected at random would be different patch types. Thus, the higher the value the greater the likelihood that any 2 randomly drawn cells would be different patch types. Because Simpson's index is a probability, it can be interpreted in both absolute and relative terms. FRAGSTATS also computes a *modified Simpson's diversity index* (MSIDI) based on Pielou's (1975) modification of Simpson's diversity index; this index was used by Romme (1982). The modification eliminates the intuitive interpretation of Simpson's index as a probability, but transforms the index into one that belongs to a general class of diversity indices to which Shannon's diversity index belongs (Pielou 1975). Thus, the modified Simpson's and Shannon's diversity indices are similar in many respects and have the same applicability.

Patch richness (PR) measures the number of patch types present; it is not affected by the relative abundance of each patch type or the spatial arrangement of patches. Therefore, two landscapes may have very different structure yet have the same richness. For example, one landscape may be comprised of 96% patch type A and 1% each of patch types B-E, whereas another landscape may be comprised of 20% each of patch types A-E. Although patch richness would be the same, the functioning of these landscapes and the structure of the animal and plant communities would likely be greatly different. Because richness does not account for the relative abundance of each patch type, rare patch types and common patch types contribute equally to richness. Nevertheless, patch richness is a key element of landscape structure because the variety of landscape elements present in a landscape can have an important influence on a variety of ecological processes. Because many organisms are associated with a single patch type, patch richness often correlates well with species richness.

Richness is partially a function of scale. Larger areas are generally richer because there is generally greater heterogeneity over larger areas than over comparable smaller areas. This contributes to the species-area relationship predicted by island biogeographic theory (MacArthur and Wilson 1967). Therefore, comparing richness among landscapes that vary in size can be problematic. *Patch richness density* (PRD) standardizes richness to a per area basis that facilitates comparison among landscapes, although it does not correct for this interaction with scale. FRAGSTATS also computes a relative richness index. *Relative patch richness* (RPR) is similar to patch richness, but it represents richness as a percentage of the maximum potential richness as specified by the user (Romme 1982). This form may have more interpretive value than absolute richness or richness density in some applications. Note that relative patch richness and patch richness are completely redundant and would not be used simultaneously in any subsequent statistical analysis.

Evenness measures the other aspect of landscape diversity--the distribution of area among patch types. There are numerous ways to quantify evenness and most diversity indices have a corresponding evenness index derived from them. In addition, evenness can be expressed as its compliment--dominance (i.e., evenness = 1 - dominance). Indeed, dominance has often been the chosen form in landscape ecological investigations (e.g., O'Neill et al. 1988, Turner et al. 1989, Turner 1990a), although we prefer evenness because larger values imply greater landscape diversity. FRAGSTATS computes three evenness indices (*Shannon's evenness index*, SHEI; *Simpson's evenness index*, SIEI; *modified Simpson's evenness index*, MSIEI), corresponding to the three diversity indices. Each evenness index isolates the evenness component of diversity by controlling for the contribution of richness to the diversity index. Evenness is expressed as the observed level of diversity divided by the maximum possible diversity for a given patch richness. Maximum diversity for any level of richness is achieved when there is an equal distribution of area among patch types. Therefore, the observed diversity divided by the maximum diversity (i.e., equal distribution) for a given number of patch types represents the proportional reduction in the diversity index attributed to lack of perfect evenness. As the evenness index approaches 1, the observed diversity approaches perfect evenness. Because evenness is represented as a proportion of maximum evenness, Shannon's evenness index does not suffer from the limitation of Shannon's diversity index with respect to interpretability.

Limitations.–The use of diversity measures in community ecology has been heavily criticized because diversity conveys no information on the actual species composition of a community. Species diversity is a community summary measure that does not take into account the uniqueness or potential ecological, social, or economical importance of individual species. A community may have high species diversity yet be comprised largely of common or undesirable species. Conversely, a community may have low species diversity yet be comprised of especially unique, rare, or highly desired species. Although these criticisms have not been discussed explicitly with regards to the landscape ecological application of diversity measures, these criticisms are equally valid when diversity measures are applied to patch types instead of species. In addition, diversity indices like Shannon’s index and Simpson’s index combine richness and evenness components into a single measure, even though it is usually more informative to evaluate richness and evenness independently.

Code	Metric (acronym)
Landscape Metrics	
L1	Patch Richness (PR)
L2	Patch Richness Density (PRD)
L3	Relative Patch Richness (RPR)
L4	Shannon's Diversity Index (SHDI)
L5	Simpson's Diversity Index (SIDI)
L6	Modified Simpson's Diversity Index (MSIDI)
L7	Shannon's Evenness Index (SHEI)
L8	Simpson's Evenness Index (SIEI)
L9	Modified Simpson's Evenness Index (MSIEI)

(L1) Patch Richness	
$PR = m$	m = number of patch types (classes) present in the landscape, excluding the landscape border if present.
Description	PR equals the number of different patch types present within the landscape boundary.
Units	None
Range	PR ≥ 1, without limit
Comments	*Patch richness* is perhaps the simplest measure of landscape composition, but note that it does not reflect the relative abundances of patch types. Note, this metric is redundant with both patch richness density and relative patch richness.

(L2) Patch Richness Density	
$PRD = \frac{m}{A}(10{,}000)(100)$	m = number of patch types (classes) present in the landscape, excluding the landscape border if present. A = total landscape area (m^2).
Description	PR equals the number of different patch types present within the landscape boundary divided by total landscape area (m^2), multiplied by 10,000 and 100 (to convert to 100 hectares). Note, total landscape area (A) includes any internal background present.

Units	Number per 100 hectares
Range	PRD > 0, without limit
Comments	*Patch richness density* standardizes richness to a per area basis that facilitates comparison among landscapes. Note, this metric is redundant with both patch richness and relative patch richness.

(L3) Relative Patch Richness	
$RPR = \frac{m}{m_{max}}(100)$	m = number of patch types (classes) present in the landscape, excluding the landscape border if present.
Description	RPR equals the number of different patch types present within the landscape boundary divided by the maximum potential number of patch types specified by the user, based on the particular patch type classification scheme, multiplied by 100 (to convert to percent).
Units	Percent
Range	$0 < RPR \leq 100$ RPR approaches 0 when the landscape contains a single patch type, yet the number of potential patch types is very large. RPR = 100 when all possible patch types are represented in the landscape.
Comments	*Relative patch richness* is similar to patch richness, but it represents richness as a percentage of the maximum potential richness as specified by the user. Note, this metric is redundant with both patch richness and patch richness density.

(L4) Shannon's Diversity Index	
$SHDI = -\sum_{i=1}^{m}(P_i * \ln P_i)$	P_i = proportion of the landscape occupied by patch type (class) i.
Description	SHDI equals minus the sum, across all patch types, of the proportional abundance of each patch type multiplied by that proportion. Note, P_i is based on total landscape area (A) excluding any internal background present.
Units	Information

Range	SHDI ≥ 0, without limit SHDI = 0 when the landscape contains only 1 patch (i.e., no diversity). SHDI increases as the number of different patch types (i.e., patch richness, PR) increases and/or the proportional distribution of area among patch types becomes more equitable.
Comments	*Shannon's diversity index* is a popular measure of diversity in community ecology, applied here to landscapes. Shannon's index is somewhat more sensitive to rare patch types than Simpson's diversity index.

(L5) Simpson's Diversity Index	
$$SIDI = 1 - \sum_{i=1}^{m} P_i^2$$	P_i = proportion of the landscape occupied by patch type (class) i.
Description	SIDI equals 1 minus the sum, across all patch types, of the proportional abundance of each patch type squared. Note, P_i is based on total landscape area (A) excluding any internal background present.
Units	None
Range	0 ≤ SIDI < 1 SIDI = 0 when the landscape contains only 1 patch (i.e., no diversity). SIDI approaches 1 as the number of different patch types (i.e., patch richness, PR) increases and the proportional distribution of area among patch types becomes more equitable.
Comments	*Simpson's diversity index* is another popular diversity measure borrowed from community ecology. Simpson's index is less sensitive to the presence of rare types and has an interpretation that is much more intuitive than Shannon's index. Specifically, the value of Simpson's index represents the probability that any 2 pixels selected at random would be different patch types.

(L6) Modified Simpson's Diversity Index	
$$MSIDI = -\ln \sum_{i=1}^{m} P_i^2$$	P_i = proportion of the landscape occupied by patch type (class) i.
Description	MSIDI equals minus the logarithm of the sum, across all patch types, of the proportional abundance of each patch type squared. Note, P_i is based on total landscape area (A) excluding any internal background present.

Units	None
Range	MSIDI ≥ 0, without limit MSIDI = 0 when the landscape contains only 1 patch (i.e., no diversity). MSIDI increases as the number of different patch types (i.e., patch richness, PR) increases and the proportional distribution of area among patch types becomes more equitable.
Comments	*Modified Simpson's diversity index* eliminates the intuitive interpretation of Simpson's index as a probability, but transforms the index into one that belongs to a general class of diversity indices to which Shannon's diversity index belongs.

(L7) Shannon's Evenness Index	
$$SHEI = \frac{-\sum_{i=1}^{m}(P_i \cdot \ln P_i)}{\ln m}$$	P_i = proportion of the landscape occupied by patch type (class) i. m = number of patch types (classes) present in the landscape, excluding the landscape border if present.
Description	SHEI equals minus the sum, across all patch types, of the proportional abundance of each patch type multiplied by that proportion, divided by the logarithm of the number of patch types. In other words, the observed Shannon's Diversity Index divided by the maximum Shannon's Diversity Index for that number of patch types. Note, P_i is based on total landscape area (A) excluding any internal background present.
Units	None
Range	0 ≤ SHEI ≤ 1 SHDI = 0 when the landscape contains only 1 patch (i.e., no diversity) and approaches 0 as the distribution of area among the different patch types becomes increasingly uneven (i.e., dominated by 1 type). SHDI = 1 when distribution of area among patch types is perfectly even (i.e., proportional abundances are the same).
Comments	*Shannon's evenness index* is expressed such that an even distribution of area among patch types results in maximum evenness. As such, evenness is the complement of dominance.

(L8) Simpson's Evenness Index

$$SIEI = \frac{1 - \sum_{i=1}^{m} P_i^2}{1 - \left(\frac{1}{m}\right)}$$		P_i = proportion of the landscape occupied by patch type (class) i. m = number of patch types (classes) present in the landscape, excluding the landscape border if present.
Description	SIEI equals 1 minus the sum, across all patch types, of the proportional abundance of each patch type squared, divided by 1 minus 1 divided by the number of patch types. In other words, the observed Simpson's Diversity Index divided by the maximum Simpson's Diversity Index for that number of patch types. Note, P_i is based on total landscape area (A) excluding any internal background present.	
Units	None	
Range	0 ≤ SIEI ≤ 1 SIDI = 0 when the landscape contains only 1 patch (i.e., no diversity) and approaches 0 as the distribution of area among the different patch types becomes increasingly uneven (i.e., dominated by 1 type). SIDI = 1 when distribution of area among patch types is perfectly even (i.e., proportional abundances are the same).	
Comments	*Simpson's evenness index* is expressed such that an even distribution of area among patch types results in maximum evenness. As such, evenness is the complement of dominance.	

(L9) Modified Simpson's Evenness Index		
$$MSIEI = \frac{-\ln \sum_{i=1}^{m} P_i^2}{\ln m}$$		P_i = proportion of the landscape occupied by patch type (class) i. m = number of patch types (classes) present in the landscape, excluding the landscape border if present.
Description	MSIEI equals minus the logarithm of the sum, across all patch types, of the proportional abundance of each patch type squared, divided by the logarithm of the number of patch types. In other words, the observed modified Simpson's diversity index divided by the maximum modified Simpson's diversity index for that number of patch types. Note, P_i is based on total landscape area (A) excluding any internal background present.	
Units	None	

Range	0 ≤ MSIEI ≤ 1 MSIDI = 0 when the landscape contains only 1 patch (i.e., no diversity) and approaches 0 as the distribution of area among the different patch types becomes increasingly uneven (i.e., dominated by 1 type). MSIDI = 1 when distribution of area among patch types is perfectly even (i.e., proportional abundances are the same).
Comments	*Modified Simpson's evenness index* is expressed such that an even distribution of area among patch types results in maximum evenness. As such, evenness is the complement of dominance.

LITERATURE CITED

Allen, T. F. H., and T. B. Starr. 1982. Hierarchy: Perspectives for Ecological Complexity. University of Chicago Press, Chicago. 310 pp.

Allen, T. F. H., R. V. O'Neill, and T. W. Hoekstra. 987. Inter-level relations in ecological research and management: some working principles from hierarchy theory. J. of Applied Systems Analysis 14:63-79.

Baker, W. L., and Y. Cai. 1992. The r.le programs for multiscale analysis of landscape structure using the GRASS geographical information system. Landscape Ecology 7: 291-302.

Baskent, E. Z., and G. A. Jordan. 1995. Characterizing spatial structure of forest landscapes. Can. J. For. Res. 25:1830-49.

Bendell, P. R., and J. E. Gates. 1987. Home range and microhabitat partitioning of the southern flying squirrel (*Glaucomy volans*). J. Mammology 68:243-255.

Bradshaw, G. A. 1991. Characterizing canopy gap structure in forests using wavelet analysis. J. Ecol. 80:205-215.

Brittingham, M. C., and S. A. Temple. 1983. Have cowbirds caused forest songbirds to decline? Bio-Science 33:31-35.

Buechner, M. 1989. Are small-scale landscape features important factors for field studies of small mammal dispersal sinks? Landscape Ecology 2:191-199.

Burgess, R. L., and D.M. sharpe, eds. 1981. Forest Island Dynamics in Man-Dominated Landscapes. Springer-Verlag, New York.

Burrough, P. A. 1986. Principles of Geographical Information Systems for Land Resources Assessment. Monographs on Soil and Resources Survey No. 12. Clarendon Press, Oxford.

Cardille, J., M. Turner, M. Clayton, S. Gergel, and S. Price. 2005. METALAND: Characterizing spatial patterns and statistical context of landscape metrics. BioScience 55:983-988.

Chasko, G. G, J. E. Gates. 1982. Avian habitat suitability along a transmission-line corridor in an oak-hickory forest region. Wildl. Monogr. 82.

Chen, J., and J. F. Franklin. 1990. Microclimatic pattern and basic biological responses at the clearcut edges of old-growth Douglas-fir stands. Northwest Environ. J. 6:424-425.

Clark, P. J., and F. C. Evans. 1954. Distance to nearest neighbor as a measure of spatial relationships in populations. Ecology 35:445-453.

Cushman, S.A., K. McGarigal, and M. Neel. 2008. Parsimony in landscape metrics: strength, universality, and consistency. Ecological Indicators 8:691-703.

Dale, M. R. T. 1999. Spatial pattern analysis in plant ecology. Cambridge University Press, Cambridge.

Dale, M. R. T. 2000. Lacunarity analysis of spatial pattern: a comparison. Landscape Ecol. 15:467-468.

Dale, M.R.T., and M. Mah. 1998. The use of wavelets for spatial pattern analysis in ecology. Journal of Vegetation Science 9:805-814.

Dale, V. H., S. M. Pearson, H. L. Oferman, and R. V. O'Neill. 1994. Relating patterns of land-use change to faunal biodiversity in the central Amazon. Conservation Biology 8:1027-1036.

Dickman, C. R. 1987. Habitat fragmentation and vertebrate species richness in an urban environment. J. Appl. Ecol. 24:337-351.

Dunning, J. B., B. J. Danielson, and H. R. Pulliam. 1992. Ecological processes that affect populations in complex landscapes. Oikos 65:169-175.

Fahrig, L., and J. Paloheimo. 1988. Effect of spatial arrangement of habitat patches on local population size. Ecology 69:468-475.

Fahrig, L., and G. Merriam. 1985. Habitat patch connectivity and population survival. Ecology 66:1762-1768.

Ford, E. D., and E. Renshaw. 1984. The interpretation of process from pattern using two-dimensional spectral analysis: modeling single species patterns in vegetation. Vegetatio 56:113-123.

Forman, R. T. T. 1995. Land mosaics: the ecology of landscapes and regions. Cambridge University Press, Cambridge, England.

Forman, R. T. T., and M. Godron. 1986. Landscape Ecology. John Wiley & Sons, New York. 619 pp.

Forman, R. T. T., A. E. Galli, and C. F. Leck. 1976. Forest size and avian diversity in New Jersey woodlots with some land use implications. Oecologia 26:1-8.

Forsman, E. D., E. C. Meslow, and H. M. Wight. 1984. Distribution and biology of the spotted owl in Oregon. Wildl. Monogr. 87. 64 pp.

Fortin, M.-J. 1994. Edge detection algorithms for two-dimensional ecological data. Ecology 75:956-965.

Fortin, M.-J., R. J. Olson, S. Ferson, L. Iverson, C. Hunsaker, G. Edwards, D. Levine, K. Butera, and V. Klemas. 2000. Issues related to the detection of boundaries. Landscape Ecol. 15:453-466.

Fortin, M.-J., and P. Drapeau. 1995. Delineation of ecological boundaries: comparison of approaches and significance test. Oikos 72:323-332.

Franklin, J. F., and R. T. T. Forman. 1987. Creating landscape pattern by forest cutting: ecological consequences and principles. Landscape Ecology 1:5-18.

Gardner, R. H., B. T. Milne, M.G. Turner, and R.V. O'Neill. 1987. Neutral models for the analysis of broad-scale landscape pattern. Landscape Ecol. 1:19-28.

Gardner, R. H., R. V. O'Neill, and M. G. Turner. 1993. Ecological implications of landscape fragmentation. Pages 208-226 in S. T. A. Pickett and M. G. McDonnell, editors. Humans as components of ecosystems: subtle human effects and ecology of population areas. Springer-Verlag, New York.

Gardner, R. H., and R. V. O'Neill. 1991. Pattern, process, and predictability: the use of neutral models for landscape analysis. Pages 289-307 In M. G. Turner and R. H. Gardner, eds. Quantitative Methods in Landscape Ecology. Springer-Verlag, New York.

Gilpin, M. E., and I. Hanski (eds). 1991. Metapopulation Dynamics: Empirical and Theoretical Investigations. Academic Press, San Diego. 336 pp.

Graham, R. L., C. T. Hunsaker, R. V., O'Neill, and B. Jackson. 1991. Ecological risk assessment at the regional scale. Ecol. Appl. 1:196-206.

Gratkowski, H. J. 1956. Windthrow around staggered settings in old-growth Douglas-fir. For. Sci. 2:60-74.

Greig-Smith, P. 1983. Quantitative plant ecology. University of California Press, Berkeley.

Gustafson, E. J., and G. R. Parker. 1994. Using an index of habitat patch proximity for landscape design. Landscape and Urban Planning 29:117-30.

Gustafson, E. J., G. R. Parker, and S. E. Backs. 1994. Evaluating spatial pattern of wildlife habitat: a case study of the wild turkey (*Meleagris gallopavo*). Am. Midl. Nat. 131:24-33.

Gustafson, E. J., and G. R. Parker. 1992. Relationships between landcover proportion and indices of landscape spatial pattern. Landscape Ecology 7:101-110.

Gustafson, E. J. 1998. Quantifying landscape spatial pattern: What is the state of the art. Ecosystems:143-156.

Haila, Y., I. K. Hanski, and S. Raivio. 1987. Breeding bird distribution in fragmented coniferous taiga in southern Finland. Ornis Fennica 64:90-106.

Haines-Young, R., and M. Chopping. 1996. Quantifying landscape structure: a review of landscape indices and their application to forested landscapes. Progress in Physical Geography 20(4):418-445.

Hansen, A., and F. di Castri (eds). 1992. Landscape Boundaries. Springer, New York.

Hardt, R. A., and R. T. T. Forman. 1989. Boundary form effects on woody colonization of reclaimed surface mines. Ecology 70:1252-1260.

Hargis, C. D., J. A. Bissonette, and J. L. David. 1998. The behavior of landscape metrics commonly used in the study of habitat fragmentation. Landscape Ecol. 13:167-186.

Harris, L. D. 1984. The Fragmented Forest: Island Biogeographic Theory and the Preservation of Biotic Diversity. University of Chicago Press, Chicago. 211 pp.

Hayden, I. J., J. Faaborg, and R. L. Clawson. 1985. Estimates of minimum area requirements for Missouri forest birds. Missouri Academy of Science 19:11-22.

Haydon, D. T., J. K. Friar, and E. R. Pianka. 2000. Fire-driven dynamic mosaics in the Great Victoria Desert, Australia. Landscape Ecol. 15:407-423.

He, H.S., and D.J. Mladenoff. 1999. Spatially explicit and stochastic simulation of forest-landscape fire disturbance and succession. Ecology 80:81-99.

He, H.S., B.E. DeZonia, and D.J. Mladenoff. 2000. An aggregation index (AI) to quantify spatial patterns of landscapes. Landscape Ecology 15:591-601.

Helliwell, D. R. 1976. The effects of size and isolation on the conservation value of wooded sites in Britain. J. Biogeogr. 3:407-416.

Iverson, L. R. 1989. Land use changes in Illinois, USA: the influence of landscape attributes on current and historic land use. Landscape Ecology 2:45-61.

Jaeger, J. A. G. 2000. Landscape division, splitting index, and effective mesh size: new measures of landscape fragmentation. Landscape Ecol. 15:115-130.

Johnson, A. R., B. T. Milne, J. A. Wiens, and T. O. Crist. 1992. Animal movements and population dynamics in heterogeneous landscapes. Landscape Ecol. 7:63-75.

Kareiva, P. 1990. Population dynamics in spatially complex environments: theory and data. Phil. Trans. R. Soc. Lond. B 330:175-190.

Keitt, T.H., D.L. Urban, and B.T. Milne. 1997. Detecting critical scales in fragmented landscapes. Conservation Ecol. 1(1):4. (online)

Kolasa, J., and C. D. Rollo. 1991. Introduction: The heterogeneity of heterogeneity: a glossary. Pages 1-23 In J. Kolasa and S. T. A. Pickett, eds., Ecological Heterogeneity. Springer-Verlag, New

York.

Kotliar, N. B., and J. A. Wiens. 1990. Multiple scales of patchiness and patch structure: a hierarchical framework for the study of heterogeneity. Oikos 59:253-260.

Kremsater, L. and F. L. Bunnell.1999. Edge effects: theory, evidence and implications to management of western North American forests.

Kroodsma, R. L. 1982. Edge effect on breeding forest birds along a power-line corridor. J. of Applied Ecology 19:361-370.

Krummel, J. R., R. H. Gardner, G. Sugihara, R. V. O'Neill, and P. R. Coleman. 1987. Landscape patterns in a disturbed environment. Oikos 48:321-324.

LaGro, J., Jr. 1991. Assessing patch shape in landscape mosaics. Photogrammetric Eng. Remote Sens. 57:285-93.

Lamberson, R.H., R. McKelvey, B.R. Noon, and C. Voss. 1992. A dynamic analysis of northern spotted owl viability in a fragmented forest landscape. Conservation Biology 6(4):1-8.

Lande, R. 1987. Extinction thresholds in demographic models of territorial populations. American Naturalist 130:624-635.

Legendre, P., and M.-J. Fortin. 1989. Spatial pattern and ecological analysis. Vegetatio 80:107-38.

Legendre, P, and L. Legendre. 1999. Numerical Ecology, second edition. Elsevier Science, New York.

Lehmkuhl, J. F., and M. G. Raphael. 1993. Habitat pattern around northern spotted owl locations on the Olympic Peninsula, Washington. J. Wildl. Manage. 57:302-315.

Leopold, A. 1933. Game Management. Charles Scribners, New York.

Levins, R. 1970. Extinctions. Pages 77-107 In M. Gertenhaber, ed. Some Mathematical Questions in Biology, vol 2. Lectures on Mathematics in the Life Sciences. Amer. Math. Soc., Providence, Rhode Island.

Li, H., and J. F. Reynolds. 1995. On definition and quantification of heterogeneity. Oikos 73:280-284.

Li, H., and J. F. Reynolds. 1993. A new contagion index to quantify spatial patterns of landscapes. Landscape Ecology 8:155-162.

Logan, W., E. R. Brown, D. Longrie, G. Herb, and R. A. Corthell. 1985. Edges. Pages 115-127 In E. R. Brown, tech. ed. Management of wildlife and fish habitats in forests of western Oregon and Washington. USDA For. Serv. Publ. No. R6-F&WL-192-1985.

MacArthur, R. H., and E. O. Wilson. 1967. The Theory of Island Biogeography. Princeton University Press, Princeton. 203 pp.

Mader, H-J. 1984. Animal habitat isolation by roads and agricultural fields. Biological Conservation 29:81-96.

Mandelbrot, B. B. 1982. The Fractal Geometry of Nature. W. H. Freeman and Co., New York.

Mandelbrot, B. B. 1977. Fractals, Form, Chance and Dimension. W. H. Freeman and Co., New York.

Mandelbrot, B. B. 1982. The Fractal Geometry of Nature. W. H. Freeman and Co., New York.

McGarigal, K., and B.J. Marks. 1995. FRAGSTATS: spatial pattern analysis program for quantifying landscape structure. Gen. Tech. Report PNW-GTR-351, USDA Forest Service, Pacific Northwest Research Station, Portland, OR.

McGarigal K., S. Tagil, and S.A. Cushman. 2009. Surface metrics: An alternative to patch metrics for the quantification of landscape structure. Landscape Ecology 24:433–450.

McGarigal, K., and W.C. McComb. 1995. Relationships between landscape structure and breeding birds in the Oregon Coast Range. Ecol. Monogr. 65:235-260.

McGarigal, K., S.A. Cushman, M.C. Neel, and E. Ene. 2002. FRAGSTATS: Spatial Pattern Analysis Program for Categorical Maps. Computer software program produced by the authors at the University of Massachusetts, Amherst, available at the following web site: http://www.umass.edu/landeco/research/fragstats/fragstats.html.

McGarigal K., and S.A. Cushman. 2005. The gradient concept of landscape structure. In: Wiens J and Moss M (eds) Issues and Perspectives in Landscape Ecology. Cambridge University Press, Cambridge, pp112-119.

McKelvey, K., B.R. Noon, and R. Lamberson. 1992. Conservation planning for species occupying fragmented landscapes: the case of the northern spotted owl. Pages 338-357 In J. Kingsolver, P. Kareiva, and R. Hyey, eds. Biotic interactions and global change. Sinauer Associates, Sunderland, MA.

Milne, B.T. 1991. Lessons from applying fractal models to landscape patterns. Pages 199-235 in Turner, M.G., and R.H. Gardner, editors. Quantitative methods in landscape ecology. Springer-Verlag, New York.

Milne, B. T. 1988. Measuring the fractal geometry of landscapes. Applied Mathematics and Computation 27:67-79.

Moore, N. W., and M. D. Hooper. 1975. On the number of bird species in British woods. Biol. Conserv. 8:239-250.

Morgan, K. A., and J. E. Gates. 1982. Bird population patterns in forest edge and strip vegetation at Remington Farms, Maryland. J. Wildl. Manage. 46:933-944.

Musick, H. B., and H. D. Grover. 1991. Image textural measures as indices of landscape pattern. Pages 289-307 in Turner, M.G., and R.H. Gardner, editors. Quantitative methods in landscape ecology. Springer-Verlag, New York.

Neel, M.C., S.A. Cushman, and K. McGarigal. 2004. Behavior and stability of landscape metrics across controlled gradients of landscape structure. Land. Ecol. 19:435-455.

Noss, R.F. 1983. A regional landscape approach to maintain diversity. *BioScience* 33:700-706.

Noss, R. F. 1988. Effects of edge and internal patchiness on habitat use by birds in a Florida hardwood forest. Ph.D. Thesis. Univ. of Florida, Gainesville. 109 pp.

Noss, R.F., and A.Y. Cooperrider. 1994. Saving Nature's Legacy : Protecting and Restoring Biodiversity. Island Press.

O'Neill , R. V., C. T. Hunsaker, S. P. Timmins, B. L. Jackson, K. B. Jones, K. H. Ritters, and J. D. Wickham.1996. Scale problems in reporting landscape pattern at the regional scale. Landscape Ecology 11:

O'Neill, R.V., J.R. Krummel, R.H. Gardner, G. Sugihara, B. Jackson, D.L. DeAngelis, B.T. Milne, M.G. Turner, B. Zygmunt, S.W. Christensen, V.H. Dale, and R.L. Graham. 1988. Indices of landscape pattern. Landscape Ecol. 1:153-162.

Patton, D. R. 1975. A diversity index for quantifying habitat "edge". Wildl. Soc. Bull. 3:171-173.

Pearson, S. M., M. G. Turner, R. H. Gardner, and R. V. O’Neill. 1996. An organism-based perspective of habitat fragmentation. Pages 77-95 In R. C. Szaro and D. W. Johnston, eds. Biodiversity in Managed Landscapes: Theory and Practice. Oxford University Press, New York.

Pickover, C. A. 1990. Computers, pattern, chaos and beauty: graphics from an unseen world. New York: St. Martin’s.

Pielou, E.C. 1984. The interpretation of ecological data. Wiley, new York.

Pielou, E. C. 1975. Ecological Diversity. Wiley-Interscience, New York.

Plotnick, R. E., R. H. Gardner, and R.V. O'Neill. 1993. Lacunarity indices as measures of landscape texture. Landscape Ecol. 8:201-211.

Plotnick, R. E., R. H. Gardner, W. W. Hargrove, K. Pretegaard, and M. Perlmutter.1996. Lacunarity analysis: a general technique for the analysis of spatial patterns. Phys. Rev. E53:5461-5468.

Ranney, J. W., M. C. Bruner, and J. B. Levenson. 1981. The importance of edge in the structure and dynamics of forest islands. Pages 67-94 In R. L. Burgess and D. M. Sharpe, eds. Forest Island Dynamics in Man-Dominated Landscapes. Springer-Verlag, New York.

Renshaw, E., and E. D. Ford. 1984. The description of spatial pattern using two-dimensional spectral analysis. Vegetatio 56:75-85.

Ricklefs, R. E. 1987. Community diversity: relative roles of local and regional processes. Science 235:167-171.

Riitters, K. H., R. V. O'Neill, C. T. Hunsaker, J. D. Wickham, D. H. Yankee, S. P. Timmins, K. B. Jones, and B. L. Jackson. 1995. A factor analysis of landscape pattern and structure metrics. Landscape Ecol. 10: 23-40.

Riitters, K. H., R. V. O'Neill, J. D. Wickham, and K. B. Jones. 1996. A note on contagion indices for landscape analysis. Landscape Ecol. 11:197-202.

Ripple, W. J., G. A. Bradshaw, and T. A. Spies. 1991. Measuring landscape pattern in the Cascade Range of Oregon, USA. Biological Conserv. 57:73-88.

Robbins, C. S., D. K. Dawson, and B. A. Dowell. 1989. Habitat area requirements of breeding forest birds of the middle Atlantic states. Wildl. Monogr. 103. 34 pp.

Rogers, C. A. 1993. Describing landscapes: indices of structure. M.S. Thesis, Simon Fraser University, Burnaby, British Columbia. 170 pp.

Romme, W. H. 1982. Fire and landscape diversity in subalpine forests of Yellowstone National Park. Ecol. Monogr. 52:199-221.

Rosenberg, D. K., B. R. Noon, and E. C. Meslow. 1997. Biological corridors: form, function, and efficacy. BioScience 47:677-687.

Roughgarden, J., S. D. Gaines, and S. W. Pacala. 1987. Supply side ecology: the role of physical transport processes. Pages 491-518 In J. H. R. Gee and P. S. Giller, eds. Organization of Communities Past and Present. Blackwell Scientific Publications, Oxford.

Saunders, D. A., R. J. Hobbs, and C. R. Margules. 1991. Biological consequences of ecosystem fragmentation: a review. Cons. Biol. 5:18-32.

Schumaker, N. H. 1996. Using landscape indices to predict habitat connectivity. Ecology 77:1210-25.

Shannon, C., and W. Weaver. 1949. The mathematical theory of communication. Univ. Illinois Press, Urbana.

Simpson, E. H. 1949. Measurement of diversity. Nature 163:688.

Strelke, W. K., and J. G. Dickson. 1980. Effect of forest clearcut edge on breeding birds in Texas. J. Wildl. Manage. 44:559-567.

Taylor, P. D., L. Fahrig, K. Henein, and G. Merriam. 1993. Connectivity is a vital element of landscape structure. Oikos 73:43-48.

Temple, S. A. 1986. Predicting impacts of habitat fragmentation on forest birds: a comparison of two models. Pages 301-304 In J. Verner, M. L. Morrison, and C. J. Ralph, eds. Wildlife 2000: Modeling Habitat Relationships of Terrestrial Vertebrates. Univ. of Wisconsin Press, Madison, WI.

Terborgh, J. 1989. Where Have all the Birds Gone? Princeton University Press, New Jersey. 207 pp.

Thomas, J. W., C. Maser, and J. E. Rodiek. 1979. Edges. Pages 48-59 In J. W. Thomas, tech. ed. Wildlife habitats in managed forests, the Blue Mountains of Oregon and Washington. USDA For. Serv. Handb. 553.

Thomas, J. W., C. Maser, and J. E. Rodiek. 1978. Edges--their interspersion, resulting diversity, and its measurement. Pages 91-100 In R. M. Degraff, tech. coord. Proceedings of the workshop on nongame bird habitat management in the coniferous forests of the western United States. Gen. Tech. Rep. PNW-64.

Thompson, C.M., and K. McGarigal. 2002. The influence of research scale on bald eagle habitat selection along the lower Hudson River, New York. Landscape Ecology 17:569-586.

Turner, M. G. 1989. Landscape ecology: the effect of pattern on process. Ann. Rev. Ecol. Syst. 20:171-197.

Turner, M. G. 1990a. Spatial and temporal analysis of landscape patterns. Landscape Ecology 4:21-30.

Turner, M. G. 1990b. Landscape changes in nine rural counties of Georgia. Photogram. Engine. and Rem. Sens. 56:379-386.

Turner, M.G. 2005. Landscape ecology: what is the state of the science? Annu Rev Ecol Evol Syst 36:319-44.

Turner, M. G., and R. H. Gardner, editors. 1991. Quantitative methods in landscape ecology. Springer-Verlag, New York.

Turner, M. G., and C. L. Ruscher. 1988. Changes in the spatial patterns of lands use in Georgia. Landscape Ecology 1:241-251.

Turner, M. G., R. V. O'Neill, R. H. Gardner, and B. T. Milne. 1989. Effects of changing spatial scale on the analysis of landscape pattern. Landscape Ecology 3:153-162.

Urban, D. L., R. V. O'Neill, and H. H. Shugart, Jr. 1987. Landscape ecology: A hierarchical perspective can help scientist understand spatial patterns. BioScience 37:119-127.

Vaisanen, R. A., O. Jarvinen, and P. Rauhala. 1986. How are extensive, human-caused habitat alterations expressed on the scale of local bird populations in boreal forest? Ornis Scandinavica 17:282-292.

Voss, R. F. 1988. Fractals in nature: from characterization to simulation. Pages 21-70 In H.O. Petigen and D. Saupe, eds. The Science of Fractal Images. Springer-Verlag, New York.

Wallin, D. O., F. J. Swanson, B. Marks, J. H. Cissel, and J. Kertis. 1996. Comparison of managed and pre-settlement landscape dynamics in forests of the Pacific Northwest, USA. Forest Ecology and Management 85:291-309.

Wegner, J. F., and H. G. Merriam. 1979. Movements by birds and small mammals between a wood and adjoining farmland habitats. J. Appl. Ecol. 16:349-357.

Whitcomb, R. F., C. S. Robbins, J. F. Lynch, B. L. Whitcomb, M. K. Klimkiewicz, and D Bystrak. 1981. Effects of forest fragmentation on avifauna of the eastern deciduous forest. Pages 125-205 in R. L. Burgess and D. M. Sharpe, eds. Forest Island Dynamics in Man-Dominated Landscapes. Springer-Verlag, New York.

Wiens, J.A. 1976. Population responses to patchy environments. Ann. Rev. Ecol. Syst. 7:81-120.

Wiens, J. A. 1981. Scale problems in avian censusing. Studies in Avian Biology 6:513-521.
Stauffer, D. 1985. Introduction to Percolation Theory. Taylor and Francis, London.

Wiens, J. A. 1989. Spatial scaling in ecology. Functional Ecol. 3:385-397.

Wiens, J. A., C. S. Crawford, and J. R. Gosz. 1985. Boundary dynamics: a conceptual framework for studying landscape ecosystems. Oikos 45: 421-427.

Wilcove, D. S. 1985. Nest predation in forest tracts and the decline of migratory songbirds. Ecology 66:1211-1214.

Wilcox, B.A., and D.D. Murphy. 1985. Conservation strategy: the effects of fragmentation on extinction. *American Naturalist* 125:879-887.

Wimberly, M. C., T. A. Spies, C. J. Long, and C. Whitlock. 2000. Simulating historical variability in the amount of old forests in the Oregon Coast Range. Conservation Biology 14:167-180.

With, K. A. 1997. The application of neutral landscape models in conservation biology. Conservation Biology 11:1069-1080.

With, K. A. 1999. Is landscape connectivity necessary and sufficient for wildlife management? Pages 97-115 in J. A. Rochelle, L. A. Lehmann, and J. Wisniewski, editors. Forest fragmentation: wildlife and management implications. Brill, The Netherlands.

With, K. A., and T. O. Crist. 1995. Critical thresholds in species' responses to landscape structure. Ecology 76:2446-59.

With, K. A., and A.W. King. 1999a. Dispersal success on fractal landscapes: a consequence of lacunarity thresholds. Landscape Ecology 14:73-82.

With, K. A., and A.W. King. 1999b. Extinction thresholds for species in fractal landscapes. Conservation Biology 13:314-326.

With, K. A., R. H. Gardner, and M. G. Turner. 1997. Landscape connectivity and population distributions in heterogeneous environments. Oikos 78:151-169.

Yahner, R. H. 1986. Spatial distribution of white-footed mice (Peromyscus leucopus) in fragmented forest stands. Proceedings of the Pennsylvania Academy of Science 60:165-166.

Yahner, R. H., and D. P. Scott. 1988. Effects of forest fragmentation on depredation of artificial nests. J. Wildl. Manage. 52:158-161.