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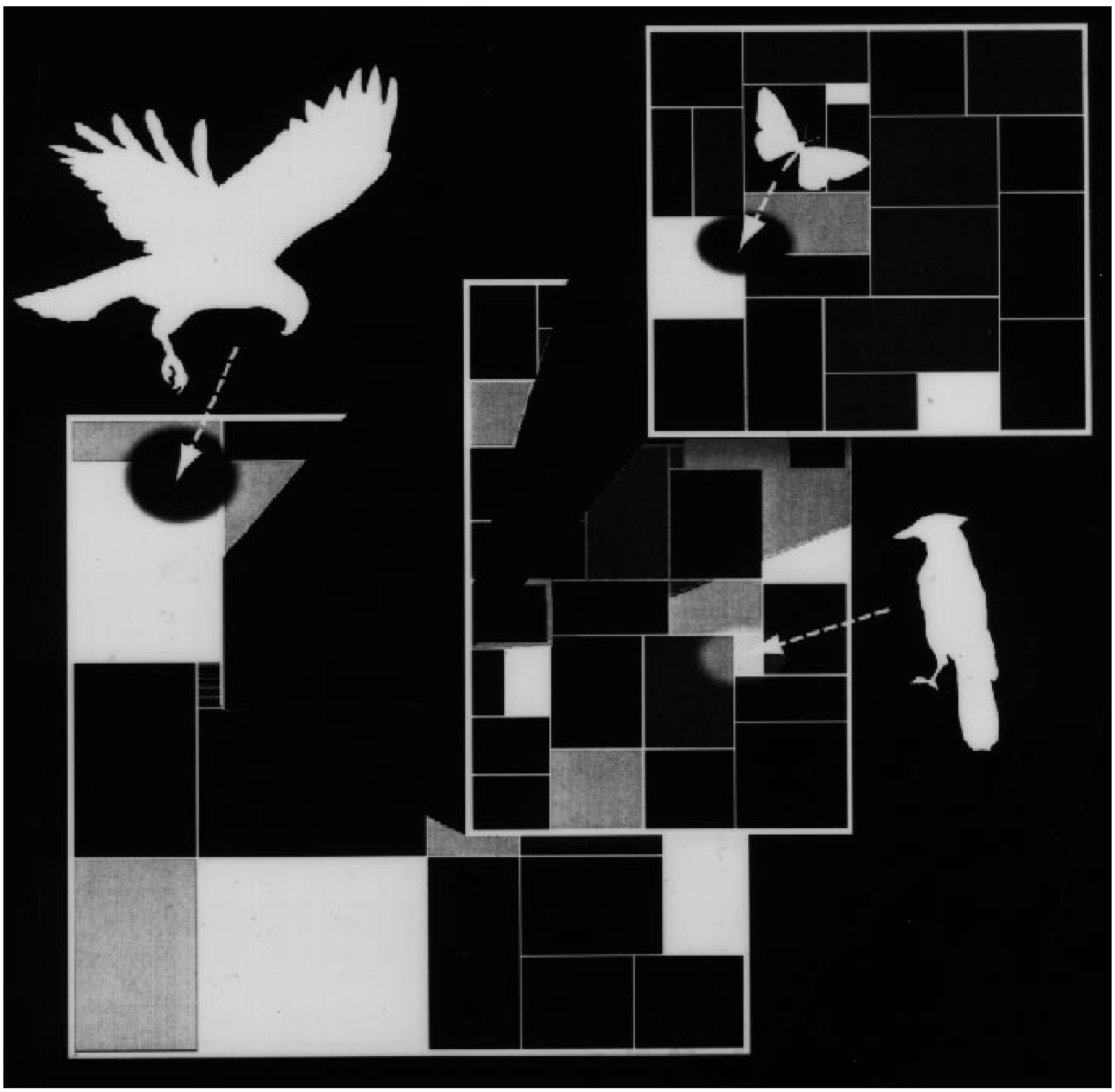
FRAGSTATS: Spatial Pattern Analysis Program for Quantifying Landscape Structure



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This paper is a product of the Coastal Oregon Productivity Enhancement Program of which the Pacific Northwest Research Station (PNW) is a major partner. Members of the Forest Ecosystem Team, the Andrews Forest Ecosystem Group, and the Cascade Center for Ecosystem Management participated in development of this software product. The Cascade Center for Ecosystem Management is a partnership of researchers from PNW and Oregon State University and land managers from the Willamette National Forest. Partial funding was also provided by the U.S. Department of the Interior, Bureau of Land Management.

Abstract

McGarigal, Kevin; Marks, Barbara J. 1995. FRAGSTATS: spatial pattern analysis program for quantifying landscape structure. Gen. Tech. Rep. PNW-GTR-351. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 122 p.

This report describes a program, FRAGSTATS, developed to quantify landscape structure. FRAGSTATS offers a comprehensive choice of landscape metrics and was designed to be as versatile as possible. The program is almost completely automated and thus requires little technical training. Two separate versions of FRAGSTATS exist: one for vector images and one for raster images. The vector version is an Arc/Info AML that accepts Arc/Info polygon coverages. The raster version is a C program that accepts ASCII image files, 8- or 16-bit binary image files, Arc/Info SVF files, Erdas image files, and IDRISI image files. Both versions of FRAGSTATS generate the same array of metrics, including a variety of area metrics, patch density, size and variability metrics, edge metrics, shape metrics, core area metrics, diversity metrics, and contagion and interspersion metrics. The raster version also computes several nearest neighbor metrics.

In this report, each metric calculated by FRAGSTATS is described in terms of its ecological application and limitations. Example landscapes are included, and a discussion is provided of each metric as it relates to the sample landscapes. Several important concepts and definitions critical to the assessment of landscape structure are discussed. The appendices include a complete list of algorithms, the units and ranges of each metric, examples of the FRAGSTATS output files, and a users guide describing how to install and run FRAGSTATS.

Keywords: Landscape ecology, landscape structure, landscape pattern, landscape analysis, landscape metrics, spatial statistics.

Preface and Version 2.0 Upgrade Information

As the authors of FRAGSTATS, we are very concerned about the potential for misuse of this program. Like most tools, FRAGSTATS is only as good as the user. FRAGSTATS crunches out a lot of numbers about the input landscape. These numbers can easily become “golden” in the hands of uninformed users. Unfortunately, the garbage in-garbage out axiom applies here. We have done our best in the documentation to stress the importance of defining landscape, patch, matrix, and landscape context at a scale and in a manner relevant and meaningful to the phenomenon under consideration. We have stressed the importance of understanding the exact meaning of each metric before it is used. These and other important considerations in any landscape structural analysis are discussed in the documentation. We strongly urge you to read the entire documentation, especially the section, “Concepts and Definitions,” before running FRAGSTATS.

We welcome and encourage your criticisms and suggestions about the program, as well as questions about how to run FRAGSTATS or interpret the output (after you have read the entire documentation). We are interested in learning about how others have applied FRAGSTATS in ecological investigations and management applications. Therefore, we encourage you to contact us and describe your application after using FRAGSTATS.

This release of FRAGSTATS (version 2.0) differs from the previous version in only minor ways. Several bugs have been corrected. The most important change is the added option to treat a specified proportion of the landscape boundary and background edge (instead of just all or none) as true edge in the edge metrics (bound_wght option). This fraction also is used as the edge contrast weight for landscape boundary and background edge segments in the calculation of edge contrast metrics. In addition, the convention for naming the output file containing patch IDs in the raster version has been modified to comply with DOS requirements on a personal computer (PC) (id_image option). Similarly, the output file name extensions in the PC raster version have been shortened and renamed to comply with DOS requirements and to avoid conflicts with ERDAS conventions (out_file). The nearest neighbor algorithm has been modified slightly to compute actual edge-to-edge distance (previous version used cell midpoints rather than edge). Finally, FRAGSTATS verifies that all interior and exterior background patches have been classified correctly.

The FRAGSTATS software is available electronically from the following ftp site: ftp.fsl.orst.edu. If you do not have Internet access, a diskette with the software can be obtained by sending a 3.5 inch floppy diskette and a self-addressed, stamped floppy disk mailer to:

Barbara Marks
Department of Forest Science
Oregon State University
Forest Science Lab 020
Corvallis, OR 97331-7501

Every effort has been made to ensure that FRAGSTATS was bug-free at the time of distribution. If bugs should be discovered, they will be corrected and updated on the ftp server only.

The following procedure describes how to obtain the FRAGSTATS software electronically:

1. Connect to the ftp server by issuing the following command:

```
ftp ftp.fsl.orst.edu
```

2. Enter “anonymous” when prompted for a log-in name.

3. Enter your e-mail address when prompted for a password.

4. Change the directory to pub/fragstats.2.0 with the following command:

```
cd pub/fragstats.2.0
```

The file changes.notes in this directory contains a record and description of all the modifications made to the software. This file should be checked periodically.

5. If you are ftp’ing from a Unix machine, enter the following commands at the ftp prompt:

```
binary
get frag.tar
quit
```

To extract the files, at your system prompt type:

```
tar xvf frag.tar
```

6. If you are ftp’ing from a DOS machine, enter the following commands at the ftp prompt:

```
binary
get frag.zip
quit
```

To extract the files, at your system prompt type:

```
pkunzip -d frag.zip
```

(The program pkunzip is available in the fragstats.2.0 directory, if you need it).

We hope that FRAGSTATS is of great assistance in your work, and we look forward to hearing about your applications.

Contents

Introduction

Growing concerns over the loss of biodiversity have spurred land managers to seek better ways of managing landscapes at a variety of spatial and temporal scales. Several developments have made possible the ability to analyze and manage entire landscapes to meet multiresource objectives. The developing field of landscape ecology has provided a strong conceptual and theoretical basis for understanding landscape structure, function, and change (Forman and Godron 1986, Turner 1989, Urban and others 1987). Growing evidence that habitat fragmentation is detrimental to many species and may contribute substantially to the loss of regional and global biodiversity (Harris 1984, Saunders and others 1991) has provided empirical justification for the need to manage entire landscapes, not just the components. The development of GIS (geographical information systems) technology, in particular, has made a variety of analytical tools available for analyzing and managing landscapes. In response to this growing theoretical and empirical support and to technical capabilities, public land management agencies have begun to recognize the need to manage natural resources at the landscape scale.

A good example of these changes is in wildlife science. Wildlife ecologists often have assumed that the most important ecological processes affecting wildlife populations and communities operate at local spatial scales (Dunning and others 1992). Vertebrate species richness and abundance, for example, often are considered functions of variation in local resource availability, vegetation composition and structure, and the size of the habitat patch (Cody 1985, MacArthur and MacArthur 1961, Willson 1974). Correspondingly, most wildlife research and management activities have focused on the within-patch scale, typically small plots or forest stands. Wildlife ecologists have become increasingly aware, however, that habitat variation and its effects on ecological processes and vertebrate populations occur at many spatial scales (Wiens 1989a, 1989b). In particular, there has been increasing awareness of the potential importance of coarse-scale habitat patterns to wildlife populations and a corresponding surge in landscape ecological investigations that examine vertebrate distributions and population dynamics over broad spatial scales (for example, McGarigal and McComb, in press). The recent attention to metapopulation theory (Gilpin and Hanski 1991) and the proliferation of mathematical models on dispersal and spatially distributed populations (Kareiva 1990) are testimony to these changes. Recent conservation efforts for the northern spotted owl (*Strix occidentalis caurina*) demonstrate the willingness and ability of public land management agencies to analyze and manage wildlife populations at the landscape scale (Interagency Scientific Committee 1990, Lamberson and others 1992, Murphy and Noon 1992).

The emergence of landscape ecology to the forefront of ecology is testimony to the growing recognition that ecological processes affect and are affected by the dynamic interaction among ecosystems. This surge in interest in landscape ecology also is shown in recent efforts to include a landscape perspective in policies and guidelines for managing public lands. Landscape ecology embodies a way of thinking that many see as very useful for organizing land management approaches. Specifically, landscape ecology focuses on three characteristics of the landscape (from Forman and Godron 1986: 11):

1. **Structure**, the spatial relationships among the distinctive ecosystems or “elements” present—more specifically, the distribution of energy, materials, and species in relation to the sizes, shapes, numbers, kinds, and configurations of the ecosystems.

2. **Function**, the interactions among the spatial elements, that is, the flows of energy, materials, and species among the component ecosystems.

3. **Change**, the alteration in the structure and function of the ecological mosaic over time.

Thus, landscape ecology involves the study of landscape patterns, the interactions among patches within a landscape mosaic, and how these patterns and interactions change over time. In addition, landscape ecology involves applying these principles to formulate and solve real-world problems. Landscape ecology considers the development and dynamics of spatial heterogeneity and its affects on ecological processes and the management of spatial heterogeneity (Risser and others 1984).

Landscape ecology is largely founded on the idea that the patterning of landscape elements (patches) strongly influences ecological characteristics, including vertebrate populations. The ability to quantify landscape structure is prerequisite to the study of landscape function and change. For this reason, much emphasis has been placed on developing methods to quantify landscape structure (for example, Li 1990, O'Neill and others 1988, Turner 1990b, Turner and Gardner 1991). Most efforts to date have been tailored to meet the needs of specific research objectives and have employed user-generated computer programs to perform the analyses. Such user-generated programs allow the inclusion of customized analytical methods and easy linkages to other programs, such as spatial simulation models, yet generally lack the advanced graphics capabilities of commercially available GIS (Turner 1990b). Most user-generated programs are limited to a particular hardware or are embedded within a larger software package designed to accomplish a specific research objective (for example, to model fire disturbance regimes). We are aware of only one other published software program that offers a broad array of landscape metrics. The r.le programs (Baker and Cai 1992), however, are intended to be part of the Geographical Resources Analysis Support System (GRASS).

This report describes a program called FRAGSTATS[1] that we developed to quantify landscape structure. FRAGSTATS offers a comprehensive choice of landscape metrics and was designed to be as versatile as possible. The program is almost completely automated and thus requires little technical training. Two separate versions of FRAGSTATS exist: one for vector images and one for raster images. The vector

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[1] This software is in the public domain, and the recipient may not assert any proprietary rights thereto nor represent it to anyone as other than an Oregon State University-produced program. FRAGSTATS is provided "as-is" without warranty of any kind, including, but not limited to, the implied warranties of merchantability and fitness for a particular purpose. The user assumes all responsibility for the accuracy and suitability of this program for a specific application. In no event will the authors, Oregon State University, or the USDA Forest Service be liable for any damages, including lost profits, lost savings, or other incidental or consequential damages, arising from the use of or the inability to use this program.

version is an Arc/Info AML that accepts Arc/Info polygon coverages.[2] The raster version is a C program that accepts ASCII image files, 8- or 16-bit binary image files, Arc/Info SVF files, Erdas image files, and IDRISI image files. Both versions of FRAGSTATS generate the same array of metrics, although a few additional metrics are computed in the raster version.

In this report, each metric calculated by FRAGSTATS is described by its ecological application and limitations. Example landscapes are included as is a discussion of each metric as it relates to the sample landscapes. In addition, several important concepts and definitions critical to the assessment of landscape structure are discussed. The appendices include a complete list of algorithms, the units and ranges of each metric, examples of the FRAGSTATS output files, and a users guide describing in detail how to install and run FRAGSTATS.

Concepts and Definitions

It is beyond the scope and purpose of this document to provide a glossary of terms and a comprehensive discussion of the many concepts embodied in landscape ecology. Instead, a few key terms and concepts essential to using FRAGSTATS and to measuring spatial heterogeneity are defined and discussed; ***a thorough understanding of these concepts is prerequisite to the effective use of FRAGSTATS***.

Landscape—What is a "landscape"? Surprisingly, there are many different interpretations of this well-used term. The disparity in definitions makes it difficult to communicate clearly and even more difficult to establish consistent management policies. Definitions invariably include an area of land containing a mosaic of patches or landscape elements. Forman and Godron (1986: 11) define 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. From a wildlife perspective, for example, landscape might be defined as an area of land containing a mosaic of **habitat** patches, within which a particular "focal" or "target" habitat patch often is embedded (Dunning and others 1992). Because habitat patches can be defined only relative to a particular organism's perception of the environment (that is, each organism defines habitat patches differently and at different scales), landscape size would differ among organisms (Wiens 1976); 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 (for example, 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 differs depending on what constitutes a mosaic of habitat or resource patches meaningful to that particular organism (fig. 1).

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[2] The use of trade or firm names in this publication is for reader information and does not imply endorsement by the U.S. Department of Agriculture of any product or service.

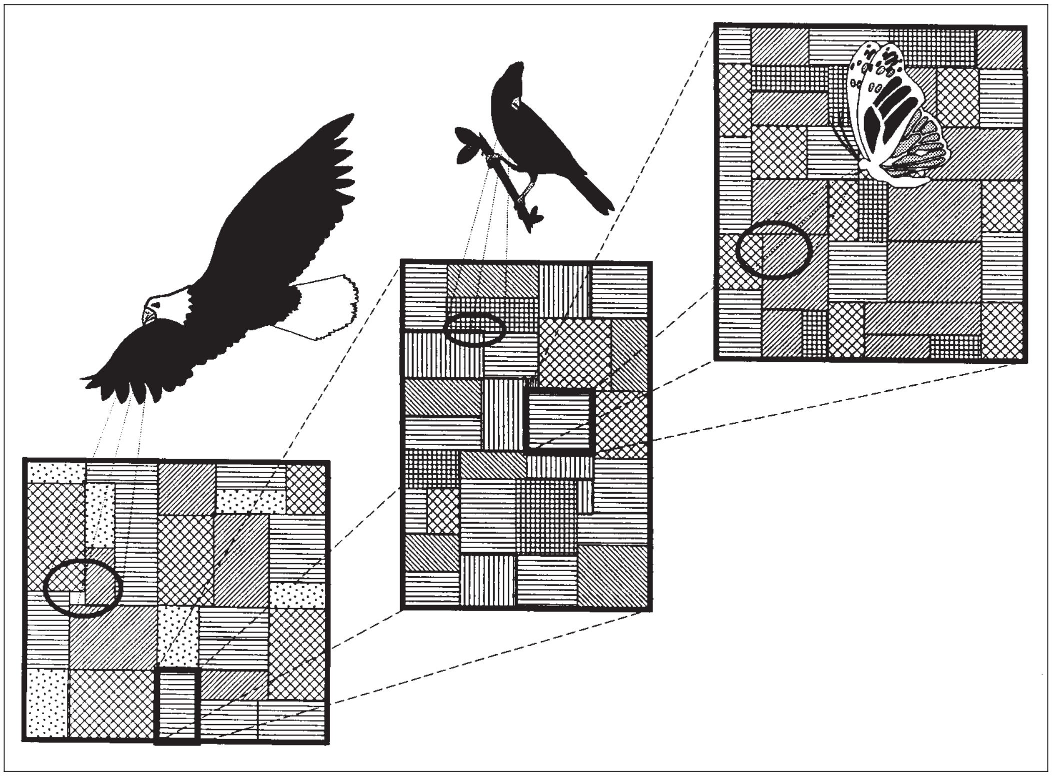


Figure 1—Multiscale view of “landscape” from an organism-centered perspective. Because the eagle, cardinal, and butterfly perceive their environments differently and at different scales, what constitutes a single habitat patch for the eagle may constitute an entire landscape or patch-mosaic for the cardinal, and a single habitat patch for the cardinal may comprise an entire landscape for the butterfly that perceives patches on an even finer scale.

This definition contrasts with the more anthropocentric definition that a landscape corresponds to an area of land equal to or larger than, say, a large basin (several thousand hectares). Indeed, Forman and Godron (1986) suggest a lower limit for landscapes at a “few kilometers in diameter,” although they recognize that most of the principles of landscape ecology apply to ecological mosaics at any scale. This may be a more pragmatic definition than the organism-centered definition and perhaps corresponds to our human perception of the environment, but it has limited use in managing wildlife populations if it is accepted 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 (for example, an individual log) to an entire ecoregion. If this organism-centered definition of a landscape is accepted, then a logical consequence of this is a mandate to manage wildlife habitats across the full range of spatial scales; each scale, whether 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, but rather to suggest that there are many appropriate ways to define landscape, depending on the situation being considered. The important point is that a landscape is not necessarily defined by its size but by an interacting mosaic of patches relevant to the phenomenon under consideration (at any scale). The investigator or manager must define landscape appropriately; this is the first step in any landscape-level research or management endeavor.***

Patch—Landscapes are composed of a mosaic of patches (Urban and others 1987). Landscape ecologists have used several 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). We prefer the term "patch"; but 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 given situation. From a timber management perspective, for example, 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" (Wiens 1976).

Patches are dynamic and occur on many spatial and temporal scales that, from an organism-centered perspective, differ as a function of each animal's perceptions (Wiens 1976, 1989a; Wiens and Milne 1989). A patch at any given scale has an internal structure reflecting patchiness at finer scales, and the mosaic containing that patch has a structure 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. 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 where 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 differs among species. Similarly, "extent" is the coarsest scale of heterogeneity, or upper threshold of heterogeneity, to which an organism responds (Kolasa and Rollo 1991, Kotliar and Wiens 1990). At the level of the individual, extent is determined by the lifetime home range of the individual (Kotliar and Wiens 1990) and differs among individuals and species. More generally, however, extent differs with the organizational level (individual, population, metapopulation) under consideration; for example, the upper threshold of patchiness for the population would probably greatly exceed that of the individual. From an organism-centered perspective, patches therefore 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 (grain size and extent). Even a relatively discrete patch boundary, for example between an aquatic surface (a lake) and a terrestrial surface, becomes more and more like a continuous gradient as one progresses to a finer and finer resolution. Most environmental dimensions possess one or more "domains of scale" (Wiens 1989a) 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 (that is, domains of scale) but not at others.

KEY POINT ***It is not our intent to argue for a particular definition of patch. Rather, we wish to point out that (1) patch must be defined relative to the phenomenon under investigation or its management; (2) regardless of the phenomenon under consideration (for example, a species or geomorphological disturbance), patches are dynamic and occur at multiple scales; and (3) patch boundaries are only meaningful when referenced to a particular scale. The investigator or manager must establish the basis for delineating among patches (that is, patch type classification system) and a scale appropriate to the phenomenon under consideration.***

Matrix—A landscape is composed typically of several types of landscape elements (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). In a large contiguous area of mature forest embedded with numerous small disturbance patches (for example, 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. But in some landscapes, or at a certain point in time during the trajectory of a landscape, the matrix element will not be obvious, and it may not be appropriate to consider any element as the matrix. The designation of a matrix element depends mainly on the phenomenon under consideration. In a study of geomorphological processes, the geological substrate may serve to define the matrix and patches; in a study of vertebrate populations, vegetation structure may serve to define the matrix and patches. What constitutes the matrix also depends on the scale of investigation or management. 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.

KEY POINT ***The investigator or manager must determine whether a matrix element exists and should be designated given the scale and phenomenon under consideration. This should be done before the analysis of landscape structure, because this decision will influence the choice and interpretation of landscape metrics.***

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 and others 1989, Wiens 1989a). 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 to be sampled. Grain is the size of the individual units of observation. For example, a fine-grained map might structure information into 1-hectare units, whereas a map with resolution an order of magnitude coarser would have information structured into 10-hectare units (Turner and others 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 1989a). From a statistical perspective, we can neither extrapolate beyond the population sample nor infer differences among objects smaller than the experimental units. Likewise, in the assessment of landscape structure, we cannot detect pattern beyond the extent of the landscape or below the resolution of the grain (Wiens 1989a).

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. 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. In practice, extent and grain are often dictated by the scale of the imagery being used (for example, aerial photo scale) 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. It would be meaningless, for example, to define grain as 1-hectare units if the organism under consideration perceives and responds to habitat patches at a resolution of 1 square meter. A strong landscape pattern at 1-hectare resolution may have no significance to the organism under study. The reverse is also true; that is, defining grain as 1-square-meter units if the organism under consideration perceives habitat patches at a resolution of 1 hectare. 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 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. Unfortunately, the technical capabilities of GIS for 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 accurately be generated from the data.

Information may be available at several scales, and it may be necessary to extrapolate information from one scale to another. It also may be necessary to integrate data represented at different spatial scales. It is suggested that information can be transferred across scales if both grain and extent are specified (Allen and others 1987), yet it is unclear how observed landscape patterns differ 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 differ 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 and others 1989). Until more is learned, it is critical that attempts to compare landscapes measured at different scales be done cautiously in investigations of landscape structure.

KEY POINT ***The most important considerations in any landscape ecological investigation or landscape structural analysis are (1) to explicitly define the scale of the investigation or analysis, (2) to describe any observed patterns or relations 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 and others 1987). The importance of the landscape context depends on the phenomenon of interest, but typically differs with "openness" of the landscape. The openness depends not only on the phenomenon under consideration but also on the basis used for delineating the landscape boundary. From a geomorphological or hydrological perspective, for example, 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 by 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 (Haila and others 1987; Ricklefs 1987; Vaisanen and others 1986; Wiens 1981, 1989b).

Landscape metrics quantify the structure of the landscape only within the designated landscape boundary. 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. 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 (that is, 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 patch mosaic within the landscape and the landscape context. Consideration always should be given to the landscape context and the openness of the landscape relative to the phenomenon under consideration when choosing and interpreting landscape metrics.***

Landscape structure—Landscapes are distinguished by spatial relations among component parts. A landscape can be characterized by both its composition and configuration (sometimes referred to as landscape physiognomy or landscape pattern) (Dunning and others 1992, Turner 1989), and these two aspects of a landscape can independently or in combination affect ecological processes and organisms. The difference between landscape composition and configuration is analogous to the difference between floristics (for example, the types of plant species present) and vegetation structure (for example, foliage height diversity) so commonly considered in wildlife-habitat studies at the within-patch scale.

Landscape composition refers to features associated with the presence and amount of each patch type within the landscape but without being spatially explicit. In other words, landscape composition encompasses the variety and abundance of patch types within a landscape but not the placement or location of patches within the landscape mosaic. Landscape composition is important to many ecological processes and organisms. For example, many vertebrate species require specific habitat types, and the total amount of suitable habitat (a function of landscape composition) likely influences the occurrence and abundance of these vertebrate species. There have been many attempts to model animal populations within landscapes based on landscape composition alone; such models have been referred to as "island models" by Kareiva (1990). Island models represent the discrete patchwork mosaic of the landscape; the key feature of these models is population subdivision. Yet these models do not specify the relative distances among patches or their positions relative to each other. Thus, although these models provide strong analytical solutions, they may be overly simplified for most natural populations; but we have learned much about population dynamics in spatially complex environments based on models of landscape composition alone (Kareiva 1990).

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 to measure diversity, there are literally hundreds of possible ways to quantify landscape composition. The investigator or manager must choose the formulation best representing their concerns.

Landscape configuration refers to the physical distribution or spatial character of patches within the landscape. Some aspects of configuration, such as patch isolation or patch contagion, are measures of the placement of patch types relative to other patch types, the landscape boundary, or other features of interest. Other aspects of configuration, such as shape and core area, are measures of the spatial character of the patches. Many attempts have been made to explicitly incorporate landscape configuration into models of ecological processes and population dynamics within heterogeneous landscapes; such models have been referred to as “stepping-stone models” by Kareiva (1990). In contrast to island models, stepping-stone models have an explicit spatial dimension and can account for dispersal distances and environmental variability with a spatial structure. Recently, we have seen dramatic increases in the level of sophistication in stepping-stone models, and some results have had profound effects on the design of managed landscapes (for example, Lamberson and others 1992, McKelvey and others 1992).

There are many aspects to landscape configuration with much literature available on methods and indices developed for representing them. Landscape configuration can be quantified by using statistics in terms of the landscape unit itself (that is, the patch). The spatial pattern being represented is the spatial character of the individual patches. The location of patches relative to each other in the landscape (the configuration of patches within the landscape) is not explicitly represented. Landscape metrics quantified in terms of the individual patches (for example, mean patch core area or mean patch shape) are spatially explicit at the level of the individual patch. Such metrics represent a recognition that the ecological properties of a patch are influenced by the surrounding neighborhood (for example, edge effects) and that the magnitude of these influences are affected by patch size and shape. These metrics simply quantify, for the landscape as a whole, the average patch characteristics or some measure of variability in patch characteristics. Although these metrics are not spatially explicit at the landscape level, they have clear ecological relevance when considered from a patch dynamics standpoint (Pickett and White 1985). As an example, a number of bird species are sensitive to patch core area (a function of patch size and shape) because of negative intrusions from the surrounding landscape (for example, Robbins and others 1989, Temple 1986). Quantifying mean patch core area across the landscape could provide a good index to landscape suitability for such species.

Landscape metrics quantified in terms of the spatial relation of patches and matrix comprising the landscape (for example, nearest neighbor, contagion) are spatially explicit at the landscape level because the relative location of individual patches within the landscape is represented in some way. Such metrics represent a recognition that ecological processes and organisms are affected by the interspersion and juxtaposition of patch types within the landscape. For example, the population dynamics of species with limited dispersal ability are likely affected by the distribution of suitable habitat patches. Both the distance between suitable patches and the spatial arrangement of suitable patches can influence population dynamics (Kareiva 1990, Lamberson and others 1992, McKelvey and others 1992). Likewise, patch juxtaposition is especially important to organisms that require two or more habitat types because the close proximity of resources provided by different patch types is critical for their survival and reproduction. Patch juxtaposition also is important for species adversely affected by edges, because the types of patches juxtaposed along an edge will influence the character of that edge.

A number of landscape configuration metrics can be formulated either by individual patches or by the whole landscape, depending on the emphasis sought. For example, fractal dimension is a measure of shape complexity (Burrough 1986, Mandelbrot 1982, Milne 1988) that can be computed for each patch and then averaged for the landscape, or it can be computed from the landscape as a whole (by using the box-count method [Morse and others 1985]). Similarly, core area can be computed for each patch and then represented as mean patch core area for the landscape, or it can be computed simply as total core area in the 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 depends on user preference or the emphasis sought (patch or landscape). The same is true for several other common landscape metrics. Typically, these metrics are spatially explicit at the patch level but not at the landscape level.

Not all landscape metrics can be classified easily as representing landscape composition or landscape configuration. Landscape metrics, such as mean patch size and patch density, are not really spatially explicit at either the patch or landscape level because they do not depend explicitly on the spatial character of the patches or their relative location. Moreover, mean patch size and patch density of a particular patch type reflect both the amount of a patch type present (composition) and its spatial distribution (configuration). Because mean patch size and patch density differ with spatial heterogeneity of the landscape, it often is more appropriate to consider them as indices of landscape configuration. In addition, some landscape metrics clearly represent spatial heterogeneity but are not spatially explicit at all. These metrics differ with the heterogeneity of the landscape but do not depend explicitly on the relative location of patches within the landscape or their individual spatial character. For example, total edge or edge density is a function of the amount of border between patches. For a given edge density there could be 2 patches or 10 patches, they could be clustered or maximally dispersed, or they could be skewed to one side of the landscape or in the middle. It is not important that all metrics be classified by the simple composition versus configuration dichotomy. What is important, however, is that the investigator or manager recognize that landscape structure consists of both composition and configuration and that various metrics have been developed to represent these aspects of landscape structure separately or in combination.

Finally, it is important to understand how measures of landscape structure are influenced by the designation of a matrix element. If an element is designated as matrix and therefore presumed to function as such (that is, 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 (for example, mean patch size or mean patch shape) across all patches. 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 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 depends on how the landscape is defined, including the choice of patch types and the designation of a matrix.

KEY POINT ***The importance of fully understanding each landscape metric before it is used cannot be emphasized enough. Specifically, these questions should be asked of each metric before it is used: Does it represent landscape composition, configuration, or both? What aspect of configuration does it represent? What scale, if any, is spatially explicit? How is it affected by the designation of a matrix element? Based on answers to these questions, does the metric represent landscape structure in a manner ecologically meaningful to the phenomenon under consideration? Only after answering these questions should one attempt to draw conclusions about the structure of the landscape analyzed.***

FRAGSTATS Overview

FRAGSTATS is a spatial pattern analysis program for quantifying landscape structure. The landscape subject to analysis is user defined and can represent any spatial phenomenon. FRAGSTATS quantifies the areal extent and spatial distribution of patches (that is, polygons on a map coverage) within a landscape; the user must establish a sound basis for defining and scaling the landscape (including the extent and grain of the landscape) and the scheme by which patches within the landscape are classified and delineated (we strongly recommend reading the preceding section, “Concepts and Definitions”). The output from FRAGSTATS is meaningful only if the landscape mosaic is meaningful for the phenomenon under consideration.

FRAGSTATS does not limit the scale (extent or grain) of the landscape subject to analysis. But, the distance- and area-based metrics computed in FRAGSTATS are reported in meters and hectares, respectively, and thus landscapes of extreme extent or resolution may result in rather cumbersome numbers and be subject to rounding errors. FRAGSTATS, however, outputs data files in ASCII format that can be manipulated with any database management program to rescale metrics or to convert them to other units (for example, converting hectares to acres).

There are two versions of FRAGSTATS: one accepts Arc/Info polygon coverages (vector), and one accepts a raster image in various formats. The vector version of FRAGSTATS is an Arc/Info AML developed on a SUN workstation running Arc/Info version 6.1; it will not run with earlier versions of Arc/Info. Because of limitations in Arc/Info, the AML calls several C programs developed in a Unix environment and compiled with the GNU C compiler (they may not compile with other compilers). The raster version of FRAGSTATS also was developed on a SUN workstation in the Unix operating environment. It is written in C and also compiled with the GNU C compiler. Both versions of FRAGSTATS respond to command line input or allow the user to answer a series of prompts. Both versions of FRAGSTATS generate the same array of metrics (see table 1), although a few additional metrics (that is, nearest neighbor metrics and contagion) are computed in the raster version, and the format of the output files is exactly the same. The raster version of FRAGSTATS also has been compiled to run in the DOS environment on a personal computer (PC). The directions for running the DOS version on a PC are exactly the same as the Unix version.

It is important to realize that vector and raster images depict edges differently. Vector images portray a line in the form it is digitized. Raster images, however, portray lines in stairstep fashion. Consequently, the measurement of edge length is biased upward in raster images; that is, 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 (cell size), and the consequences of this bias in use and interpretation of edge-based metrics must be weighed relative to the phenomenon under investigation. Because of this bias, the vector and raster versions of FRAGSTATS will not produce identical results for a landscape.

In some investigations, it may be desirable or necessary to create a raster image from the initial vector image and run the raster version of 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. During the rasterization process, it is possible for disjunct patches to join or for a contiguous patch to be subdivided. This problem can be quite severe (for example, resulting in numerous one-cell patches) if the cell size chosen is too large relative to the minimum patch dimension in the vector image.

FRAGSTATS accepts images in several forms, including images that contain *background* and a landscape *border* (figs. 2 and 3). Every image will include a *landscape boundary* that defines the perimeter of the landscape and surrounds the patch mosaic of interest. Every patch within the landscape boundary must have a positive patch type code, whereas every patch outside the landscape boundary (border or background, see below) must have a negative patch type code. An image may include *background* (also referred to as “mask”), an undefined area either interior or exterior to the landscape of interest. Background can exist as “holes” in the landscape, can partially or completely surround the landscape of interest, and can occur on the edge of the designated landscape of interest and span the landscape boundary (that is, be broken into two pieces, one inside the landscape boundary and one outside). The background value can be any nonpatch code; background patches within the landscape boundary must e positive and those outside the landscape boundary must be negative, like all other patch types. The background class is ignored in all metrics but those involving edge. The user specifies how boundary and background edge segments should be handled (see below). An

Table 1—Metrics computed in FRAGSTATS, grouped by subject area[a]

Scale	Acronym	Metric (units)
Area metrics:		
Patch	AREA	Area (ha)
Patch	LSIM	Landscape similarity index (percent)
Class	CA	Class area (ha)
Class	%LAND	Percentage of landscape
Class/landscape	TA	Total landscape area (ha)
Class/landscape	LPI	Largest patch index (percent)
Patch density, patch size and variability metrics:		
Class/landscape	NP	Number of patches
Class/landscape	PD	Patch density (number/100 ha)
Class/landscape	MPS	Mean patch size (ha)
Class/landscape	PSSD	Patch size standard deviation (ha)
Class/landscape	PSCV	Patch size coefficient of variation (percent)
Edge metrics:		
Patch	PERIM	Perimeter (m)
Patch	EDCON	Edge contrast index (percent)
Class/landscape	TE	Total edge (m)
Class/landscape	ED	Edge density (m/ha)
Class/landscape	CWED	Contrast-weighted edge density (m/ha)
Class/landscape	TECI	Total edge contrast index (percent)
Class/landscape	MECI	Mean edge contrast index (percent)
Class/landscape	AWMECI	Area-weighted mean edge contrast index (percent)
Shape metrics:		
Patch	SHAPE	Shape index
Patch	FRACT	Fractal dimension
Class/landscape	LSI	Landscape shape index
Class/landscape	MSI	Mean shape index
Class/landscape	AWMSI	Area-weighted mean shape index
Class/landscape	DLFD	Double log fractal dimension
Class/landscape	MPFD	Mean patch fractal dimension
Class/landscape	AWMPFD	Area-weighted mean patch fractal dimension
Core area metrics:		
Patch	CORE	Core area (ha)
Patch	NCORE	Number of core areas
Patch	CAI	Core area index (percent)
Class	C%LAND	Core area percentage of landscape
Class/landscape	TCA	Total core area (ha)
Class/landscape	NCA	Number of core areas
Class/landscape	CAD	Core area density (number/100 ha)
Class/landscape	MCA1	Mean core area per patch (ha)
Class/landscape	CASD1	Patch core area standard deviation (ha)
Class/landscape	CACV1	Patch core area coefficient of variation (percent)
Class/landscape	MCA2	Mean area per disjunct core (ha)
Class/landscape	CASD2	Disjunct core area standard deviation (ha)
Class/landscape	CACV2	Disjunct core area coefficient of variation (percent)
Class/landscape	TCAI	Total core area index (percent)
Class/landscape	MCAI	Mean core area index (percent)

Table 1—Metrics computed in FRAGSTATS, grouped by subject area[a] (continued)

Scale	Acronym	Metric (units)
Nearest neighbor metrics:		
Patch	NEAR	Nearest neighbor distance (m)
Patch	PROXIM	Proximity index
Class/landscape	MNN	Mean nearest neighbor distance(m)
Class/landscape	NNSD	Nearest neighbor standard deviation (m)
Class/landscape	NNCV	Nearest neighbor coefficient of variation (percent)
Class/landscape	MPI	Mean proximity index
Diversity metrics:		
Landscape	SHDI	Shannon's diversity index
Landscape	SIDI	Simpson's diversity index
Landscape	MSIDI	Modified Simpson's diversity index
Landscape	PR	Patch richness (number)
Landscape	PRD	Patch richness density (number/100 ha)
Landscape	RPR	Relative patch richness (percent)
Landscape	SHEI	Shannon's evenness index
Landscape	SIEI	Simpson's evenness index
Landscape	MSIEI	Modified Simpson's evenness index
Contagion and interspersion metrics:		
Class/landscape	IJI	Interspersion and Juxtaposition index (percent)
Landscape	CONTAG	Contagion index (percent)

[a] See appendix 3 for mathematical definitions of the metrics.

image also may include a *landscape border*—a strip of land surrounding the landscape of interest (that is, 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. If a border patch is a patch type of code 34, then its label must be -34. The border can be any width and provides information on patch type adjacency for patches on the edge of the landscape. It is ignored in all but the edge contrast, interspersion, and contagion metrics.

The convention described above for classifying interior and exterior background patches is often hard to adhere to with raster images. The raster version of FRAGSTATS will accept images in which all background patches have been set to the same patch type code. When reading the image, FRAGSTATS notes if any interior (positive) or exterior (negative) background patches are present. If the landscape contains both positively and negatively classified background patches, FRAGSTATS assumes the user has followed the convention stated above. If only one type of background was found (only interior or only exterior), however, FRAGSTATS will verify that each background patch was classified correctly. If FRAGSTATS finds that an interior background patch was incorrectly classified as exterior background, it will be reclassified as interior background, and a message will be issued. Incorrectly classified exterior background patches also will be reclassified as exterior, if necessary. A warning will be issued if FRAGSTATS finds background patches along the boundary and a border is present. It is impossible to tell whether these patches should be interior or exterior. Be aware that if background patches are not classified correctly, the following indices may not be calculated correctly at the class and landscape level: landscape shape index, total edge, edge density, contrast weighted edge density, and total edge contrast index.

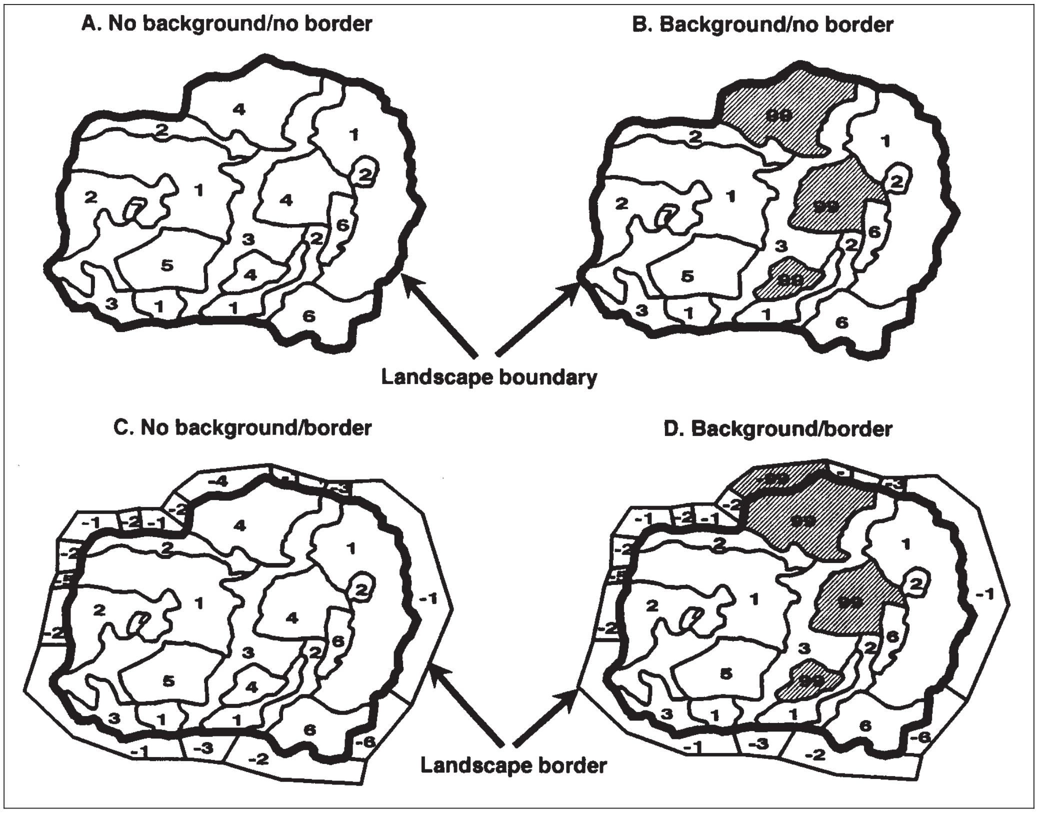


Figure 2—Alternative image formats accepted in the vector version of FRAGSTATS. Landscape boundary, background, and border are defined in the text.

Under most circumstances, it is probably not valid to assume that all edges function the same. Indeed, there is good evidence that edges differ in their effects on ecological processes and organisms depending on the nature of the edge (for example, type of adjacent patches, degree of structural contrast, orientation) (Hansen and di Castri 1992). Accordingly, the user can specify a file containing edge contrast weights for each combination of patch types (classes). 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 (see “Edge Metrics,” below). If this weight file is not provided, these edge contrast metrics are not computed and are reported as “NA” or “**.**” in the output files (see below). Generally, if a landscape border is designated, a weight file will be specified also, because the main reason for specifying a border is when information on edge contrast is deemed important. However, a border is also useful for determining patch type adjacency for the interspersion and contagion indices. Any scheme can be used to establish weights as long as it is meaningful to the phenomenon under investigation.

Regardless of the image format (figs. 2 and 3), the user must specify how the landscape boundary and any edge segments bordering a specified background class should be treated relative to the edge metrics. This has various effects depending on whether a contrast weight file is specified, whether a landscape border is present,

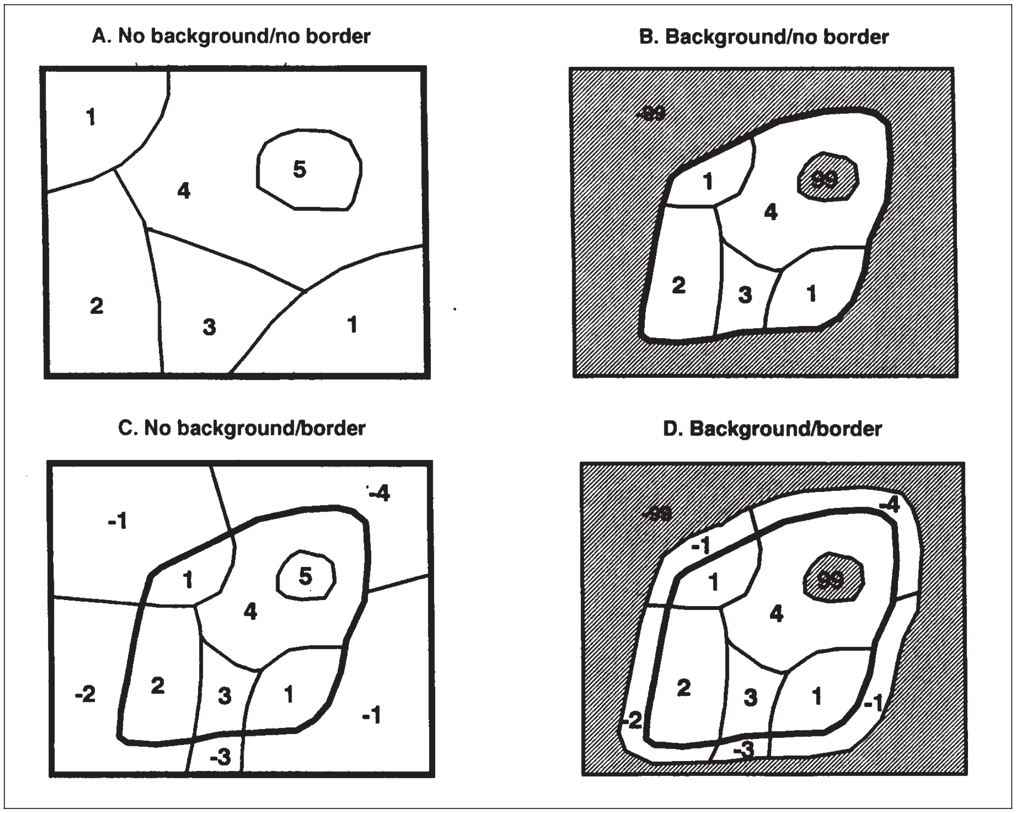
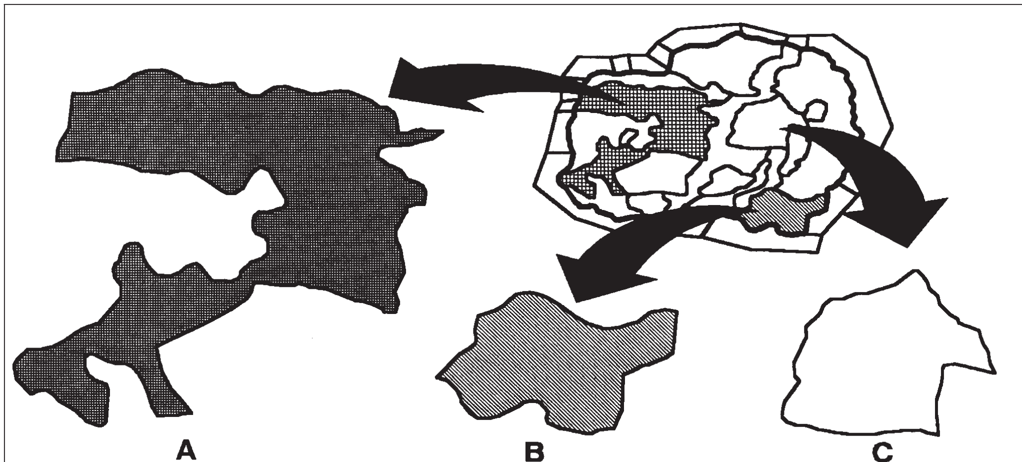


Figure 3—Alternative image formats accepted in the raster version of FRAGSTATS. Landscape boundary, background, and border are defined in the text.

and whether a background class is designated. If a contrast weight file is specified, then all patch edges are evaluated for edge contrast based on the weight file and the edge contrast metrics (see “Edge Metrics,” below) are computed. In this scenario, if a landscape border is present, then edge segments along the landscape boundary are evaluated for edge contrast based on the weight file. Conversely, if a landscape border is absent, then edge segments along the landscape boundary are treated as either maximum-contrast edge (weight = 1), no-contrast edge (weight = 0), or some intermediate, average-contrast edge (weight = user specified), depending on how the user decides to handle boundary and background edge. Regardless of whether a landscape border is present or not, if a background class is specified, then edge segments bordering the background class are treated according to the user-specified edge contrast. In other words, it is possible for a landscape border to be present and still have a background class designated. The background may occur as “holes” in the landscape or along the landscape boundary. In either case, edge segments bordering background are treated according to the decision regarding boundary and background edge. Note, however, that the presence of a landscape border and a background class and the decision on how to treat these edges will have no effect on the edge contrast metrics if a contrast weight file is not specified—because these metrics will not be computed.

Regardless of whether an edge contrast weight file is specified, the presence of a landscape border, the specification of a background class, and the decision regarding how to treat the boundary and background edge will affect metrics based on patch type adjacency as well as those based on edge length. Metrics based on patch type adjacency (for example, interspersion and contagion indices) consider only edge segments with adjacent patch information. Therefore, if a landscape border is present, then edge segments along the border are considered in these calculations. Conversely, if a landscape border is absent, then the entire landscape boundary is ignored in these calculations. Similarly, if a background class is specified, then edge segments bordering background are ignored in these calculations. Metrics based on edge length (for example, total edge or edge density) are affected by these considerations as well. If a landscape border is present, then edge segments along the border are evaluated to determine which segments represent true edge and which do not. Conversely, if a landscape border is absent, then a user-specified proportion of the landscape boundary is treated as true edge and the remainder is ignored. As an example, if the user specifies that 50 percent of the landscape boundary or background should be treated as true edge, then 50 percent of the landscape boundary will be incorporated into the edge length metrics. 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.

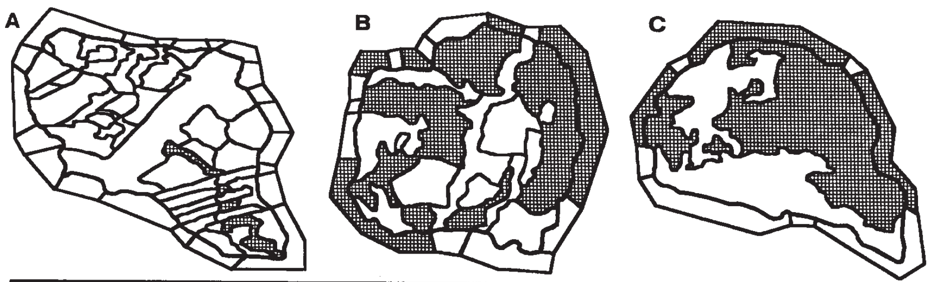
We recommend including a landscape border, especially if edge contrast or patch type adjacency is deemed important. In most cases, some portions of the landscape boundary will constitute true edge (an edge with a contrast weight greater than 0) and others will not, and it will be difficult to estimate the proportion of the landscape boundary representing true edge. It also will be difficult to estimate the average edge contrast weight 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 effects of the decision for treating 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 of 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 on the landscape boundary should be considered carefully. In addition, unless there is a strong ecological reason for designating a background class, we recommend that background not be included because it only complicates the calculation and interpretation of edge-based metrics. Ideally, a landscape should have a border and contain no background.



	A	B	C
LID	NCVEG	NCVEG	NCVEG
PID	104	400	200
TYPE	MLS	COS	MGF
AREA	51.33	16.83	18.59
LSIM	48.80	7.62	8.41
PERIM	6230	1922	1907
EDGECON	16.96	42.02	80.05
SHAPE	2.45	1.32	1.25
FRACT	1.33	1.26	1.25
CORE	8.46	2.35	4.62
NCORE	2	1	1
CAI	16.48	13.94	24.87
NEAR*	25.00	155.08	216.91
PROXIM*	200.34	2.38	0

Figure 4—Example of FRAGSTATS patch indices for three sample patches drawn from a sample landscape. See text and appendix 3 for descriptions and definitions of the metrics. Indices with an asterisk were computed from the raster version of FRAGSTATS.

FRAGSTATS computes three groups of metrics. For a given landscape mosaic, FRAGSTATS computes several statistics for (1) each patch in the mosaic (fig. 4); (2) each patch type (class) in the mosaic (fig. 5); and (3) the landscape mosaic as a whole (fig. 6) (see table 1 for a description of the acronyms for each metric). In the assessment of landscape structure, patch indices serve primarily as the computational basis for several of the landscape metrics; the individual patch indices may have little interpretive value. But sometimes patch indices can be important and informative in landscape-level investigations. Many vertebrates, for example, require suitable habitat patches larger than some minimum size (for example, Robbins and others 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 (for example, 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 (see 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 ultimately will depend on the objectives of the investigation.

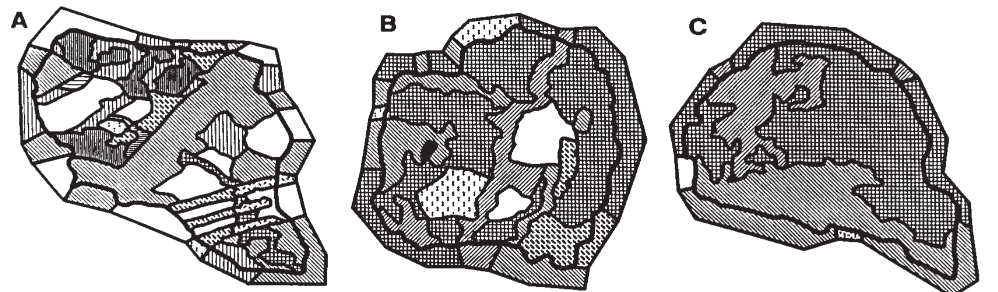


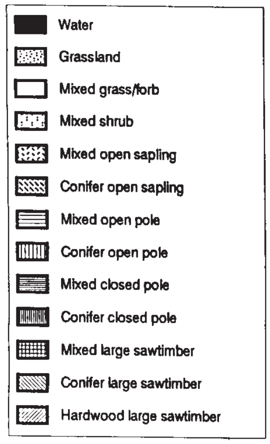
	A	B	C		A	B	C
LID	FNVEG	NCVEG	TCVEG	DLFD	1.52	1.52	1.15
TYPE	MLS	MLS	MLS	MPFD	1.34	1.29	1.31
CA	13.35	144.49	149.65	AWMPFD	1.35	1.29	1.29
TA	284.74	296.07	279.78	C%LAND	0	9.99	22.90
%LAND	4.69	48.80	53.49	TCA	0	29.57	64.08
LPI	2.50	17.34	46.79	NCA	0	7	2
NP	4	5	3	CAD	0	2.36	0.71
PD	1.40	1.69	1.07	MCA1	0	5.91	21.36
MPS	3.34	28.90	49.88	CASD1	0	5.01	29.90
PSSD	2.48	19.94	57.59	CACV1	0	84.77	139.97
PSCV	74.30	69.00	115.45	MCA2	0	4.22	32.04
TE	4137	15198	9192	CASD2	0	5.01	31.60
ED	14.53	51.33	32.86	CACV2	0	118.58	98.62
CWED	5.85	11.37	1.85	TCAI	0	20.47	42.82
TECI	40.27	19.31	4.21	MCAI	0	14.34	17.09
MECI	53.18	21.33	4.83	MNN*	82.28	53.86	67.88
AWMECI	35.98	20.60	3.82	NNSD*	14.54	26.92	2.99
LSI	1.93	3.22	2.62	NNCV*	17.67	49.98	4.41
MSI	1.59	1.70	1.78	MPI*	5.81	288.93	135.83
AWMSI	1.83	1.91	2.02	IJI	47.80	75.67	49.99

Figure 5—Example of FRAGSTATS class indices for the mixed, large sawtimber (MLS) patch type in three sample landscapes. See text and appendix 3 for descriptions and definitions of the metrics. Indices with an asterisk were computed from the raster version of FRAGSTATS.

In many landscape ecological applications, the primary interest is in the amount and distribution of a particular patch type (class). A good example is in the study of forest fragmentation. Forest fragmentation is a landscape-level process in which forest tracts are progressively subdivided into smaller, geometrically more complex (initially but not necessarily ultimately), and more isolated forest fragments as a result of both natural processes and human land use activities (Harris 1984). 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. Forest fragmentation is the prevalent landscape change in several human-dominated forest regions of the world, and is increasingly recognized as a major cause of declining biodiversity (Terborgh 1989, Whitcomb and others 1981). Class indices separately quantify the amount and distribution of each patch type in the landscape and thus can be considered indices of fragmentation for each patch type.

In other landscape ecological applications, the primary interest is in the structure (composition and configuration) of the entire landscape(s). A good example is in the study of landscape diversity. Leopold (1933) noted that wildlife diversity is greater in more diverse landscapes. Thus, the quantification of landscape diversity has assumed





	A	B	C		A	B	C
LID	FNVEG	NCVEG	TCVEG	MCA1	0.64	2.52	19.12
TA	284.74	296.07	279.78	CASD1	3.22	6.93	24.23
LPI	25.08	17.34	46.79	CACV1	500.70	274.89	126.75
NP	43	17	5	MCA2	2.52	3.06	13.65
PD	15.10	5.74	1.79	CASD2	5.99	7.53	22.22
MPS	6.62	17.42	55.96	CACV2	238.10	245.90	162.76
PSSD	10.59	15.05	46.13	TCAI	9.73	14.48	34.16
PSCV	159.96	86.40	82.44	MCAI	2.24	8.47	19.16
TE	26313	19822	10334	MNN*	136.00	155.40	67.90
ED	92.41	66.95	36.94	NNSD*	144.76	90.47	2.99
CWED	37.19	21.17	3.69	NNCV*	106.45	58.23	4.41
TECI	35.31	26.50	6.38	MPI*	12.83	87.14	81.50
MECI	37.57	31.87	5.91	SHDI	1.79	1.50	1.00
AWMECI	40.52	30.28	5.77	SIDI	0.79	0.70	0.60
LSI	5.01	3.88	2.73	MSIDI	1.56	1.22	0.92
MSI	1.47	1.64	2.02	PR	10	7	3
AWMSI	1.60	1.86	2.17	PRD	3.51	2.36	1.07
DLFD	1.26	1.49	1.22	RPR	37.04	25.93	11.11
MPFD	1.31	1.29	1.31	SHEI	0.78	0.77	0.91
AWMPFD	1.29	1.30	1.30	SIEI	0.88	0.82	0.90
TCA	27.69	42.86	95.58	MSIEI	0.68	0.63	0.84
NCA	11	14	7	IJI	74.03	64.71	46.52
CAD	3.86	4.73	2.50	CONTAG*	57.70	58.64	67.00

Figure 6—Example of FRAGSTATS landscape indices for three sample landscapes. See text and appendix 3 for descriptions and definitions of the metrics. Indices with an asterisk were computed from the raster version of FRAGSTATS.

a preeminent role in landscape ecology. A major focus of landscape ecology is on quantifying the relations between landscape structure and ecological processes. Consequently, much emphasis has been placed on developing methods to quantify landscape structure (for example, Li 1990, O'Neill and others 1988, Turner 1990b, Turner and Gardner 1991) and a great variety of landscape structural indices have been developed for this purpose. Many of these published indices have been incorporated into FRAGSTATS, although sometimes in modified form.

By default, FRAGSTATS creates four output files. The user supplies a basename for the output files, and FRAGSTATS appends the extensions .full, .patch, .class, and .land to the basename. All files created are ASCII and viewable. However, only the basename.full file is in a format intended for displaying results. The basename.full file contains all the patch, class, and landscape metrics calculated for an input landscape (see appendix 1 for an example of the basename.full file). The name of each metric is spelled out along with its value and units. This file's main utility is for viewing results; its format is not intended for input to other data management or analysis programs.

The other three files are formatted to facilitate input into database management programs. The basename.patch file contains the patch metrics for a landscape; the file contains one record for each patch in the landscape. Similarly, the basename.class file contains the class metrics; the file contains one record for each class in the landscape. Finally, the basename.land file contains the landscape metrics; the file contains one record for the landscape. The first record in all these files is a header consisting of the acronyms for all the metrics that follow. The user has the option of suppressing the output of the patch or class metrics, or both. If these metrics are suppressed, the corresponding basename ASCII file is not created and the metrics are not included in the basename.full file.

FRAGSTATS Metrics

This section provides a general overview and discussion of the various metrics computed in FRAGSTATS; detailed mathematical definitions and descriptions of each metric, including the units and range in values, are provided in appendix 3. Metrics are grouped in logical fashion by the aspect of landscape structure measured; for example, the core area metrics (those based on core area measurements) computed at the patch, class, and landscape levels are discussed together. For each group, the general applicability of the metrics to landscape ecological investigations and some of their limitations are discussed. In addition, the results presented in figures 4 to 6 are discussed relative to each group of metrics at the end of each section (in reduced font size on a shaded background).

General Considerations

Metrics involving standard deviation employ the population standard deviation formula, not the sample formula, because all patches in the landscape (or class) are included in the calculations. In other words, the landscape is considered a population of patches and every patch is counted; FRAGSTATS does not sample patches from the landscape, it censuses the entire landscape. Even if each landscape represents a sample from a larger region, it is still more appropriate to compute the standard deviation for each landscape by using the population formula. In this case, it is appropriate to use the sample formula when calculating the variation among landscapes by using the FRAGSTATS output for each landscape. The difference between the population and sample formulas is insignificant when sample sizes (number of patches) are large (greater than 20). However, when quantifying landscapes with few patches, the differences can be significant.

FRAGSTATS computes several statistics for each patch and class in the landscape and for the landscape as a whole. At the class and landscape level, some of the metrics quantify landscape composition, and others quantify landscape configuration. As previously discussed, composition and configuration can affect ecological processes independently and interactively. Thus, it is especially important to understand for each metric what aspect of landscape structure 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 structure. In most cases, redundant metrics will be very highly or even perfectly correlated; at the landscape level, *patch density* (PD) and *mean patch size* (MPS), for example, will be perfectly correlated because they represent the same information. These redundant metrics are alternate ways of representing the same information; they are included in FRAGSTATS because the preferred form of representing a particular aspect of landscape structure will differ among applications and users. The user needs to understand these redundancies, because in most applications only one of each set of redundant metrics should be employed. In particular applications, some metrics may be empirically redundant; not because they measure the same aspect of landscape structure, but because for the particular landscapes under investigation, different aspects of landscape structure are statistically correlated. The distinction between this form of redundancy and the former is important, because little can be learned by interpreting inherently redundant metrics, but much can be learned about landscapes by interpreting empirically redundant metrics.

Many of the patch indices have counterparts at the class and landscape levels; for example, many of the class indices (such as, mean shape index) represent the same basic information as the corresponding patch indices (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, the algorithms of course differ slightly (see appendix 3). Class indices represent the spatial distribution and pattern within a landscape of a single patch type; 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 fragmentation of a particular patch type; most of the landscape indices can be interpreted more broadly as landscape heterogeneity indices because they measure the overall landscape structure. Hence, it is important to interpret each index in a manner appropriate to its scale (patch, class, or landscape).

Area Metrics

FRAGSTATS computes several simple statistics representing area at the patch, class, and landscape levels (table 1). Area metrics quantify landscape composition, not landscape configuration. 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. 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. There is considerable evidence, for example, that bird species richness and the occurrence and abundance of some species are strongly correlated with patch size (Robbins and others 1989). 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 relations derived from field studies.

Class area (CA) is a measure of landscape composition; specifically, how much of the landscape is comprised of a particular patch type. This is an important measure in several ecological applications. For example, an important by-product of habitat fragmentation is quantitative habitat loss. In the study of forest fragmentation, it is therefore important to know how much of the target patch type (habitat) exists within the landscape. In addition, although many vertebrate species specializing on a particular habitat have minimum area requirements (Robbins and others 1989), not all species require that the suitable habitat be present in one contiguous patch. Northern spotted owls, for example, have minimum area requirements for late-seral forest that differs geographically; yet, individual spotted owls use late-seral forest that may be distributed among many patches (Forsman and others 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 is used in the computations for many of the class and landscape metrics.

Total landscape area (TA) often does not have a great deal of interpretive value for evaluating landscape structure, but it is important because it defines the extent of the landscape. Total landscape area also is used in the computations for many of the class and landscape metrics. Total landscape area is included as both a class and landscape index (and included in the corresponding output files) because it is important regardless of whether the primary interest is in class or landscape indices.

These metrics quantify area in absolute terms (hectares), but it often is desirable to quantify area in relative terms as a percentage of total landscape area. Therefore, at the class level, FRAGSTATS computes the *percentage of landscape* (%LAND) occupied by each patch type. At the patch level, the *landscape similarity index* (LSIM) equals the percentage of the landscape occupied by the same patch type as the patch (and is equivalent to %LAND). It is included as a patch characteristic because some ecological properties of a patch can be influenced by the abundance of similar patches in the surrounding landscape. For example, island biogeographic theory predicts that the probability of patch occupancy for some species or species richness is a function of both patch size and isolation (MacArthur and Wilson 1967). One aspect of isolation is the amount of similar habitat within a specified distance. Thus, the dynamics of a local population contained within a patch are likely to be influenced by the size of the metapopulation occupying the entire landscape. Indeed, there is some evidence that regional habitat availability has a strong influence on local bird populations at the patch level (Askins and Philbrick 1987). Finally, FRAGSTATS computes a *largest patch index* (LPI) at the class and landscape levels that quantifies the percentage of total landscape area comprised by the largest patch.

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 pattern. Otherwise, these area metrics have few limitations.

Patch-level example—Figure 4 depicts three patches extracted from a sample landscape that differ in size and landscape similarity. Roughly 50 percent of the landscape is similar to patch A (LSIM) and thus comprised of mixed, large sawtimber (MLS). In contrast, patches B and C represent relatively rare patch types, because only 8 percent of the landscape is comprised of these patch types. Thus, patch A is less insular than patches B and C. The dynamics of some ecological processes are likely to be different among patches A, B, and C. An organism inhabiting patch A and dependent on mixed, large sawtimber is likely to experience a different population dynamic than a similar organism occupying either patch B or C because of the larger regional population size and probable increased interaction among individuals inhabiting the landscape. On the other hand, because of their rarity, patches B and C probably would contribute more to faunal species richness than would patch A.

Class-level example—Figure 5 depicts three sample landscapes that differ in the amount and pattern of mixed, large sawtimber habitat. According to *class area* (CA), landscapes B and C have more than 10 times as much mixed, large sawtimber as landscape A. Roughly 50 percent of landscapes B and C are mixed, large sawtimber, in contrast to only 5 percent of landscape A, according to the *percentage of landscape* (%LAND) measure. Thus, the dynamics of some ecological processes are likely to be quite different in landscape A than in either B or C. Populations of organisms associated with mixed, large sawtimber habitat, for example, are likely to be much smaller in landscape A and perhaps subject to a higher probability of local extinction than in either B or C. On the other hand, the mixed, large sawtimber habitat in landscape A probably contributes proportionately more to landscape diversity and species richness than in either B or C.

In addition, although *class area* and *percentage of landscape* indicate that landscapes B and C are similar in composition with respect to mixed, large sawtimber habitat, other indices suggest that they differ greatly in configuration. For example, the *largest patch index* (LPI) represents the three landscapes along a continuum from most to least fragmented and clearly distinguishes between landscapes B and C in terms of landscape configuration. The largest patch in landscape B comprises only 17 percent of the landscape, whereas in landscape C it comprises 47 percent of the landscape. Thus, although mixed, large sawtimber is equally abundant in both landscapes, the *largest patch index* indicates that it is fragmented into smaller patches in landscape B than in landscape C.

Landscape-level example—Figure 6 depicts three sample landscapes that differ in composition and pattern. The *largest patch index* (LPI) indicates that almost half of landscape C, the least heterogeneous landscape, is comprised of a single patch. However, the largest patch in landscape A comprises much more of the landscape than the largest patch in landscape B, even though landscape A is considerably more heterogeneous than B. If a single large patch comprising more than 25 percent is important for the presence of a particular species, then landscape A could include suitable habitat but landscape B would not. This illustrates both the potential usefulness of this index in particular applications and the limitations of this index as a measure of overall heterogeneity.

Patch Density, Size, and Variability Metrics

FRAGSTATS computes several simple statistics representing the number or density of patches, the average size of patches, and the variation in patch size at the class and landscape levels (table 1). These metrics usually are best considered as representing landscape configuration, even though they are not spatially explicit measures. *Number of patches* (NP) of a particular habitat type may affect a variety of ecological processes, depending on the landscape context; for example, the number 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 of patches also can alter the stability of species interactions and opportunities for coexistence in both predator-prey and competitive systems (Kareiva 1990). In addition, habitat subdivision, as indexed by the number of patches, may affect the propagation of disturbances across a landscape (Franklin and Forman 1987). Specifically, a highly subdivided patch type may be more resistent to the propagation of some disturbances (for example, disease, fire), and thus more likely to persist in a landscape than a patch type that is contiguous. Conversely, habitat fragments may suffer higher rates of disturbance for some disturbance types (for example, windthrow) than do contiguous habitats. The number of patches in a landscape mosaic (pooled across patch types) can have the same ecological applicability but more often serves as an index of spatial heterogeneity of the entire landscape mosaic. A landscape with more patches has a finer grain; that is, the spatial heterogeneity occurs at a finer resolution. Although the number of patches in a class or landscape may be fundamentally important to various ecological processes, often it does not have any 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 it could be a useful index to interpret. Number of patches is probably most valuable, however, as the basis for computing other, more interpretable metrics.

Patch density (PD) is a limited, fundamental aspect of landscape structure. Patch density has the same basic utility as an index as does the number of patches, except that the former expresses number of patches by per unit area, which facilitates comparisons among landscapes of various sizes. Of course, if total landscape area is held constant, then patch density and number of patches convey the same information. If numbers of patches, not their area or distribution, is particularly meaningful, then patch density for a particular patch type could serve as a good fragmentation index. If class area is held constant, then a landscape with a greater density of patches of a target patch type would be considered more fragmented than a landscape with a lower density of patches of that patch type. Similarly, the density of patches in the entire landscape mosaic could serve as a good heterogeneity index because a landscape with greater patch density would have more spatial heterogeneity.

Another class and landscape index based on the number of patches is *mean patch size* (MPS). As discussed previously, the area of each patch comprising a landscape mosaic is perhaps the single most important and useful piece of information contained in the landscape. The area comprised by each patch type (class) is equally important;

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.

Like patch area, the range in mean patch size is ultimately constrained by the grain and extent of the image and minimum patch size; relations cannot be detected beyond these lower and upper limits of resolution. Mean patch size at the class level is a function of the number of patches in the class and total class area. In contrast, patch density is a function of total landscape area. Therefore, at the class level, these two indices represent slightly different aspects of class structure. For example, two landscapes could have the same number and size distribution of patches for a given class and thus have the same mean patch size; yet, if total landscape area differed, patch density could be very different between the landscapes. Or two landscapes could have the same number of patches and total landscape area and thus have the same patch density; yet, if class area differed, mean patch size could be very different between landscapes. These differences should be kept in mind when class metrics are selected for a particular application. In addition, 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 hectares 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 hectares could represent a class with five 10-hectare patches or a class with 2-, 3-, 5-, 10-, and 30-hectare 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 functions of number of patches and total landscape area. In contrast to the class level, these indices are completely redundant. Although both indices may be useful for “describing” one or more landscapes, they would never be used simultaneously in a statistical analysis of landscape structure. Including both of these indices in a discriminant analysis, for example, would cause a singularity in the correlation matrix and inhibit the eigenanalysis.

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 not captured by mean patch size and other first-order statistics. Consider two 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 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 two of the simplest measures of variability—standard deviation and coefficient of variation.

Patch size standard deviation (PSSD) is a measure of absolute variation; it is a function of the mean patch size and the difference in 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 depends on mean patch size. Two landscapes may have the same patch size standard deviation; for example, 10 hectares. Yet, one landscape may have a mean patch size of 10 hectares, while the other may have a mean patch size of 100 hectares. In this case, the interpretations of landscape structure would be very different, even though absolute variation is the same. Specifically, the former landscape has greatly differing and smaller patch sizes, and the latter has more uniformly sized, larger patches. For this reason, *patch size coefficient of variation* (PSCV) is generally preferable to standard deviation for comparing variability among landscapes. Patch size coefficient of variation measures relative variability about the mean (that is, 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. Patch size coefficient of variation nevertheless can be misleading regarding landscape structure in the absence of information on the number of patches or patch density and other structural characteristics. Two landscapes may have the same PSCV, but one landscape may have 100 patches with a mean patch size of 10 hectares, while the other may have 10 patches with a mean patch size of 100 hectares. In such a case, the interpretations of landscape structure could be very different, even though the coefficient of variation is the same. The choice of standard deviation or coefficient of variation ultimately will depend on whether absolute or relative variation is more meaningful in a particular application. Because these measures are not wholly redundant, interpreting both may be appropriate 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 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 two different conditions: (1) when there is only one patch in the landscape, and (2) when there is more than one 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.

Class-level example—Figure 5 depicts three sample landscapes that differ in the amount and pattern of mixed, large sawtimber habitat. Because *total landscape area* (TA) is similar among the landscapes, *number of patches* (NP) and *patch density* (PD) convey the same information. Although the three landscapes differ considerably in amount and distribution of mixed, large sawtimber, neither *number of patches* nor *patch density* capture these landscape structural differences very well. For example, landscapes A and B differ dramatically in amounts of this patch type yet have about the same number and density of patches. The number and density of patches do indicate, however, that the mixed, large sawtimber is more subdivided in landscape B than in landscape C, and because *class area* (CA) is similar among landscapes, landscape B can be considered more fragmented than landscape C.

In contrast to the previous indices, *mean patch size* (MPS) does a good job of ranking the three landscapes with respect to mixed, large sawtimber fragmentation (A being most fragmented, C least). *Mean patch size* is most informative, however, when interpreted in conjunction with *class area*, *patch density*, and patch size variability. *Patch size standard deviation* (PSSD) measures absolute variation in patch size and is affected by the average patch size. *Patch size standard deviation* in landscape A is several times smaller than in landscape B, thereby reflecting the smaller patch sizes in landscape A. But according to *patch size coefficient of variation* (PSCV), these two landscapes have similar variability in patch sizes relative to their respective mean patch sizes (standard deviation roughly equivalent to the mean in both landscapes). The greater *patch size coefficient of variation* in landscape C compared to the other landscapes indicates a much larger relative variation in patch size.

According to these area metrics, landscape A contains several small and similar-sized, mixed, large sawtimber patches. Landscape B also contains several similar-sized, mixed, large sawtimber patches, but the patches are much larger. Thus, the mixed, large sawtimber in landscapes A and B is fragmented to a similar degree, but landscape A has lost more of this habitat than has landscape B. Overall, landscape A is much farther along in the fragmentation process than landscape B. Similarly, landscapes B and C contain the same amount of mixed, large sawtimber, but the habitat is fragmented into a greater number of smaller fragments in landscape B because of past timber management activities. Thus, the mixed, large sawtimber habitat is more fragmented in landscape B than in landscape C, although they have both undergone the same degree of habitat loss. Finally, landscapes A and B have been subject to more human disturbance in the form of timber management activities than has landscape C. Differences in patch size variability suggest that the human-altered landscapes contain more uniformity in patch size than the unaltered landscape.

<u>Landscape-level example</u>—Figure 6 depicts three sample landscapes that differ in composition and pattern. Because *total landscape area* (TA) is similar among the landscapes, *number of patches* (NP), *patch density* (PD), and *mean patch size* (MPS) all convey the same information. All three metrics do a good job of representing the strong landscape diversity or heterogeneity gradient among landscapes. Although these metrics indicate that the habitat patterns in landscape A are much finer grained than those in B and C, they do not indicate anything about the number of different patch types present or their relative abundance and spatial distribution. Thus, these metrics are more meaningful when considered in conjunction with other indices.

According to *patch size standard deviation* (PSSD), patch size in landscape A is much less variable than in landscape C in absolute terms. Sixty-five percent of the patches in landscape A are within 20 hectares in size (± 1 standard deviation); whereas 65 percent of the patches in landscape C are within 100 hectares in size. Based on standard deviation, the variation in patch size therefore is much greater in landscape C than in landscape A. However, according to *patch size coefficient of variation* (PSCV), relative to mean patch size, the patches in landscape A are actually much more variable in size than those in landscape C. Depending on whether you view variation in absolute (PSSD) or relative (PSCV) terms, you can reach very different conclusions regarding these landscapes. The choice between measures will depend on the application, but in most cases coefficient of variation is more meaningful.

Edge Metrics

FRAGSTATS computes several statistics representing the amount of edge or degree of edge contrast at the patch, class, and landscape levels (table 1). Edge metrics usually are best considered as representing landscape configuration, even though they are not spatially explicit at all. Total 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 relations (Logan and others 1985; Morgan and Gates 1982; Strelke and Dickson 1980; Thomas and others 1978, 1979). 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 (Chen and Franklin 1990, Gratkowski 1956, Ranney and others 1981). These changes, combined with changes in seed dispersal and herbivory, can influence vegetation composition and structure (Ranney and others 1981). The proportion of a forest patch affected in this manner depends, therefore, on patch shape and orientation and on 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.

Early wildlife management efforts 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). This concept of edge as a positive influence has guided land management practices until recently. Recent studies have suggested, though, that changes in vegetation, invertebrate populations, predation, brood parasitism, and competition along forest edges has resulted in the population declines of several vertebrate species dependent upon forest interior conditions (Brittingham and Temple 1983, Kroodsma 1982, Noss 1988, Robbins and others 1989, Strelke and Dickson 1980, Temple 1986, Wilcove 1985, Yahner and Scott 1988). 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. Most of the adverse effects of forest fragmentation on organisms seem to be either directly or indirectly related to edge effects. 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.

At the patch level, edge is a function of patch *perimeter* (PERIM). The edge effect on a patch can be indexed by using the perimeter-to-area ratio employed in the shape indices discussed below. At the class and landscape levels, edge can be quantified in other ways. *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 involving comparisons of landscapes of different sizes, this index may not be useful. *Edge density* (ED) standardizes edge to a per unit area basis that facilitates comparisons among landscapes of various sizes. In comparisons of landscapes of identical size, total edge and edge density are completely redundant.

These edge indices are affected by the resolution of the image. Generally, the finer the resolution (the greater the detail with which edges are delineated), the greater the edge length. At coarse resolutions, edges may appear as relatively straight lines; 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, vector and raster images portray lines differently. 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 for the use and interpretation of these indices must be weighed relative to the phenomenon under investigation.

The contrast between a patch and its neighborhood can influence a number of important ecological processes (Forman and Godron 1986). The edge effects described previously are influenced by the degree of contrast between patches. Microclimatic changes (for example, wind, light intensity and quality) likely will extend farther into a patch along an edge with high structural contrast than along an edge with low structural contrast (Ranney and others 1981). Similarly, the adverse effects of brown-headed cowbird (*Molothrus ater*) nest parasitism on some forest-dwelling neotropical migratory bird species are likely to be greatest along high-contrast forest edges (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). Because of edge effects, the interface between some patch types can have sufficiently distinctive characteristics to be considered a separate type of habitat (Reese and Ratti 1988).

Patch insularity is a function of many things, including distance between the patch and its nearest neighbor, age of the patch or its duration of isolation, connectivity of the patch with neighbors (for example, through corridors), and the character of the intervening landscape. The permeability of a landscape for some organisms may depend on the character of the intervening landscape. The degree of contrast between the focal 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 and others 1992), depends 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 (Hansen and di Castri 1992, Wiens and others 1985). High-contrast edges may prohibit or inhibit some organisms from seeking supplementary resources in surrounding patches. Conversely, some species (for example, great horned owl, *Bubo virginianus*) seem to prefer the juxtaposition of patch types with high contrast, as in the process of landscape complementation (Dunning and others 1992).

Clearly, edge contrast can assume various meanings for different ecological processes. Contrast therefore can be defined in several ways, but it always reflects the magnitude of difference between patches for one or more ecological attributes at a given scale that are important to the phenomenon under investigation (Kotliar and Wiens 1990, Wiens and others 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 probably is 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 probably is better than assuming all edges are alike. From an avian habitat-use standpoint, for example, we might weight edges somewhat subjectively by 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 (Logan and others 1985; Thomas and others 1978, 1979).

FRAGSTATS computes several indices based on edge contrast at the patch, class, and landscape levels (table 1). At the patch level, the *edge contrast index* (EDGECON) 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. Total patch perimeter is reduced proportionate to the degree of contrast in the perimeter and reported as a percentage of the total perimeter. A patch with a 10-percent edge contrast index has very little contrast with its neighborhood; it has the equivalent of 10 percent of its perimeter in maximum-contrast edge. A patch with a 90-percent edge contrast index has high contrast with its neighborhood. 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. This index ignores patch distinctions; it quantifies edge contrast for the landscape as a whole, thereby focusing on the landscape condition, not the average patch condition, as does the *mean edge contrast index* (MECI). This latter index quantifies the average edge contrast for patches of a particular patch type (class level) or for all patches in the landscape. FRAGSTATS also computes an *area-weighted mean edge contrast index* (AWMECI) by weighting patches according to their size. Larger patches are weighted more heavily than smaller patches in calculating the average patch edge contrast for the class or landscape. This area-weighted index may be more appropriate than the unweighted mean index in cases where larger patches play a dominant role in the landscape dynamics relative to the phenomenon under consideration. In such cases, it may make sense to weight larger patches more heavily when characterizing landscape structure. Otherwise, small patches will have an equal effect on the average edge contrast index, when in fact they play a disproportionately small role in the overall landscape function.

These edge contrast indices are relative measures. Given any amount or density of edge, they measure the degree of contrast in that edge. For this reason, these indices are probably best interpreted in conjunction with total edge or edge density.

High values of these indices mean that the edge present, regardless of whether it is 10 meters or 1000 meters, is of high contrast, and vice versa. Note that these indices consider landscape boundary segments even if they have a contrast of zero (the patch extends beyond the landscape boundary). These zero-contrast boundary segments are included in the calculation of these indices because we believe that boundary segments should be treated equal to internal edge segments in determining the degree of contrast in the patch, class, or landscape. Similarly, background edges are included in the calculation of these indices as well. Therefore, if a landscape border is absent, the choice of how to treat the landscape boundary and background edge (that is, user-specified average edge contrast) could have significant effects on these indices, depending on the size and heterogeneity of the landscape. If a landscape border is present, this decision can still have significant effects on these indices if there is a large amount of background edge.

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 different sizes. Unlike edge density, however, this index reduces the length of each edge segment proportionate to the degree of contrast. Thus, 100 meters per hectare of maximum-contrast edge (weight = 1) is unaffected; but 100 meters per hectare of edge with a contrast weight of 0.2 is reduced by 80 percent to 20 meters per hectare of contrast-weighted edge. This index measures the equivalent maximum-contrast edge density. 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 the equivalent of 80 meters of maximum-contrast edge per hectare exist in the landscape. A landscape with 100 meters per hectare 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 meters per hectare 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.

Edge contrast indices are limited by the considerations discussed above for metrics based on total edge length. These indices are calculated and reported in the output files only if an edge contrast weight file is specified. The usefulness of these indices is directly related to the meaningfulness of the weighting scheme used to quantify edge contrast. 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.

Patch-level example—Figure 4 depicts three patches extracted from a sample landscape that differ in edge contrast. According to the *edge contrast index* (EDGECON), patch A has the least contrast with its neighborhood, where contrast represents the degree of difference in floristic and vegetation structure among patches. This is because patch A is a mixed, large sawtimber patch surrounded mainly by conifer and hardwood, large sawtimber patches. Thus, the differences in vegetation composition and structure along the patch perimeter are relatively subtle; moreover, the ecotones between patch A and these other large sawtimber patches are probably gradual. Consequently, although there are important differences between these adjacent patches that warrant their discrimination, the contrast between them is very low. An animal dispersing from patch A, for example, might not be impeded at all by the low-contrast boundary of patch A. In contrast, patch C is a mixed grass and forb (MGF) patch surrounded mostly by large sawtimber patches. Hence, the degree of structural contrast between patch C and its neighborhood is very high. The *edge contrast index* indicates that the perimeter of patch C has the equivalent of 80 percent of its perimeter in maximum-contrast edge, whereas the perimeter of patch A has the equivalent of only 17 percent of its perimeter in maximum-contrast edge. The *edge contrast index* seems to do a good job of quantifying differences in insularity among these patches.

Class-level example—Figure 5 depicts three sample landscapes that differ in the amount and pattern of mixed, large sawtimber habitat. Because these landscapes are similar in size, *total edge* (TE) and *edge density* (ED) are largely redundant. Both indices are highest for landscape B and lowest for landscape A. Depending on the application, the interpretation of these differences may change. The process of habitat fragmentation, for example, involves both habitat loss and changes in habitat pattern. Over the course of fragmentation, the proportion of the landscape composed of the target habitat type would go from 100 percent to 0 percent. The total amount of class edge would be expected to peak when roughly 50 percent of the landscape is comprised of this habitat type, depending on the pattern of habitat loss (Franklin and Forman 1987). Thus, from a fragmentation perspective, *total edge* and *edge density* are best interpreted in conjunction with the percent of landscape index. In this case, although landscapes B and C have undergone the same amount of mixed, large sawtimber loss (that is, have similar %LAND values), *total edge* and *edge density* indicate that this habitat in landscape B is more highly fragmented than in landscape C. Alternatively, consider a species that requires mixed, large sawtimber edge habitat. *Total edge* or *edge density* might be used to model habitat suitability. In this case, landscape A would be least suitable and landscape B most suitable.

If edge contrast is deemed important, then the edge contrast indices may lead to a slightly different interpretation of the mixed, large sawtimber habitat context in these landscapes. *Contrast-weighted edge density* (CWED) indicates that although landscape C has roughly 33 meters of mixed, large sawtimber edge per hectare, it has the equivalent of less than 2 meters of maximum-contrast edge per hectare. Thus, mixed, large sawtimber habitat in landscape C is not very insular; it is surrounded by patches similar in structure, and any edge effects on this habitat (or organisms inhabiting it) are likely to be relatively weak. *Contrast-weighted edge density* indicates that landscape C has the least equivalent maximum-contrast edge density. This differs from the results of *total edge* and *edge density*, which both indicate that landscape A has the least edge. If the contrast-weighting scheme used here is particularly meaningful, then *contrast-weighted edge density* may be a more insightful index of edge effects than either *total edge* or *edge density*.

Edge contrast also can be measured in relative terms by using the *total edge contrast index* (TECI), *mean edge contrast index* (MECI), and *area-weighted mean edge contrast index* (AWMECI). These three indices are largely redundant in the sample landscapes and therefore lead to the same conclusions. The *total edge contrast index* indicates that the mixed, large sawtimber edge present in landscape C has very low contrast; specifically, every 100 meters of edge has a maximum-contrast equivalent of only 4 meters. In contrast, the mixed, large sawtimber edge in landscape A has much higher contrast; every 100 meters of edge has a maximum-contrast equivalent of 40 meters. Although landscape A has the lowest *total edge* and *edge density*, all three relative contrast indices indicate that its edge contrast is the greatest. Similarly, although landscape B has the greatest amount of mixed, large sawtimber edge, the contrast is moderate relative to landscapes A and C.

Landscape-level example—Figure 6 depicts three sample landscapes that differ in composition and pattern. Because these landscapes are similar in size, *total edge* (TE) and *edge density* (ED) are largely redundant. Both indices are highest for landscape A and lowest for landscape C, corresponding to the overall magnitude of spatial heterogeneity in these landscapes. Conclusions regarding the overall ranking of landscapes based on *contrast-weighted edge density* (CWED) are similar; although, it is apparent that landscape C contains low-contrast edges amounting to an equivalent of only 3.7 meters per hectare of maximum-contrast edge. Landscape B has roughly twice as much total edge as landscape C, but roughly 6 times more equivalent maximum-contrast edge. Likewise, the conclusions based on the *total edge contrast index* (TECI), *mean edge contrast index* (MECI), and *area-weighted mean edge contrast index* (AWMECI) are similar, although edge contrast is reported in relative terms.

Shape Metrics

FRAGSTATS computes several statistics that quantify landscape configuration by complexity of patch shape at the patch, class, and landscape levels (table 1). The interaction of patch shape and size can influence a number of important ecological processes. Patch shape has been shown to influence interpatch 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 edge metrics).

Shape is a difficult parameter to quantify concisely in a metric. FRAGSTATS computes two types of shape indices; both are based on perimeter-area relations. 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 (for example, wildlife clearings). This *shape index* (SHAPE) measures the complexity of patch shape compared to a standard shape. In the vector version of FRAGSTATS, patch shape is evaluated with a circular standard; shape index is minimum for circular patches and increases as patches become increasingly noncircular. Similarly, in the raster version of FRAGSTATS, patch shape is evaluated with a square standard. Although there are other means of quantifying patch shape (Lee and Sallee 1970), this shape index is widely applicable and used in landscape ecological research (Forman and Godron 1986). This shape index can be applied at the class and landscape levels as well. *Mean shape index* (MSI) measures the average patch shape, or the average perimeter-to-area ratio, for a particular patch type (class) or for all patches in the landscape. FRAGSTATS also computes an *area-weighted mean shape index* (AWMSI) of patches at the class and landscape levels by weighting patches according to their size. Specifically, larger patches are weighted more heavily than smaller patches in calculating the average patch shape for the class or landscape. This index may be more appropriate than the unweighted mean shape index in cases where larger patches play a dominant role in the landscape function relative to the phenomenon under consideration. The difference between the unweighted and weighted mean shape indices can be particularly noticeable when sample sizes are small (only a few patches).

An alternative to these patch shape indices based on the "average" patch characteristics at the class and landscape levels is the *landscape shape index* (LSI). This 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. This index quantifies the amount of edge present in a landscape relative to what would be present in a landscape of the same size but with a simple geometric shape (circle in vector, square in raster) and no internal edge (landscapes comprised of a single circular or square patch). Landscape shape index is identical to the shape index at the patch level (SHAPE), except that the former treats the entire landscape as if it were one patch and any patch edges (or class edges) as though they belong to the perimeter. The landscape boundary must be included as edge in the calculation to use a circle or square standard for comparison. Unfortunately, this may not be meaningful in cases where the landscape boundary does not represent true edge 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, probably would be more meaningful. If the landscape boundary represents true edge or the shape of the landscape is particularly important, then the landscape shape index can be a useful index, especially when comparing a range of landscape sizes.

These shape indices have important limitations. First, vector and raster images use different shapes as standards. Thus, the absolute value of these indices differs between vector and raster images. The implications of this difference should be considered relative to the phenomenon under investigation. Second, these shape indices are limited in the same manner as the edge indices discussed above in the differences between how lines are portrayed in vector and raster images. Perimeter length will be biased upward in raster images because of the stair-stepping pattern of line segments, and the magnitude of this bias will differ in relation to the grain or resolution of the image. Third, as an index of shape, the perimeter-to-area ratio method is relatively insensitive to differences in patch morphology. Thus, although patches may possess quite different shapes, they may have identical areas and perimeters and shape indexes. For this reason, these shape indices are not useful as measures of patch morphology; they are best considered as measures of overall shape complexity. Finally, the mean shape index and area-weighted mean shape index are subject to the limitations of first-order statistics (for example, the average patch shape for a class or the landscape may not be very meaningful if the distribution of patch shapes is complex).

The other basic type of shape index computed by FRAGSTATS is the fractal dimension. In landscape ecological research, patch shapes are frequently characterized via the fractal dimension (Iverson 1989, Krummel and others 1987, Milne 1988, Ripple and others 1991, Turner and Ruscher 1988). 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 $P \approx \sqrt{A}^{D}$ (that is, $\log P \approx 1/2D \log A$). For simple

Euclidean shapes (circles, rectangles, and so forth), P ≈ $\sqrt{A}$ and D = 1 (the dimension of a line). As the polygons become more complex, the perimeter becomes increasingly plane filling and P ≈ A with D → 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* (FRACT) of each patch separately. The value of the fractal dimension calculated in this manner depends on patch size or the units used, or both (Rogers 1993). Caution therefore 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 by 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 using this perimeter-area method is equal to 2 divided by the slope; D is neither equal to the slope (Krummel and others 1987) nor to 2 times the slope (Gustafson and Parker 1992, O'Neill and others 1988), as reported by some authors. We refer to this index as the *double log fractal dimension* (DLFD) 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 (n is greater than 20). If insufficient data are available, an alternative to the regression approach is to calculate the *mean patch fractal dimension* (MPFD) based on the fractal dimension of each patch. FRAGSTATS also computes an *area-weighted mean patch fractal dimension* (AWMPFD) at the class and landscape levels by weighting patches according to their size, similar to the area-weighted mean shape index. These latter two indices may be particularly meaningful if the focus of the analysis is on patch characteristics; that is, when patch-level phenomena are deemed most important and patch shape is particularly meaningful.

Because the method used to calculate these fractal indices involves perimeter-area calculations, these fractal indices are subject to some of the same limitations as the shape indices discussed above. Perhaps the greatest limitation of the fractal indices is the difficulty in conceptualizing fractal dimension. Even though fractal dimension is increasingly being used in landscape ecological research, it remains an abstract concept to many and may easily be used inappropriately.

Patch-level example—Figure 4 depicts three patches extracted from a sample landscape and differing in shape. In particular, patch A has a much more complex shape than either patch B or C. Accordingly, the *shape index* (SHAPE) for patch A is almost twice as large as that for the other two patches. The *fractal dimension* (FRACT) results are consistent with the *shape index*; however, the magnitude of differences among patches in *fractal dimension* is notably less than *shape index* values. In addition, the subtle difference in shape complexity between patch B and C is reflected in a rather small difference in their shape indices. Overall, these shape indices do a good job of quantifying obvious differences in shape complexity among these patches, but *fractal dimension* appears to be less sensitive to differences than is the *shape index*.

Class-level example—Figure 5 depicts three sample landscapes that differ in the amount and pattern of mixed, large sawtimber habitat. In this case, the landscape boundary does not all represent mixed, large sawtimber edge. Therefore, the *landscape shape index* (LSI) is not particularly meaningful because it treats the entire landscape boundary as edge. The *mean shape index* (MSI) values for all three landscapes are greater than 1, indicating that the average patch shape in all three landscapes is noncircular. The mixed, large sawtimber patches in landscape A (most fragmented) are least irregular in shape, whereas the patches in landscape C (least fragmented) are most irregular. The *area-weighted mean shape index* (AWMSI) supports these conclusions. In addition, the area-weighted values for all three landscapes are greater than the unweighted values, indicating that the larger patches in each landscape are more irregular in shape than the average. These results indicate that human-induced fragmentation in landscapes A and B caused a simplification in patch shapes compared to the geometrically complex patch shapes found in the natural, unaltered landscape (C).

Because of the small sample sizes, *double log fractal dimension* (DLFD) is probably not a reliable index for these three landscapes. *Mean patch fractal dimension* (MPFD) values do agree in rank order with *mean shape index* values. According to the latter index, landscape A contains the simplest average patch shape, but according to *mean patch fractal dimension*, the opposite is true. The reason for the discrepancy between these indices is not clear; however, the *mean shape index* is more consistent with the results of other indices and therefore is probably more reliable in this case.

Landscape-level example—Figure 6 depicts three sample landscapes that differ in composition and pattern. In this case, even though the landscape boundary does not represent totally true edge, the *landscape shape index* (LSI) still ranks the landscapes along an intuitive gradient from least to most heterogeneous. The *mean shape index* (MSI) values for all three landscapes are greater than 1, indicating that the average patch shape in all three landscapes is noncircular. The patches in landscape A are least irregular in shape, whereas the patches in landscape C are most irregular in shape. The *area-weighted mean shape index* (AWMSI) supports these conclusions. In addition, the area-weighted values for all three landscapes are greater than the unweighted values, indicating that the larger patches in each landscape are more irregular in shape than the average. These results reflect the simple shapes of management units in landscape A compared to the natural shapes of patches in the undisturbed landscape C.

Because of the small sample size in landscape C, *double log fractal dimension* (DLFD) is probably not a reliable index for this landscape. The index compares nicely, however, with the *mean shape index* and *area-weighted mean shape index* for landscapes A and B. As in the class-level example, the rank order of *mean patch fractal dimension* (MPFD) values do not agree with the other shape indices. The reason for the discrepancy between these indices is not clear; however, because all other shape indices are consistent with each other, *mean patch fractal dimension* is probably less reliable in this case.

Core Area Metrics

FRAGSTATS computes several statistics based on core area at the patch, class, and landscape levels (table 1). Core area is defined as the area within a patch beyond some specified edge distance or buffer width. Core area metrics reflect both landscape composition and landscape configuration. Most of the indices dealing with number or density of patches, size of patches, and differences in patch size have corresponding core area indices computed in the same manner after eliminating the edge or buffer from all patches. Like patch shape, the primary significance of core area in determining the nature of patches in a landscape appears to be related to the "edge effect." As discussed previously, 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 (see discussion, "Edge metrics," for citations). 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.

For ecological processes or organisms adversely affected by edge, it seems likely that core area would better characterize a patch than total area would. In addition, it seems likely that edge effects would differ with the type and nature of the edge (the degree of floristic and structural contrast and orientation). Unfortunately, in most cases, there is insufficient empirical support (or none) for designating separate edge widths for each unique edge type. Accordingly, the user must specify a single edge width for all edge types in FRAGSTATS.

In raster images, there are different ways to determine core area. FRAGSTATS employs a method in which the four parallel neighbors of a cell are evaluated for similarity; diagonal neighbors are ignored. This method tends to slightly overestimate the true core area. Other methods can seriously underestimate core area. For more details on the algorithm, see the "patch.c" routine in the source files.

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 width; these are *core area* (CORE) at the patch level, *total core area* (TCA) at the class and landscape levels, and *core area percentage of landscape* (C%LAND) 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. In contrast to their counterparts, these core area indices integrate into a single measure the effects 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 useful in the study of habitat fragmentation, because fragmentation affects both habitat area and configuration. On the other hand, these indices confound the effects of habitat area and configuration; for example, if the core area percentage of a landscape is small, it indicates that very little core area is available, but it does not discriminate between a small amount of the patch type (area effect) and a large amount of the patch type in a highly fragmented configuration. Thus, like many indices summarizing more than one feature (for example, diversity indices), these indices are best interpreted in conjunction with other indices to provide a more complete description of landscape structure.

From an organism-centered perspective, a single patch may contain several disjunct patches of suitable interior habitat, and considering disjunct core areas as separate patches may be appropriate. For this reason, FRAGSTATS computes the *number of core areas* (disjunct) in each patch (NCORE), as well as the number in each class and the landscape as a whole (NCA). 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 for area. Although these metrics are not particularly useful in most cases, they are used to compute other landscape metrics based on core area.

Number of core areas can be reported on a per unit area basis (*core area density*, CAD) that has the same ecological applicability as its counterpart (patch density), except that all edge area is eliminated from consideration. Alternatively, this information can be represented as mean core area. Like their counterparts, there is a difference between core area density and mean core area at the class level. Specifically, core area density is based on total landscape area, and 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 therefore are completely redundant. Furthermore, mean core area can be defined in two ways. First, mean core area can be defined as the *mean core area per patch* (MCA1). Patches with no core area are included in the average, and the total core area in a patch is considered as one observation, regardless of whether the core area is contiguous or divided into two or more disjunct areas within the patch. Mean core area also can be defined as the *mean area per disjunct core* (MCA2). The distinction between these two ways of defining mean core area should be noted.

FRAGSTATS also computes several relative core area indices that quantify 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, the *total core area index* (TCAI) at the class and landscape levels quantifies core area for the entire class or landscape as a percentage of total class or landscape area, respectively. At the class and landscape levels, FRAGSTATS also computes the *mean core area index* (MCAI) of patches comprising the class or landscape. Note that the total core area index is equivalent to an area-weighted mean core area index; thus, the latter is not computed.

These core area indices are basically edge-to-interior ratios like the shape indices discussed previously, the main difference being that the core area indices treat edge as an area of varying width and not as a line (perimeter) around each patch. In addition, these core area indices are relative measures. They do not reflect patch size, class area, or total landscape area; they quantify the percentage of available area, whether 10 hectares or 1000 hectares, comprised of core. These indices do not confound area and configuration like the previous core area indices; rather, they isolate the configuration effect. For this reason, these core area indices are probably best interpreted in conjunction with total area at the corresponding scale. In conjunction with total class area, these indices could serve as effective fragmentation indices for a particular class.

Variation in core area size may convey more useful information than mean core area does. Like variation in patch size, FRAGSTATS computes corresponding measures of variability among patches in core area size. Core area standard deviation and core area coefficient of variation have the same ecological applicability as patch size standard deviation and patch size coefficient of variation, except that all edge area is eliminated from consideration. FRAGSTATS computes both the *patch core area standard deviation* (CASD1) and *patch core area coefficient of variation* (CACV1), which represent the variation in core area per patch (associated with MCA1), as well as the *disjunct core area standard deviation* (CASD2) and *disjunct core area coefficient of variation* (CACV2), which represent the variation in the size of disjunct core areas (associated with MCA2). In contrast to their counterparts, these core area metrics reflect the interaction of patch size and shape and edge width and, therefore, may serve as better heterogeneity indices when edge width can be meaningfully specified and edge effects are of particular interest. Standard deviation can be difficult to interpret without doing so in conjunction with other statistics (for example, mean patch size or mean core area). For this reason, core area coefficient of variation usually is preferable to core area standard deviation. Also, note that core area standard deviation and coefficient of variation can equal 0 under three conditions: (1) when there is only one core area in the landscape; (2) when there is more than one core area greater than 0 in size, but they are all the same size; and (3) when there is more than one patch, but none has a core area (CORE = 0). In all three cases, there is no variability in core area size; yet, the ecological implications could be quite different.

All the core area indices are affected by the interaction of patch size, patch shape, and the specified edge width. Increasing edge width will decrease core area, and vice versa; therefore, these indices are meaningful only if the specified edge width is relevant and meaningful to the phenomenon under investigation. In many cases, there is no empirical basis for specifying any particular edge width, and so it must be chosen somewhat arbitrarily. The usefulness of these metrics is directly related to the arbitrariness in the specified edge width, and this should be clearly understood when using these metrics. The utility of core area indices compared to their area-based counterparts depends on the resolution, minimum patch dimensions, and edge widths employed. Given, for example, a landscape with a resolution of 1 square meter and minimum patch dimensions of 100 by 100 meters, if an edge width of 1 meter is specified, then the core area indices and their counterparts will be nearly identical and the core area indices will be relatively insensitive to differences in patch size and shape. In this case, core area indices will offer little over their counterparts in terms of unique characterization of landscape structure.

Patch-level example—Figure 4 depicts three patches extracted from a sample landscape that differ in core area based on a 100-meter edge width for all edge types. Although patch A is almost three times larger than patch C, it has less than twice the *core area* (CORE). This is because patch A has a more complex shape than patch C and therefore a greater edge-to-interior ratio. Although patches B and C are almost equal in size, patch B has half the *core area* of patch C because of the interaction among patch size, patch shape, and edge width. With a 100-meter edge width, the subtle difference in shape between patch B and C results in a large difference in *core area*. A much larger edge width (for example, 200 m) would result in both patches having no *core area* because of their small size, and a much smaller edge width (10 m) would result in both patches having similar core areas. Thus, the affect of patch shape on *core area* depends on both patch size and edge width.

According to the *number of core areas* (NCORE), patches B and C both contain one core area because of their simple shapes. Patch A, however, contains two core areas because it is narrower than 200 meters in the middle and widens on both sides. Thus, under certain conditions, it may be more meaningful to treat patch A as two separate patches. If an organism avoids edge habitat for 100 meters, then from the organism's perspective, patch A may actually contain two separate suitable habitat patches. Like *core area*, though, *number of core areas* is affected by the interaction of patch size, patch shape, and edge width. With a much larger edge width (say, 200 m) or much smaller edge width (10 m), patch A would contain only one core area.

Although patch A is almost three times larger than patch B and has a more complex shape, it has roughly the same *core area index* (CAI) as patch B. Thus, these two patches have about the same proportion of core area, even though they differ markedly in absolute size and shape. In contrast, the *core area index* of patch B is about half that of patch C, even though they are similar in size. Because of the interaction of patch size, patch shape, and edge width, the slightly more complex shape of patch B results in disproportionately less core area and therefore a much smaller *core area index* than patch C. Again, note the affect of the interaction among patch size, patch shape, and edge width on this index.

Class-level example—Figure 5 depicts three sample landscapes that differ in the amount and pattern of mixed, large sawtimber habitat based on a 100-meter edge width for all edge types. According to the *percentage of landscape* (%LAND) in this patch type, roughly 50 percent of landscapes B and C are mixed, large sawtimber. According to the *core area percentage of landscape* (C%LAND), however, only 10 percent of this habitat type in landscape B is core area, whereas 23 percent of this habitat type in landscape C is core area. Thus, the *core area percentage of landscape* clearly indicates that landscape B is fragmented to a much greater degree than landscape C. But inspection of this index alone does not indicate whether differences in the amount of core area are from differences in total habitat area or habitat configuration, or both. Nevertheless, for an organism requiring interior mixed, large sawtimber habitat, the *core area percentage of landscape* suggests that landscape C contains twice the suitable habitat as landscape B. This would not necessarily be true if landscapes B and C were greatly different in size because this index is a relative measure. All core area indices are affected by the interaction of patch size, patch shape, and edge width. Given either a much larger edge width (200 m) or much smaller edge width (10 m), the index values change dramatically, especially in landscapes A and B, because of the size and shapes of the mixed, large sawtimber patches in these landscapes.

Total core area (TCA) indicates that although landscape A contains four mixed, large sawtimber patches totaling 13 hectares, there is no core area (that is, no point in these patches is more than 100 meters from the patch perimeter). Although landscapes B and C have similar amounts of mixed, large sawtimber, *total core area* indicates that landscape B has much less core area, suggesting a much more fragmented (greater edge-to-interior ratio) configuration of habitat in landscape B than in C.

Number of core areas (NCA) indicates that although landscape B has less than half as much mixed, large sawtimber core area as landscape C, it has more than three times as many disjunct core areas. Note also the difference between *number of patches* (NP) and *number of core areas*. The difference between landscape B and C is more pronounced with the latter index, thereby indicating that the habitat in landscape B is indeed more fragmented than in landscape C.

Compared to *patch density* (PD), *core area density* (CAD) does a much better job of characterizing the differences in landscape structure among landscapes. In our example, landscapes A and B have similar patch densities, but *core area density* differs dramatically between them. Landscape A has no core areas, indicating that the habitat is highly fragmented into very small patches; whereas, landscape B has a comparatively high core area density. Similarly, although landscapes B and C have similar amounts of mixed, large sawtimber habitat, the core area in landscape B is fragmented into several disjunct areas, whereas in landscape C it is more contiguous. Although the three landscapes differ considerably in both amount and distribution of mixed, large sawtimber habitat, it is difficult to interpret these landscape structural differences by *core area density* alone; this index is best interpreted in conjunction with other indices such as *class area* (CA). Also, because *total landscape area* is similar among the landscapes, *core area density* and *number of core areas* convey the same information.

Although *mean patch size* (MPS) does a good job of ranking the three landscapes by mixed, large sawtimber fragmentation (A being most fragmented, C being least), *mean core area per patch* (MCA1) distinguishes the different stages of fragmentation even more effectively. Like *mean patch size*, *mean core area per patch* is most informative when interpreted in conjunction with other indices such as *class area*, *patch density* (PD), and patch size variability (PSSD or PSCV). It is difficult to tell from MCA1 alone if differences between landscapes B and C are because of differences in habitat area or habitat configuration; by interpreting both *class area* and *mean core area per patch* it becomes clear that the differences are due solely to configuration. *Mean area per disjunct core* (MCA2) is consistent with *mean core area per patch*, but note the differences due to the differences in number of patches and number of disjunct core areas.

Variation in the amount of core area per patch or disjunct core often is of greater interest than the average condition. *Patch core area standard deviation* (CASD1) and *disjunct core area standard deviation* (CASD2) indicate that the absolute variation in core area size per patch and per disjunct core area, respectively, is six times greater in landscape C than in B. These indices alone do not say much about differences in structure among the three landscapes, however, unless the user simultaneously considers the *mean core area per patch* or *mean area per disjunct core*, respectively. *Patch core area coefficient of variation* (CACV1) measures relative variability and indicates that core area variability decreases progressively from the least (C) to the most (A) fragmented landscape. This suggests that timber management activities have tended to produce greater homogeneity in core areas for this habitat type. *Disjunct core area coefficient of variation* (CACV2) measures relative variability among disjunct core areas and indicates that the disjunct core areas in landscape B are slightly more variable than in landscape C. The choice between the coefficient of variation measures depends on the application.

The *total core area index* (TCAI) represents the landscapes along a continuum from most to least fragmented. According to this index, only 20 percent of the mixed, large sawtimber in landscape B is “interior” habitat; the remaining 80 percent is “edge” habitat. Without any other information, it could be deduced that this habitat type is highly fragmented in landscape B. When *total core area index* is interpreted in conjunction with *class area* or the *percentage of landscape*, it becomes quite clear that landscapes B and C differ exclusively in habitat configuration and not habitat area, and that landscape B is indeed more fragmented than landscape C. The *mean core area index* (MCAI) indicates that the mixed, large sawtimber habitat in all three landscapes is highly fragmented (that is, all have high edge-to-interior ratios). According to this index, however, the mixed, large sawtimber patches in landscapes B and C have roughly the same average core area index. Yet, the *total core area index* and other indices clearly indicate that landscape B is in fact more fragmented than landscape C. These differences illustrate some important differences between the total and mean core area indices. The *mean core area index* represents the average patch characteristic and may not necessarily represent the overall landscape structural condition very well. This may be appropriate and meaningful when the focus of the application is on patch-level phenomena. When the focus is on landscape structure, however, the mean patch condition may be misleading. For example, the *mean core area index* for landscape C is affected by the great variation in core area index among the three patches. The large core area index of the largest patch is offset by the 0 core area index of the smallest patch and the very small core area index of the midsized patch. This bias is characteristic of first-order statistics, such as the mean, and is particularly pronounced in this case because of the small sample size (n = 3 patches) in landscape C.

Landscape-level example—Figure 6 depicts three sample landscapes that differ in composition and pattern based on a 100-meter edge width for all edge types. *Total core area* (TCA) indicates that landscapes A, B, and C contain progressively more core area, and because *total landscape area* (TA) is similar, they represent a continuum from most to least patchy. All core area indices are affected by the interaction of patch size, patch shape, and edge width. With a much larger (say, 200 m) or smaller edge width (10 m), the index values change dramatically, especially in landscapes A and B, because of the size and shapes of the mixed, large sawtimber patches in these landscapes.

Number of core areas (NCA) indicates that although landscape A has the greatest *number of patches* (NP), it does not have the greatest *number of core areas*, because many of the patches in landscape A do not have any core area. Because *total landscape area* is similar among landscapes, *number of core areas* and *core area density* (CAD) are largely redundant. Note that although landscapes A and B have fewer core areas than patches, landscape C has more core areas than patches. The rank order of landscapes based on *number of core areas* is different than that based on *number of patches* and *total core area*. This reversal occurs because of the relation between patch sizes and shapes in these landscapes and the designated edge width of 100 meters. With a much larger edge width (say, 200 m) or smaller edge width (10 m), *number of core areas* changes dramatically, especially in landscapes A and B, because of the size and shapes of the patches in those landscapes. For this reason, particular attention should be given to the interpretation of *number of core areas*, *core area density*, and *total core area* because they can lead to a different rank ordering of landscapes along a gradient in landscape heterogeneity.

Although *mean patch size* (MPS) does a good job of ranking the three landscapes by their spatial heterogeneity, *mean core area per patch* (MCA1) distinguishes among these landscapes even more distinctly. Because *mean core area per patch* is affected by patch shape, it captures an aspect of spatial pattern not captured by *mean patch size*. Like *mean patch size*, *mean core area per patch* is most informative when interpreted in conjunction with other indices such as *total landscape area*, *patch density* (PD), and patch size variability (PSSD or PSCV). *Mean area per disjunct core* (MCA2) is consistent with *mean core area per patch*, but note the differences due to the differences in number of patches and number of disjunct core areas, especially in landscape A.

Patch core area standard deviation (CASD1) and *disjunct core area standard deviation* (CASD2) indicate that the absolute variation in core area size per patch and per disjunct core area, respectively, decreases progressively from landscape C to A, and in this manner they mimic the results of *patch size standard deviation*. These indices alone do not tell us much about differences in structure among the three landscapes unless the *mean core area per patch* or *mean area per disjunct core*, respectively, also is considered. *Patch core area coefficient of variation* (CACV1) measures relative variability and, in contrast to the standard deviation, indicates that core area variability increases progressively from the least (C) to the most (A) patchy landscape. Thus, although patch core area varies less in absolute terms in landscape A than C, it varies much more in relative terms. Hence, timber management activities have tended to produce smaller, but more variable, core areas. *Disjunct core area coefficient of variation* (CACV2) measures relative variability among disjunct core areas. This index indicates that in landscape A the disjunct core areas are much less variable than the core areas per patch. The choice between coefficient of variation measures depends on the particular application.

The *total core area index* (TCAI) represents the three landscapes along a continuum from most to least patchy. According to this index, only 10 percent of landscape A is "interior" habitat, the remaining 90 percent is "edge" habitat. Without any other information on landscape A, it might be deduced that landscape A contains a great deal of spatial heterogeneity. However, the *total core area index* does not indicate how much total core area exists or how many patches the core area is distributed among and, in this respect, it is best interpreted in conjunction with other indices. The *mean core area index* (MCAI) mimics the results of the *total core area index*, although the values are smaller because patches in each landscape with 0 core area contribute equally to the mean and reduce the average value.

Nearest Neighbor Metrics

FRAGSTATS computes a few statistics based on nearest neighbor distance at the patch, class, and landscape levels (table 1) for the raster version only. Nearest neighbor distance is defined as the distance from a patch to the nearest neighboring patch of the same type, based on edge-to-edge distance. Nearest neighbor metrics quantify landscape configuration. Nearest neighbor distance can influence a number of important ecological processes. 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. Several authors have claimed, for example, that patch isolation explains why fragmented habitats often contain fewer bird species than contiguous habitats (Dickman 1987, Forman and others 1976, Hayden and others 1985, Helliwell 1976, Moore and Hooper 1975, Whitcomb and others 1981). Opdam (1991) reviewed a number of studies empirically demonstrating an isolation effect on bird communities in various habitat patches. Interpatch distance plays a critical role in island biogeographic theory (MacArthur and Wilson 1967) and metapopulation theory (Gilpin and Hanski 1991, Levins 1970) and has been discussed in the context of conservation biology (for example, Burkey 1989). The role of interpatch distance in metapopulations has had a preeminent role in recent conservation efforts for endangered species (Lamberson and others 1992, McKelvey and others 1992). Nearest neighbor distance clearly can be an important characteristic of the landscape, depending on the phenomenon under investigation.

FRAGSTATS computes the *nearest neighbor distance* (NEAR) and *proximity index* (PROXIM) for each patch. The proximity index was developed by Gustafson and Parker (1992) (see also, Gustafson and Parker, in press; Gustafson and others, in press; Whitcomb and others 1981) and considers the size and proximity distance of all patches having edges 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. We used the distance between the focal patch and each of the other patches within the search radius, similar to the isolation index of Whitcomb and others (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). According to the authors, the proximity index quantifies the spatial context of a habitat patch in relation to its neighbors; 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, 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. The index is dimensionless (has no units), and therefore the absolute value of the index has little interpretive value; instead it is used as a comparative index.

At the class and landscape levels, FRAGSTATS computes the *mean proximity index* (MPI) for patches comprising the class or for all patches in the landscape. At the class level, the mean proximity index measures the degree of isolation and fragmentation of the corresponding patch type, and the performance of the index under various scenarios is described in detail by Gustafson and Parker (in press). We also compute the mean proximity index at the landscape level by averaging the proximity index across all patches and patch types in the landscape, although the performance of this index as a measure of overall landscape structural complexity has not been evaluated quantitatively.

At the class and landscape levels, FRAGSTATS computes the *mean nearest neighbor distance* (MNN) for patches comprising the class or for all patches in the landscape. At the class level, mean nearest neighbor distance can be computed only if at least two patches of the corresponding type occur. At the landscape level, mean nearest neighbor distance considers only patches having neighbors. Thus, there could be 10 patches in the landscape, but 8 of them might belong to separate patch types and therefore have no neighbor within the landscape. In this case, mean nearest neighbor distance would be based on the distance between the two patches of the same type, whether close together or far apart. In either case, the mean nearest neighbor distance for this landscape might not characterize the entire landscape very well. For this reason, this index should be interpreted carefully when landscapes contain rare patch types.

Mean nearest neighbor distance is a first-order statistic and may not be meaningful if the distribution is complex. Variability in nearest neighbor distance measures a key aspect of landscape heterogeneity not captured by mean nearest neighbor distance. *Nearest neighbor standard deviation* (NNSD) is a measure of patch dispersion; a small standard deviation relative to the mean implies a fairly uniform or regular distribution of patches across landscapes, whereas a large standard deviation 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 nearest neighbor standard deviation is a function of the mean nearest neighbor distance and variation in nearest neighbor distance among patches. Thus, even though the standard deviation conveys information about nearest neighbor variability, it is a difficult parameter to interpret without doing so in conjunction with the mean nearest neighbor distance. Two landscapes may have the same nearest neighbor standard deviation, 100 meters; yet one landscape may have a mean nearest neighbor distance of 100 meters, and the other a mean nearest neighbor distance of 1000 meters. In this case, the interpretations of landscape structure 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, and the latter has a more regular but dispersed pattern of patches. In addition, standard deviation assumes 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 (for example, plot a histogram of the nearest neighbor distances for the corresponding patches), rather than relying on summary statistics such as standard deviation that make assumptions about the distribution and therefore can be misleading.

Coefficient of variation often is preferable to standard deviation for comparing variability among landscapes. *Nearest neighbor coefficient of variation* (NNCV) measures relative variability about the mean (that is, variability as a percentage of the mean), not absolute variability. Thus, it is not necessary to know the mean nearest neighbor distance to interpret this metric. Even so, nearest neighbor coefficient of variation can be misleading for landscape structure when the number of patches or patch density and other structural characteristics is not also known. Two landscapes may have the same nearest neighbor coefficient of variation, say, 100 percent; yet one landscape may have 100 patches with a mean nearest neighbor distance of 100 meters, and the other 10 patches with a mean nearest neighbor distance of 1000 meters. In this case, the interpretations of overall landscape structure could be very different, even though nearest neighbor coefficient of variation is the same; although the identical coefficients of variation values indicate that both landscapes have the same regularity or uniformity in patch distribution.

Because of limitations in Arc/Info (inability to calculate edge-to-edge distances), the vector version of FRAGSTATS does not calculate nearest neighbor metrics. To compute these indices from a vector image, the image must be rasterized first and then analyzed with the raster version of FRAGSTATS. During the rasterization process, depending on the cell size selected, polygons can merge or divide. Indeed, this problem can be quite severe and lead to erroneous results for metrics based on the number and size of patches. Therefore, considerable care should be exercised when rasterizing a vector image to ensure the desired results. The most important limitation of these nearest neighbor indices 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 process under consideration and the landscape is an “open” system relative to that organism or process, then nearest neighbor results can be misleading. Consider, for example, 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 that the organism under investigation perceives and responds to the environment will decrease the severity of this problem. Similarly, the proximity index sums the distance-weighted area of all patches whose edges are within the specified search radius of the focal patch but only considers patches within the landscape boundary. Thus, the proximity index 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 of this problem is also a function of scale. Increasing the size of the landscape relative to the average patch size or decreasing the search radius, or both, 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 a biased proximity index. The proximity index also evaluates the landscape context of patches at a specific scale of analysis defined by the size of the search radius. Therefore, this index is only meaningful if the specified search radius has some ecological justification given the phenomenon under consideration. Otherwise, the results of the proximity index will be arbitrary and therefore meaningless. Although these scaling issues are a critical consideration for all landscape metrics, they are particularly problematic for these nearest neighbor indices.

Patch-level example—Figure 4 depicts three patches extracted from a sample landscape that differ in their neighborhood context. Patch A has the smallest *nearest neighbor distance* (NEAR), followed by patches B and C. Similarly, patch A has the largest *proximity index* (PROXIM) based on a 200-meter search radius, followed by patches B and C. Note the inverse relationship between *nearest neighbor distance* and the *proximity index*. These indices support the conclusion drawn from the *landscape similarity index* (LSIM) that patch A is the least insular of the three patches. Patch A contains a closer neighbor and a greater amount of similar habitat within its immediate neighborhood than either patch B or C does. Because of the relatively small landscape extent relative to patch size, nearest neighbor distances are probably not very meaningful in this sample landscape.

Class-level example—Figure 5 depicts three sample landscapes that differ in the amount and pattern of mixed, large sawtimber habitat. *Mean nearest neighbor distance* (MNN) is greatest in landscape A, suggesting that mixed, large sawtimber patches are most isolated in this landscape, although the differences among landscapes are relatively small. *Nearest neighbor standard deviation* (NNSD) and *nearest neighbor coefficient of variation* (NNCV) are greatest in landscape B, suggesting that the dispersion of mixed, large sawtimber patches is least regular in this landscape. The *mean proximity index* (MPI) is inversely related to *mean nearest neighbor distance* based on a 200-meter search radius and indicates that mixed, large sawtimber in landscape A is most fragmented and insular. These nearest neighbor indices indicate that mixed, large sawtimber is less fragmented in landscape B than in C; yet, most other fragmentation indices indicate the opposite. These differences likely reflect the relatively small extent of these landscapes relative to patch size. Under these conditions, nearest neighbor indices are not particularly meaningful and their interpretations can be misleading.

Landscape-level example—Figure 6 depicts three sample landscapes that differ in composition and pattern. *Mean nearest neighbor distance* (MNN) is smallest in landscape C, suggesting that patches are least insular in this landscape. *Nearest neighbor standard deviation* (NNSD) and *nearest neighbor coefficient of variation* (NNCV) are greatest in landscape A, suggesting that the dispersion of patches is least regular in this landscape. The *mean proximity index* (MPI) is smallest in landscape A, based on a 200-meter search radius, and indicates that patches are most fragmented and insular in this landscape, although the interpretation of this index at the landscape level is somewhat difficult. Because of the relatively small extent of these landscapes, nearest neighbor indices are not particularly meaningful.

Diversity Metrics

FRAGSTATS computes several statistics that quantify diversity at the landscape level (table 1). These metrics quantify landscape composition. Diversity measures have been used extensively in a variety of ecological applications. They originally gained popularity as measures of plant and animal species diversity. FRAGSTATS computes three diversity indices. These diversity measures are influenced by two 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 (for example, Shannon's diversity index [Shannon and Weaver 1949]) are more sensitive to richness than evenness. Thus, rare types have a disproportionately large influence on the magnitude of the index. Other indices (for example, Simpson's diversity index [Simpson 1949]) are relatively less sensitive to richness and thus place more weight on the common species. These diversity indices have been applied by landscape ecologists to measure one aspect of landscape structure—landscape composition (see O'Neill and others 1988, Romme 1982, Turner 1990b).

The most popular diversity index is *Shannon's diversity index* (SHDI), which is 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 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. The value of Simpson's index represents the probability that any two patches selected at random will be different types; the higher the value, the greater the diversity. 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 in a general class of diversity indices to which Shannon's diversity index also belongs (Pielou 1975). The modified Simpson's and Shannon's diversity indices are similar in many respects and have the same applicability.

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 summary measure of a community 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 mainly 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 regarding 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, these diversity indices combine richness and evenness components into a single measure, even though it usually is more informative to evaluate richness and evenness independently.

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. Two landscapes may have very different structure yet have the same richness; for example, one landscape may be 96 percent in patch type A and 1 percent each of patch types B through E, whereas another landscape may have 20 percent each of patch types A through E. Patch richness would be the same, but the functioning of these landscapes and the structure of the animal and plant communities likely would be quite different. Because richness does not account for relative abundance of each patch type, rare patch types and common patch types contribute equally to richness. Patch richness, nevertheless is a key element of landscape structure because the variety of landscape elements present in a landscape can have an important influence on several ecological processes. Because many organisms are associated with a single patch type, patch richness often correlates well with species richness.[3]

Richness is partially a function of scale. Larger areas are generally richer because of the greater heterogeneity over large areas than over comparable smaller areas. This contributes to the species-area relation predicted by island biogeographic theory (MacArthur and Wilson 1967). Therefore, comparing richness among landscapes differing 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). In some applications, this form may have more interpretive value than absolute richness or richness density. Relative patch richness and patch richness are completely redundant and would not be used simultaneously in any subsequent statistical analysis.

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[3] Unpublished data. McGarigal, K.; McComb, W.C. On file with: Forest Science Data Bank, a partnership between the Department of Forest Science, Oregon State University, and the U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station, 3200 Jefferson Way, Corvallis, OR 97331.

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 (that is, evenness = 1 – dominance). Indeed, dominance often has been the chosen form in landscape ecological investigations (for example, O'Neill and others 1988, Turner 1990b, Turner and others 1989), 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; and *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 based on an equal distribution among patch types. Therefore, the observed diversity divided by the maximum diversity (that is, 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 in interpretability. Evenness, like richness and diversity, does not convey any information about which patch types are most or least abundant or which may be of greater ecological significance.

Landscape-level example—Figure 6 depicts three sample landscapes that differ in composition and pattern. *Shannon's diversity index* (SHDI), *Simpson's diversity index* (SIDI), and the *modified Simpson's diversity index* (MSIDI) mainly reflect differences in patch richness and represent the landscapes along a continuum from most (A) to least (C) diverse. In landscape A, *Simpson's diversity index* indicates a 79-percent probability that two randomly chosen patches will represent different patch types. According to *patch richness* (PR), the number of different patch types ranges from 10 in landscape A to 3 in landscape C. Because these landscapes are similar in area and the maximum possible number of patch types is a constant, *patch richness density* (PRD), *relative patch richness* (RPR), and *patch richness* are largely redundant. On the average, landscape A contains three and one-half different patch types within a 100-hectare area and contains 37 percent of the potential number of patch types.

Although landscape C is the least diverse based on the diversity and richness indices, it has the most even area distribution among patch types, according to *Shannon's evenness index* (SHEI), *Simpson's evenness index* (SIEI), and the *modified Simpson's evenness index* (MSIEI). These three indices indicate that the distribution of area among patch types is 84 to 91 percent of the maximum evenness in landscape C, depending on which index is interpreted. This illustrates the potential importance of interpreting richness and evenness independently and the importance of interpreting evenness separate from diversity, which is influenced strongly by richness. Differences in evenness among landscapes based on *Simpson's evenness index* are less pronounced than with the other two evenness indices, perhaps because Simpson's metric is less influenced by rare patch types.

Contagion and Interspersion Metrics

FRAGSTATS computes two indices representing patch interspersion and juxtaposition at the class and landscape levels, although one index applies only to the landscape level (table 1). These metrics quantify landscape configuration. A contagion index was proposed first by O'Neill and others (1988), and subsequently, it has been widely used (Graham and others 1991; Gustafson and Parker 1992; Turner 1989, 1990a, 1990b; Turner and others 1989; Turner and Ruscher 1988). Li and Reynolds (in press) show that the original formula was incorrect; they introduce two forms of an alternative contagion index that correct this error and improve performance. Both contagion indices are designed for raster images in which each cell is individually evaluated for adjacency, and like adjacencies (cells not on a patch perimeter) are considered. Both indices have been applied at the landscape level to measure landscape structure.

FRAGSTATS computes one of the contagion indices proposed by Li and Reynolds (in press). This *contagion index* (CONTAG) is applicable only to raster images at the landscape level; it is based on raster "cell" adjacencies—not "patch" adjacencies. This contagion index consists of the sum, over patch types, of the product of two 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 two randomly chosen adjacent cells belong to patch types i and j. This contagion index is appealing because of the straightforward and intuitive interpretation of this probability. Contagion measures both patch type interspersion (the intermixing of units of different patch types) as well as patch dispersion (the spatial distribution of a patch type). All other things being equal, a landscape with well-interspersed patch types will have lower contagion than a landscape with poorly interspersed patch types. According to Li and Reynolds (in press), contagion measures the extent to which landscape elements (patch types) are aggregated or clumped (dispersion); higher values of contagion may result from landscapes with a few large, contiguous patches, whereas lower values generally characterize landscapes with many small, 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 where 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 of the large proportion of total cell adjacencies comprised of like adjacencies and the uneven distribution of adjacencies among edge types. The contagion index represents the observed level of contagion as a percentage of the maximum possible, given the total number of patch types.

We present a new *interspersion and juxtaposition index* (IJI) that is compatible with both vector and raster images and applicable at both the class and landscape levels. Unlike the earlier contagion indices based on raster “cell” adjacencies, our index is based on “patch” adjacencies. Each patch is evaluated for adjacency with all other patch types; like adjacencies are not possible because a patch cannot be adjacent to a patch of the same type. For raster images, internal cells are ignored; only the patch perimeters are considered in determining the total length of each unique edge 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 (equally adjacent to each other), whereas lower values characterize landscapes in which the patch types are poorly interspersed (disproportionate distribution of patch type adjacencies). The interspersion index is not directly affected by the number, size, contiguity, or dispersion of patches per se, as is the contagion index. A landscape containing four large patches, each a different patch type, and a landscape of the same extent containing 100 small patches of four 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); the value of contagion would be quite different. Like the contagion index, the interspersion index is a relative index representing the observed level of interspersion as a percentage of the maximum possible given the total number of patch types.

Unlike the contagion index, the interspersion and juxtaposition index can be applied at both the class and landscape levels. At the class level, this index measures the juxtapositioning of a focal patch type with all others and does not reflect the interspersion of other patch types. Again, the index is not affected by the dispersion of the focal patch type per se, except that a well-dispersed patch type is more likely to be well interspersed as well. For example, the focal patch type could be aggregated in one portion of the landscape or maximally dispersed, and the value of the index would be the same if the proportion of total edge length involving the focal patch and each other patch type is the same.

The differences between the contagion index and the interspersion and juxtaposition index are important. Contagion is affected by both interspersion and dispersion. The interspersion and juxtaposition index, in contrast, is affected only by patch type interspersion and juxtaposition 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 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 because it considers only patch edges. This scale effect should be carefully considered when results from different studies are compared.

Class-level example—Figure 5 depicts three sample landscapes that differ in the amount and pattern of mixed, large sawtimber habitat. The *interspersion and juxtaposition index* (IJI) indicates that the mixed, large sawtimber edge present in landscape B is more equitably distributed among patch types than in either landscape A or C. Although landscapes A and C contain different numbers of patch types (10 vs. 3), the *interspersion and juxtaposition index* is roughly the same, indicating that the mixed, large sawtimber edge is distributed among the available patch types at about 50 percent of the maximum possible equitable distribution in both landscapes, even though the absolute amounts of edge and proportions associated with each edge type clearly are quite different.

Landscape-level example—Figure 6 depicts three sample landscapes that differ in composition and pattern. The *interspersion and juxtaposition index* (IJI) indicates that the interspersion of available patch types is greatest in landscape A and least in landscape C. This occurs because landscape C contains two patch types that are present only in the landscape border, and the amount of edge involving these two types is very small. Thus, the distribution of edge lengths among unique types is very uneven. Accordingly, the *contagion index* (CONTAG) is greatest in landscape C and least in landscape A. This reflects both the interspersion of patch types as discussed above as well as the larger, more contiguous patches in landscape C compared to landscape A.

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Appendix 1: FRAGSTATS Output File

Following is an example of the FRAGSTATS output file formatted exclusively for display purposes (that is, "basename".full). Each run of FRAGSTATS for a landscape produces an output file like this one. The results reported here correspond to the landscape displayed in figure 6 (landscape B). The results obtained by using the vector and raster versions of FRAGSTATS are included separately; note the differences in indices involving edge lengths and patch perimeters.

Vector Version

Date: 07 Oct 93 13:39:26 Thursday
Coverage: ncveg
Basename For Output Files: ncveg
Patch Type Attribute: class   Edge Dist: 100
Background Class: NONE
Max Patch Types Possible: 27
Weight File: contrast.new
Patch ID Attribute: patchid   Class Names Attribute: classdesc
Input Landscape Contains a Landscape Border
Proportion of Boundary/Background to Count as Edge: 0.00
Write Patch Indices: YES   Write Class Indices: YES
AML/Program Directory: /gis/giswork/barbara/vector/

PATCH INDICES

Patch ID:	700	Patch Type:	W
Area (ha):	1.118	Landscape Similarity (%):	0.378
Perimeter (m):	437.399	Edge Contrast (%):	6.695
Shape Index:	1.167	Fractal Dimension:	1.305
Core Area (ha):	0.000	Num Core Areas:	0
Core Area Index (%):	0.000		

CLASS INDICES

Patch Type:	W	Class Area (ha):	1.118
Total Area (ha):	296.073	Percent of Landscape (%):	0.378
Largest Patch Index (%):	0.378	Number Patches:	1
Patch Density (#/100 ha):	0.338	Mean Patch Size (ha):	1.118
Patch Size SD (ha):	0.000	Patch Size CV (%):	0.000
Total Edge (m):	437.399	Edge Den (m/ha):	1.477
Con-Wght Edge Den (m/ha):	0.099	Total Edge Contrast (%):	6.695
Mean Edge Contrast (%):	6.695	Area-Wt Mean Edge Con (%):	6.695
Landscape Shape Index:	1.243	Mean Shape Index:	1.167
Area-Weighted Mean Shape:	1.167	Double Log Fractal Index:	NA
Mean Patch Fractal:	1.305	Area-Weighted Mean Fractal:	1.305
Core % of Landscape (%):	0.000	Total Core Area (ha):	0.000
Number Core Areas:	0	Core Area Den (#/100 ha):	0.000
Mean Core Area 1 (ha):	0.000	Core Area SD 1 (ha):	0.000
Core Area CV 1 (%):	0.000	Mean Core Area 2 (ha):	0.000
Core Area SD 2 (ha):	0.000	Core Area CV 2 (%):	0.000
Total Core Area Index (%):	0.000	Mean Core Area Index (%):	0.000
Intersper/Juxtapos (%):	13.711		

PATCH INDICES

Patch ID:	200	Patch Type:	MGF
Area (ha):	18.586	Landscape Similarity (%):	8.413
Perimeter (m):	1907.330	Edge Contrast (%):	80.049
Shape Index:	1.248	Fractal Dimension:	1.245
Core Area (ha):	4.622	Num Core Areas:	1
Core Area Index (%):	24.868		

Patch ID:	500	Patch Type:	MGF
Area (ha):	6.323	Landscape Similarity (%):	8.413
Perimeter (m):	1046.888	Edge Contrast (%):	91.000
Shape Index:	1.174	Fractal Dimension:	1.258
Core Area (ha):	0.016	Num Core Areas:	1
Core Area Index (%):	0.248		

CLASS INDICES

Patch Type:	MGF	Class Area (ha):	24.908
Total Area (ha):	296.073	Percent of Landscape (%):	8.413
Largest Patch Index (%):	6.277	Number Patches:	2
Patch Density (#/100 ha):	0.676	Mean Patch Size (ha):	12.454
Patch Size SD (ha):	6.131	Patch Size CV (%):	49.232
Total Edge (m):	2954.219	Edge Den (m/ha):	9.978
Con-Wght Edge Den (m/ha):	8.375	Total Edge Contrast (%):	83.930
Mean Edge Contrast (%):	85.525	Area-Wt Mean Edge Con (%):	82.829
Landscape Shape Index:	1.655	Mean Shape Index:	1.211
Area-Weighted Mean Shape:	1.229	Double Log Fractal Index:	1.113
Mean Patch Fractal:	1.252	Area-Weighted Mean Fractal:	1.248
Core % of Landscape (%):	1.566	Total Core Area (ha):	4.638
Number Core Areas:	2	Core Area Den (#/100 ha):	0.676
Mean Core Area 1 (ha):	2.319	Core Area SD 1 (ha):	2.303
Core Area CV 1 (%):	99.324	Mean Core Area 2 (ha):	2.319
Core Area SD 2 (ha):	2.303	Core Area CV 2 (%):	99.324
Total Core Area Index (%):	18.619	Mean Core Area Index (%):	12.558
Intersper/Juxtapos (%):	62.578		

PATCH INDICES

Patch ID:	600	Patch Type:	MSH
Area (ha):	18.008	Landscape Similarity (%):	6.082
Perimeter (m):	1712.001	Edge Contrast (%):	74.276
Shape Index:	1.138	Fractal Dimension:	1.231
Core Area (ha):	4.612	Num Core Areas:	1
Core Area Index (%):	25.610		

CLASS INDICES

Patch Type:	MSH	Class Area (ha):	18.008
Total Area (ha):	296.073	Percent of Landscape (%):	6.082
Largest Patch Index (%):	6.082	Number Patches:	1
Patch Density (#/100 ha):	0.338	Mean Patch Size (ha):	18.008
Patch Size SD (ha):	0.000	Patch Size CV (%):	0.000
Total Edge (m):	2355.761	Edge Den (m/ha):	7.957
Con-Wght Edge Den (m/ha):	5.882	Total Edge Contrast (%):	73.927
Mean Edge Contrast (%):	74.276	Area-Wt Mean Edge Con (%):	74.276
Landscape Shape Index:	1.452	Mean Shape Index:	1.138
Area-Weighted Mean Shape:	1.138	Double Log Fractal Index:	NA
Mean Patch Fractal:	1.231	Area-Weighted Mean Fractal:	1.231
Core % of Landscape (%):	1.558	Total Core Area (ha):	4.612
Number Core Areas:	1	Core Area Den (#/100 ha):	0.338
Mean Core Area 1 (ha):	4.612	Core Area SD 1 (ha):	0.000
Core Area CV 1 (%):	0.000	Mean Core Area 2 (ha):	4.612
Core Area SD 2 (ha):	0.000	Core Area CV 2 (%):	0.000
Total Core Area Index (%):	25.610	Mean Core Area Index (%):	25.610
Intersper/Juxtapos (%):	30.221		

PATCH INDICES

Patch ID:	102	Patch Type:	MLS
Area (ha):	28.318	Landscape Similarity (%):	48.802
Perimeter (m):	2430.356	Edge Contrast (%):	18.807
Shape Index:	1.288	Fractal Dimension:	1.242

Core Area (ha):	8.769	Num Core Areas:	1
Core Area Index (%):	30.965		

Patch ID:	110	Patch Type:	MLS
Area (ha):	51.288	Landscape Similarity (%):	48.802
Perimeter (m):	4544.994	Edge Contrast (%):	24.408
Shape Index:	1.790	Fractal Dimension:	1.281
Core Area (ha):	12.336	Num Core Areas:	3
Core Area Index (%):	24.052		

Patch ID:	104	Patch Type:	MLS
Area (ha):	51.332	Landscape Similarity (%):	48.802
Perimeter (m):	6230.153	Edge Contrast (%):	16.959
Shape Index:	2.453	Fractal Dimension:	1.329
Core Area (ha):	8.459	Num Core Areas:	2
Core Area Index (%):	16.478		

Patch ID:	108	Patch Type:	MLS
Area (ha):	8.255	Landscape Similarity (%):	48.802
Perimeter (m):	1893.036	Edge Contrast (%):	25.391
Shape Index:	1.859	Fractal Dimension:	1.333
Core Area (ha):	0.000	Num Core Areas:	0
Core Area Index (%):	0.000		

Patch ID:	107	Patch Type:	MLS
Area (ha):	5.298	Landscape Similarity (%):	48.802
Perimeter (m):	912.608	Edge Contrast (%):	21.105
Shape Index:	1.118	Fractal Dimension:	1.253
Core Area (ha):	0.010	Num Core Areas:	1
Core Area Index (%):	0.189		

CLASS INDICES

Patch Type:	MLS	Class Area (ha):	144.491
Total Area (ha):	296.073	Percent of Landscape (%):	48.802
Largest Patch Index (%):	17.338	Number Patches:	5
Patch Density (#/100 ha):	1.689	Mean Patch Size (ha):	28.898
Patch Size SD (ha):	19.940	Patch Size CV (%):	69.001
Total Edge (m):	15198.311	Edge Den (m/ha):	51.333
Con-Wght Edge Den (m/ha):	11.374	Total Edge Contrast (%):	19.311
Mean Edge Contrast (%):	21.334	Area-Wt Mean Edge Con (%):	20.599
Landscape Shape Index:	3.218	Mean Shape Index:	1.702
Area-Weighted Mean Shape:	1.907	Double Log Fractal Index:	1.519
Mean Patch Fractal:	1.288	Area-Weighted Mean Fractal:	1.292
Core % of Landscape (%):	9.988	Total Core Area (ha):	29.573
Number Core Areas:	7	Core Area Den (#/100 ha):	2.364
Mean Core Area 1 (ha):	5.915	Core Area SD 1 (ha):	5.014
Core Area CV 1 (%):	84.772	Mean Core Area 2 (ha):	4.225
Core Area SD 2 (ha):	5.010	Core Area CV 2 (%):	118.578
Total Core Area Index (%):	20.467	Mean Core Area Index (%):	14.337
Intersper/Juxtapos (%):	75.666		

PATCH INDICES

Patch ID:	101	Patch Type:	HLS
Area (ha):	33.096	Landscape Similarity (%):	14.474
Perimeter (m):	5744.522	Edge Contrast (%):	35.092
Shape Index:	2.817	Fractal Dimension:	1.362
Core Area (ha):	0.370	Num Core Areas:	1
Core Area Index (%):	1.118		

Patch ID:	106	Patch Type:	HLS
Area (ha):	9.757	Landscape Similarity (%):	14.474
Perimeter (m):	1937.990	Edge Contrast (%):	5.734

Shape Index:	1.750	Fractal Dimension:	1.318
Core Area (ha):	0.014	Num Core Areas:	1
Core Area Index (%):	0.146		

CLASS INDICES

Patch Type:	HLS	Class Area (ha):	42.853
Total Area (ha):	296.073	Percent of Landscape (%):	14.474
Largest Patch Index (%):	11.178	Number Patches:	2
Patch Density (#/100 ha):	0.676	Mean Patch Size (ha):	21.427
Patch Size SD (ha):	11.670	Patch Size CV (%):	54.463
Total Edge (m):	7541.288	Edge Den (m/ha):	25.471
Con-Wght Edge Den (m/ha):	7.216	Total Edge Contrast (%):	27.136
Mean Edge Contrast (%):	20.413	Area-Wt Mean Edge Con (%):	28.407
Landscape Shape Index:	2.256	Mean Shape Index:	2.284
Area-Weighted Mean Shape:	2.574	Double Log Fractal Index:	1.779
Mean Patch Fractal:	1.340	Area-Weighted Mean Fractal:	1.352
Core % of Landscape (%):	0.130	Total Core Area (ha):	0.384
Number Core Areas:	2	Core Area Den (#/100 ha):	0.676
Mean Core Area 1 (ha):	0.192	Core Area SD 1 (ha):	0.178
Core Area CV 1 (%):	92.580	Mean Core Area 2 (ha):	0.192
Core Area SD 2 (ha):	0.178	Core Area CV 2 (%):	92.580
Total Core Area Index (%):	0.897	Mean Core Area Index (%):	0.632
Intersper/Juxtapos (%):	48.750		

PATCH INDICES

Patch ID:	300	Patch Type:	COS
Area (ha):	5.733	Landscape Similarity (%):	7.622
Perimeter (m):	1291.624	Edge Contrast (%):	51.324
Shape Index:	1.522	Fractal Dimension:	1.308
Core Area (ha):	0.000	Num Core Areas:	0
Core Area Index (%):	0.000		

Patch ID:	400	Patch Type:	COS
Area (ha):	16.833	Landscape Similarity (%):	7.622
Perimeter (m):	1922.240	Edge Contrast (%):	42.022
Shape Index:	1.322	Fractal Dimension:	1.257
Core Area (ha):	2.347	Num Core Areas:	1
Core Area Index (%):	13.944		

CLASS INDICES

Patch Type:	COS	Class Area (ha):	22.567
Total Area (ha):	296.073	Percent of Landscape (%):	7.622
Largest Patch Index (%):	5.685	Number Patches:	2
Patch Density (#/100 ha):	0.676	Mean Patch Size (ha):	11.283
Patch Size SD (ha):	5.550	Patch Size CV (%):	49.186
Total Edge (m):	2895.564	Edge Den (m/ha):	9.780
Con-Wght Edge Den (m/ha):	5.296	Total Edge Contrast (%):	46.407
Mean Edge Contrast (%):	46.673	Area-Wt Mean Edge Con (%):	44.386
Landscape Shape Index:	1.520	Mean Shape Index:	1.422
Area-Weighted Mean Shape:	1.372	Double Log Fractal Index:	0.738
Mean Patch Fractal:	1.282	Area-Weighted Mean Fractal:	1.270
Core % of Landscape (%):	0.793	Total Core Area (ha):	2.347
Number Core Areas:	1	Core Area Den (#/100 ha):	0.338
Mean Core Area 1 (ha):	1.174	Core Area SD 1 (ha):	1.174
Core Area CV 1 (%):	100.000	Mean Core Area 2 (ha):	2.347
Core Area SD 2 (ha):	0.000	Core Area CV 2 (%):	0.000
Total Core Area Index (%):	10.401	Mean Core Area Index (%):	6.972
Intersper/Juxtapos (%):	55.228		

PATCH INDICES

Patch ID:	103	Patch Type:	CLS
Area (ha):	11.882	Landscape Similarity (%):	14.229
Perimeter (m):	2454.529	Edge Contrast (%):	4.720
Shape Index:	2.009	Fractal Dimension:	1.336
Core Area (ha):	0.000	Num Core Areas:	0
Core Area Index (%):	0.000		

Patch ID:	111	Patch Type:	CLS
Area (ha):	2.386	Landscape Similarity (%):	14.229
Perimeter (m):	608.411	Edge Contrast (%):	12.854
Shape Index:	1.111	Fractal Dimension:	1.272
Core Area (ha):	0.000	Num Core Areas:	0
Core Area Index (%):	0.000		

Patch ID:	105	Patch Type:	CLS
Area (ha):	20.633	Landscape Similarity (%):	14.229
Perimeter (m):	3059.747	Edge Contrast (%):	3.612
Shape Index:	1.900	Fractal Dimension:	1.312
Core Area (ha):	1.308	Num Core Areas:	1
Core Area Index (%):	6.341		

Patch ID:	109	Patch Type:	CLS
Area (ha):	7.227	Landscape Similarity (%):	14.229
Perimeter (m):	2034.829	Edge Contrast (%):	27.785
Shape Index:	2.135	Fractal Dimension:	1.362
Core Area (ha):	0.000	Num Core Areas:	0
Core Area Index (%):	0.000		

CLASS INDICES

Patch Type:	CLS	Class Area (ha):	42.129
Total Area (ha):	296.073	Percent of Landscape (%):	14.229
Largest Patch Index (%):	6.969	Number Patches:	4
Patch Density (#/100 ha):	1.351	Mean Patch Size (ha):	10.532
Patch Size SD (ha):	6.729	Patch Size CV (%):	63.894
Total Edge (m):	8261.122	Edge Den (m/ha):	27.902
Con-Wght Edge Den (m/ha):	4.099	Total Edge Contrast (%):	13.426
Mean Edge Contrast (%):	12.243	Area-Wt Mean Edge Con (%):	8.595
Landscape Shape Index:	2.267	Mean Shape Index:	1.789
Area-Weighted Mean Shape:	1.926	Double Log Fractal Index:	1.626
Mean Patch Fractal:	1.320	Area-Weighted Mean Fractal:	1.325
Core % of Landscape (%):	0.442	Total Core Area (ha):	1.308
Number Core Areas:	1	Core Area Den (#/100 ha):	0.338
Mean Core Area 1 (ha):	0.327	Core Area SD 1 (ha):	0.567
Core Area CV 1 (%):	173.205	Mean Core Area 2 (ha):	1.308
Core Area SD 2 (ha):	0.000	Core Area CV 2 (%):	0.000
Total Core Area Index (%):	3.106	Mean Core Area Index (%):	1.585
Intersper/Juxtapos (%):	46.744		

LANDSCAPE INDICES

Total Area (ha):	296.073
Largest Patch Index(%):	17.338
Number of patches:	17
Patch Density (#/100 ha):	5.742
Mean Patch Size (ha):	17.416
Patch Size Standard Dev (ha):	15.048
Patch Size Coeff of Variation (%):	86.404
Total Edge (m):	19821.830
Edge Density (m/ha):	66.949
Contrast-Weight Edge Density (m/ha):	21.170
Total Edge Contrast Index (%):	26.497

Mean Edge Contrast Index (%):	31.872
Area-Wght Mean Class Edge Contrast (%):	30.281
Landscape Shape Index:	3.878
Mean Shape Index:	1.635
Area-Weighted Mean Shape Index:	1.859
Double Log Fractal Dimension:	1.489
Mean Patch Fractal Dimension:	1.294
Area-Weighted Mean Fractal Dimension:	1.296
Total Core Area (ha):	42.862
Number of Core Areas:	14
Core Area Density (#/100 ha):	4.729
Mean Core Area 1 (ha):	2.521
Core Area Standard Dev 1 (ha):	6.931
Core Area Coeff of Variation 1 (%):	274.894
Mean Core Area 2 (ha):	3.062
Core Area Standard Dev 2 (ha):	7.528
Core Area Coeff of Variation 2 (%):	245.900
Total Core Area Index (%):	14.477
Mean Core Area Index (%):	8.468
Shannon’s Diversity Index:	1.503
Simpson’s Diversity Index:	0.704
Modified Simpson’s Diversity Index:	1.218
Patch Richness:	7
Patch Richness Density (#/100 ha):	2.364
Relative Patch Richness (%):	25.926
Shannon’s Evenness Index:	0.772
Simpson’s Evenness Index:	0.821
Modified Simpson’s Evenness Index:	0.626
Interspersion/Juxtaposition (%):	64.713

Date: Tue Oct 26 12:41:29 1993
Image Name: ncveg.svf
Basename For Output Files: ncveg
Rows: 473 Cols: 465 Cellsize: 5.0 Data Type: 1
Edge Dist: 100.0 Max Patch Types Possible: 27
Background Class: -9999
Weight File: contrast.new
ID Image: ncvegid.svf
Descriptor File: classnames.dat
Image Includes a Landscape Border
Proportion of Boundary/Background to Count as Edge: 0.00
Diagonals Used; Proximity Dist (m): 200.0
Nearest Neighbor Calcs
Write Patch Indices; Write Class Indices

PATCH INDICES

Patch ID:	700	Patch Type:	W
Area (ha):	1.117	Landscape Similarity (%):	0.377
Perimeter (m):	550.000	Edge Contrast (%):	6.364
Shape Index:	1.301	Fractal Dimension:	1.056
Core Area (ha):	0.000	Num Core Areas:	0
Core Area Index (%):	0.000	Near Neigh Dist (m):	NONE
Proximity Index:	0.000		

CLASS INDICES

Patch Type:	W	Class Area (ha):	1.117
Total Area (ha):	296.068	Percent of Landscape (%):	0.377
Largest Patch Index (%):	0.377	Number Patches:	1
Patch Density (#/100 ha):	0.338	Mean Patch Size (ha):	1.117
Patch Size SD (ha):	0.000	Patch Size CV (%):	0.000
Total Edge (m):	550.000	Edge Den (m/ha):	1.858
Con-Wght Edge Den (m/ha):	0.118	Total Edge Contrast (%):	6.364
Mean Edge Contrast (%):	6.364	Area-Wt Mean Edge Con(%):	6.364
Landscape Shape Index:	1.353	Mean Shape Index:	1.301
Area-Weighted Mean Shape:	1.301	Double Log Fractal Index:	NA
Mean Patch Fractal:	1.056	Area-Weighted Mean Fractal:	1.056
Core % of Landscape (%):	0.000	Total Core Area (ha):	0.000
Number Core Areas:	0	Core Area Den (#/100 ha):	0.000
Mean Core Area 1 (ha):	0.000	Core Area SD 1 (ha):	0.000
Core Area CV 1 (%):	0.000	Mean Core Area 2 (ha):	0.000
Core Area SD 2 (ha):	0.000	Core Area CV 2 (%):	0.000
Total Core Area Index (%):	0.000	Mean Core Area Index (%):	0.000
Mean NearNeigh Dist(m):	NONE	Near Neighor SD (m):	NA
Nearest Neighbor CV (%):	NA	Mean Prox Index:	0.000
Intersper/Juxtapos (%):	13.219		

PATCH INDICES

Patch ID:	200	Patch Type:	MGF
Area (ha):	18.595	Landscape Similarity (%):	8.410
Perimeter (m):	2320.000	Edge Contrast (%):	80.925
Shape Index:	1.345	Fractal Dimension:	1.049
Core Area (ha):	5.513	Num Core Areas:	1
Core Area Index (%):	29.645	Near Neigh Dist (m):	216.910
Proximity Index:	0.000		

Patch ID:	500	Patch Type:	MGF
Area (ha):	6.305	Landscape Similarity (%):	8.410
Perimeter (m):	1340.000	Edge Contrast (%):	91.000
Shape Index:	1.334	Fractal Dimension:	1.052
Core Area (ha):	0.310	Num Core Areas:	1
Core Area Index (%):	4.917	Near Neigh Dist (m):	216.910
Proximity Index:	0.000		

CLASS INDICES

Patch Type:	MGF	Class Area (ha):	24.900
Total Area (ha):	296.068	Percent of Landscape (%):	8.410
Largest Patch Index (%):	6.281	Number Patches:	2
Patch Density (#/100 ha):	0.676	Mean Patch Size (ha):	12.450
Patch Size SD (ha):	6.145	Patch Size CV (%):	49.357
Total Edge (m):	3660.000	Edge Den (m/ha):	12.362
Con-Wght Edge Den (m/ha):	10.460	Total Edge Contrast (%):	84.613
Mean Edge Contrast (%):	85.962	Area-Wt Mean Edge Con(%):	83.476
Landscape Shape Index:	1.805	Mean Shape Index:	1.340
Area-Weighted Mean Shape:	1.342	Double Log Fractal:	1.015
Mean Patch Fractal:	1.051	Area-Weighted Mean Fractal:	1.050
Core % of Landscape (%):	1.967	Total Core Area (ha):	5.822
Number Core Areas:	2	Core Area Den (#/100 ha):	0.676
Mean Core Area 1 (ha):	2.911	Core Area SD 1 (ha):	2.601
Core Area CV 1 (%):	89.352	Mean Core Area 2 (ha):	2.911
Core Area SD 2 (ha):	2.601	Core Area CV 2 (%):	89.352
Total Core Area Index (%):	23.384	Mean Core Area Index (%):	17.281
Mean NearNeigh Dist (m):	216.910	Nearest Neighbor SD (m):	0.000
Nearest Neighbor CV (%):	0.000	Mean Prox Index:	0.000
Intersper/Juxtapos (%):	61.481		

PATCH INDICES

Patch ID:	600	Patch Type:	MSH
Area (ha):	18.010	Landscape Similarity (%):	6.083
Perimeter (m):	2150.000	Edge Contrast (%):	74.247
Shape Index:	1.267	Fractal Dimension:	1.039
Core Area (ha):	5.553	Num Core Areas:	1
Core Area Index (%):	30.830	Near Neigh Dist (m):	NONE
Proximity Index:	0.000		

CLASS INDICES

Patch Type:	MSH	Class Area (ha):	18.010
Total Area (ha):	296.068	Percent of Landscape (%):	6.083
Largest Patch Index (%):	6.083	Number Patches:	1
Patch Density (#/100 ha):	0.338	Mean Patch Size (ha):	18.010
Patch Size SD (ha):	0.000	Patch Size CV (%):	0.000
Total Edge (m):	2975.000	Edge Den (m/ha):	10.048
Con-Wght Edge Den (m/ha):	7.426	Total Edge Contrast (%):	73.901
Mean Edge Contrast (%):	74.247	Area-Wt Mean Edge Con(%):	74.247
Landscape Shape Index:	1.585	Mean Shape Index:	1.267
Area-Weighted Mean Shape:	1.267	Double Log Fractal Index:	NA
Mean Patch Fractal:	1.039	Area-Weighted Mean Fractal:	1.039
Core % of Landscape (%):	1.875	Total Core Area (ha):	5.553
Number Core Areas:	1	Core Area Den (#/100 ha):	0.338
Mean Core Area 1 (ha):	5.552	Core Area SD 1 (ha):	0.000
Core Area CV 1 (%):	0.000	Mean Core Area 2 (ha):	5.552
Core Area SD 2 (ha):	0.000	Core Area CV 2 (%):	0.000
Total Core Area Index (%):	30.830	Mean Core Area Index (%):	30.830
Mean NearNeigh Dist(m):	NONE	Near Neighor SD (m):	NA
Nearest Neighbor CV (%):	NA	Mean Prox Index:	0.000
Intersper/Juxtapos (%):	29.771		

PATCH INDICES

Patch ID:	102	Patch Type:	MLS
Area (ha):	28.317	Landscape Similarity (%):	48.806
Perimeter (m):	3100.000	Edge Contrast (%):	19.137
Shape Index:	1.456	Fractal Dimension:	1.060
Core Area (ha):	10.977	Num Core Areas:	1
Core Area Index (%):	38.766	Near Neigh Dist (m):	49.497
Proximity Index:	285.044		

Patch ID:	110	Patch Type:	MLS
Area (ha):	51.273	Landscape Similarity (%):	48.806
Perimeter (m):	5720.000	Edge Contrast (%):	24.814
Shape Index:	1.997	Fractal Dimension:	1.105
Core Area (ha):	16.308	Num Core Areas:	2
Core Area Index (%):	31.806	Near Neigh Dist (m):	82.462
Proximity Index:	52.460		

Patch ID:	104	Patch Type:	MLS
Area (ha):	51.362	Landscape Similarity (%):	48.806
Perimeter (m):	7810.000	Edge Contrast (%):	17.213
Shape Index:	2.724	Fractal Dimension:	1.152
Core Area (ha):	11.623	Num Core Areas:	2
Core Area Index (%):	22.628	Near Neigh Dist (m):	25.000
Proximity Index:	200.342		

Patch ID:	108	Patch Type:	MLS
Area (ha):	8.248	Landscape Similarity (%):	48.806
Perimeter (m):	2390.000	Edge Contrast (%):	24.791
Shape Index:	2.081	Fractal Dimension:	1.129
Core Area (ha):	0.000	Num Core Areas:	0

Core Area Index (%):	0.000	Near Neigh Dist (m):	87.321
Proximity Index:	74.190		

Patch ID:	107	Patch Type:	MLS
Area (ha):	5.298	Landscape Similarity (%):	48.806
Perimeter (m):	1090.000	Edge Contrast (%):	20.578
Shape Index:	1.184	Fractal Dimension:	1.031
Core Area (ha):	0.255	Num Core Areas:	1
Core Area Index (%):	4.814	Near Neigh Dist (m):	25.000
Proximity Index:	832.616		

CLASS INDICES

Patch Type:	MLS	Class Area (ha):	144.498
Total Area (ha):	296.068	Percent of Landscape (%):	48.806
Largest Patch Index (%):	17.348	Number Patches:	5
Patch Density (#/100 ha):	1.689	Mean Patch Size (ha):	28.899
Patch Size SD (ha):	19.945	Patch Size CV (%):	69.015
Total Edge (m):	19115.000	Edge Den (m/ha):	64.563
Con-Wght Edge Den (m/ha):	14.399	Total Edge Contrast (%):	19.470
Mean Edge Contrast (%):	21.307	Area-Wt Mean Edge Con(%):	20.843
Landscape Shape Index:	3.565	Mean Shape Index:	1.888
Area-Weighted Mean Shape:	2.125	Double Log Fractal:	1.551
Mean Patch Fractal:	1.096	Area-Weighted Mean Fractal:	1.112
Core % of Landscape (%):	13.228	Total Core Area (ha):	39.163
Number Core Areas:	6	Core Area Den (#/100 ha):	2.027
Mean Core Area 1 (ha):	7.832	Core Area SD 1 (ha):	6.555
Core Area CV 1 (%):	83.691	Mean Core Area 2 (ha):	6.527
Core Area SD 2 (ha):	6.658	Core Area CV 2 (%):	102.005
Total Core Area Index (%):	27.103	Mean Core Area Index (%):	19.603
Mean NearNeigh Dist (m):	53.856	Nearest Neighbor SD (m):	26.917
Nearest Neighbor CV (%):	49.979	Mean Prox Index:	288.930
Intersper/Juxtapos (%):	75.795		

PATCH INDICES

Patch ID:	101	Patch Type:	HLS
Area (ha):	33.065	Landscape Similarity (%):	14.464
Perimeter (m):	7190.000	Edge Contrast (%):	35.184
Shape Index:	3.126	Fractal Dimension:	1.179
Core Area (ha):	0.900	Num Core Areas:	1
Core Area Index (%):	2.722	Near Neigh Dist (m):	125.000
Proximity Index:	6.245		

Patch ID:	106	Patch Type:	HLS
Area (ha):	9.758	Landscape Similarity (%):	14.464
Perimeter (m):	2410.000	Edge Contrast (%):	5.747
Shape Index:	1.929	Fractal Dimension:	1.114
Core Area (ha):	0.275	Num Core Areas:	1
Core Area Index (%):	2.818	Near Neigh Dist (m):	125.000
Proximity Index:	21.162		

CLASS INDICES

Patch Type:	HLS	Class Area (ha):	42.822
Total Area (ha):	296.068	Percent of Landscape (%):	14.464
Largest Patch Index (%):	11.168	Number Patches:	2
Patch Density (#/100 ha):	0.676	Mean Patch Size (ha):	21.411
Patch Size SD (ha):	11.654	Patch Size CV (%):	54.428
Total Edge (m):	9405.000	Edge Den (m/ha):	31.766
Con-Wght Edge Den (m/ha):	9.048	Total Edge Contrast (%):	27.294
Mean Edge Contrast (%):	20.465	Area-Wt Mean Edge Con(%):	28.476
Landscape Shape Index:	2.472	Mean Shape Index:	2.527
Area-Weighted Mean Shape:	2.853	Double Log Fractal:	1.791

Mean Patch Fractal:	1.147	Area-Weighted Mean Fractal:	1.165
Core % of Landscape (%):	0.397	Total Core Area (ha):	1.175
Number Core Areas:	2	Core Area Den (#/100 ha):	0.676
Mean Core Area 1 (ha):	0.587	Core Area SD 1 (ha):	0.312
Core Area CV 1 (%):	53.191	Mean Core Area 2 (ha):	0.587
Core Area SD 2 (ha):	0.312	Core Area CV 2 (%):	53.191
Total Core Area Index (%):	2.744	Mean Core Area Index (%):	2.770
Mean NearNeigh Dist (m):	125.000	Nearest Neighbor SD (m):	0.000
Nearest Neighbor CV (%):	0.000	Mean Prox Index:	13.703
Intersper/Juxtapos (%):	48.817		

PATCH INDICES

Patch ID:	300	Patch Type:	COS
Area (ha):	5.725	Landscape Similarity (%):	7.627
Perimeter (m):	1580.000	Edge Contrast (%):	51.902
Shape Index:	1.651	Fractal Dimension:	1.092
Core Area (ha):	0.000	Num Core Areas:	0
Core Area Index (%):	0.000	Near Neigh Dist (m):	155.081
Proximity Index:	7.008		

Patch ID:	400	Patch Type:	COS
Area (ha):	16.855	Landscape Similarity (%):	7.627
Perimeter (m):	2420.000	Edge Contrast (%):	43.157
Shape Index:	1.474	Fractal Dimension:	1.064
Core Area (ha):	3.830	Num Core Areas:	1
Core Area Index (%):	22.723	Near Neigh Dist (m):	155.081
Proximity Index:	2.380		

CLASS INDICES

Patch Type:	COS	Class Area (ha):	22.580
Total Area (ha):	296.068	Percent of Landscape (%):	7.627
Largest Patch Index (%):	5.693	Number Patches:	2
Patch Density (#/100 ha):	0.676	Mean Patch Size (ha):	11.290
Patch Size SD (ha):	5.565	Patch Size CV (%):	49.291
Total Edge (m):	3630.000	Edge Den (m/ha):	12.261
Con-Wght Edge Den (m/ha):	6.676	Total Edge Contrast (%):	47.173
Mean Edge Contrast (%):	47.529	Area-Wt Mean Edge Con(%):	45.374
Landscape Shape Index:	1.659	Mean Shape Index:	1.562
Area-Weighted Mean Shape:	1.519	Double Log Fractal:	0.790
Mean Patch Fractal:	1.078	Area-Weighted Mean Fractal:	1.071
Core % of Landscape (%):	1.294	Total Core Area (ha):	3.830
Number Core Areas:	1	Core Area Den (#/100 ha):	0.338
Mean Core Area 1 (ha):	1.915	Core Area SD 1 (ha):	1.915
Core Area CV 1 (%):	100.000	Mean Core Area 2 (ha):	3.830
Core Area SD 2 (ha):	0.000	Core Area CV 2 (%):	0.000
Total Core Area Index (%):	16.962	Mean Core Area Index (%):	11.362
Mean NearNeigh Dist (m):	155.081	Nearest Neighbor SD (m):	0.000
Nearest Neighbor CV (%):	0.000	Mean Prox Index:	4.694
Intersper/Juxtapos (%):	54.242		

PATCH INDICES

Patch ID:	103	Patch Type:	CLS
Area (ha):	11.883	Landscape Similarity (%):	14.233
Perimeter (m):	3100.000	Edge Contrast (%):	4.742
Shape Index:	2.248	Fractal Dimension:	1.139
Core Area (ha):	0.000	Num Core Areas:	0
Core Area Index (%):	0.000	Near Neigh Dist (m):	220.511
Proximity Index:	0.000		

Patch ID:	111	Patch Type:	CLS
Area (ha):	2.390	Landscape Similarity (%):	14.233

Perimeter (m):	780.000	Edge Contrast (%):	13.269
Shape Index:	1.261	Fractal Dimension:	1.046
Core Area (ha):	0.000	Num Core Areas:	0
Core Area Index (%):	0.000	Near Neigh Dist (m):	313.050
Proximity Index:	0.000		

Patch ID:	105	Patch Type:	CLS
Area (ha):	20.610	Landscape Similarity (%):	14.233
Perimeter (m):	3810.000	Edge Contrast (%):	3.675
Shape Index:	2.098	Fractal Dimension:	1.121
Core Area (ha):	2.022	Num Core Areas:	1
Core Area Index (%):	9.813	Near Neigh Dist (m):	220.511
Proximity Index:	0.000		

Patch ID:	109	Patch Type:	CLS
Area (ha):	7.258	Landscape Similarity (%):	14.233
Perimeter (m):	2530.000	Edge Contrast (%):	27.419
Shape Index:	2.348	Fractal Dimension:	1.153
Core Area (ha):	0.000	Num Core Areas:	0
Core Area Index (%):	0.000	Near Neigh Dist (m):	313.050
Proximity Index:	0.000		

CLASS INDICES

Patch Type:	CLS	Class Area (ha):	42.140
Total Area (ha):	296.068	Percent of Landscape (%):	14.233
Largest Patch Index (%):	6.961	Number Patches:	4
Patch Density (#/100 ha):	1.351	Mean Patch Size (ha):	10.535
Patch Size SD (ha):	6.716	Patch Size CV (%):	63.747
Total Edge (m):	10425.000	Edge Den (m/ha):	35.212
Con-Wght Edge Den (m/ha):	5.165	Total Edge Contrast (%):	13.509
Mean Edge Contrast (%):	12.276	Area-Wt Mean Edge Con(%):	8.609
Landscape Shape Index:	2.504	Mean Shape Index:	1.989
Area-Weighted Mean Shape:	2.136	Double Log Fractal:	1.598
Mean Patch Fractal:	1.115	Area-Weighted Mean Fractal:	1.127
Core % of Landscape (%):	0.683	Total Core Area (ha):	2.022
Number Core Areas:	1	Core Area Den (#/100 ha):	0.338
Mean Core Area 1 (ha):	0.506	Core Area SD 1 (ha):	0.876
Core Area CV 1 (%):	173.205	Mean Core Area 2 (ha):	2.023
Core Area SD 2 (ha):	0.000	Core Area CV 2 (%):	0.000
Total Core Area Index (%):	4.799	Mean Core Area Index (%):	2.453
Mean NearNeigh Dist (m):	266.780	Nearest Neighbor SD (m):	46.269
Nearest Neighbor CV (%):	17.344	Mean Prox Index:	0.000
Intersper/Juxtapos (%):	46.635		

LANDSCAPE INDICES

Total Area (ha):	296.067
Largest Patch Index(%):	17.348
Number of patches:	17
Patch Density (#/100 ha):	5.742
Mean Patch Size (ha):	17.416
Patch Size Standard Dev (ha):	15.048
Patch Size Coeff of Variation (%):	86.405
Total Edge (m):	24880.000
Edge Density (m/ha):	84.035
Contrast-Weight Edge Density (m/ha):	26.647
Total Edge Contrast Index (%):	26.721
Mean Edge Contrast Index (%):	32.010
Area-Wght Mean Class Edge Contrast (%):	30.538
Landscape Shape Index:	4.290
Mean Shape Index:	1.813
Area-Weighted Mean Shape Index:	2.064

Double Log Fractal Dimension:	1.491
Mean Patch Fractal Dimension:	1.093
Area-Weighted Mean Fractal Dimension:	1.109
Total Core Area (ha):	57.565
Number of Core Areas:	13
Core Area Density (#/100 ha):	4.391
Mean Core Area 1 (ha):	3.386
Core Area Standard Dev 1 (ha):	4.897
Core Area Coeff of Variation 1 (%):	144.609
Mean Core Area 2 (ha):	4.428
Core Area Standard Dev 2 (ha):	5.171
Core Area Coeff of Variation 2 (%):	152.717
Total Core Area Index (%):	19.443
Mean Core Area Index (%):	11.852
Mean Nearest Neighbor (m):	155.359
Nearest Neighbor Standard Dev (m):	90.473
Nearest Neigh Coeff of Variation (%):	58.235
Mean Proximity Index:	87.144
Shannon’s Diversity Index:	1.503
Simpson’s Diversity Index:	0.704
Modified Simpson’s Diversity Index:	1.217
Patch Richness:	7
Patch Richness Density (#/100 ha):	2.364
Relative Patch Richness (%):	25.926
Shannon’s Evenness Index:	0.772
Simpson’s Evenness Index:	0.821
Modified Simpson’s Evenness Index:	0.626
Interspersion/Juxtaposition Index (%):	64.587
Contagion (%):	41.358

Appendix 2: FRAGSTATS User Guidelines

The following instructions provide the information required to install and run the vector and raster versions of FRAGSTATS. The input parameters are described only briefly here; read “FRAGSTATS Overview” to fully understand these guidelines and some of the options. These instructions assume that users have working knowledge of the UNIX operating environment.

Vector Version

Requirements and limitations—The vector version of the program is an Arc/Info AML. It was developed on a SUN workstation in a UNIX operating environment using Arc/Info version 6.1; it will not run with earlier versions of Arc/Info. The AML calls several C programs to perform functions that either are not available in AML or are difficult to implement in AML. These C programs were compiled with the GNU C compiler and may not compile with other compilers. Many loops in this AML go from the minimum to the maximum patch type value. Is it, therefore, most efficient if the patch type codes are sequential; for example, a coverage with 50 patch type codes ranging from 1 to 50 would process much faster than one with 50 codes scattered throughout the range 1000 to 2000. Because of limitations in Arc/Info (it cannot calculate edge-to-edge distances), the vector version of FRAGSTATS does not calculate nearest neighbor metrics. To compute these indices from a vector image, the image must be rasterized first and then analyzed with the raster version of FRAGSTATS. During the rasterization process, depending on the cell size selected, it is possible for polygons to merge or divide. Considerable care, therefore, should be exercised when rasterizing a vector image to ensure meaningful results. The following instructions assume that users have working knowledge of Arc/Info.

Installation—To install FRAGSTATS from the DOS compatible diskette:

1. In DOS, load the FRAGSTATS diskette in your floppy drive, move to the directory you want to install FRAGSTATS in, then type:

pkunzip -d a:\frag.zip

where “a:” should be replaced with the name of your 3.5-inch floppy drive. If your system does not have a copy of the program “pkunzip,” copy the program from the FRAGSTATS diskette, then issue the above command.

2. Three subdirectories will be created: vector, raster, and pcver. Move all the files in the vector directory to the UNIX environment by using FTP or some other file transfer utility.

3. In UNIX, move to the vector directory and rename the files fragstat.aml to fragstats.aml (mv fragstat.aml fragstats.aml). (DOS shortens file names to eight characters.)

4. In UNIX, rename the file fragstat.doc to fragstats.doc (mv fragstat.doc fragstats.doc). This file contains the user guidelines for the vector version of FRAGSTATS.

5. In UNIX, run the script “makeall” to build the C programs required by the FRAGSTATS amls.

Running FRAGSTATS—To run FRAGSTATS in Arc/Info there is a single command line, consisting of several arguments (each described below), issued from the arc prompt as follows:

&run fragstats coverage out_file patchtype edge_dist [background] [max_classes] [weight_file] [patch_id] [descriptor] [bound_wght] [write_patch] [write_class] [path]

NOTE: If fragstats is run without the command line arguments, the user will be prompted for all the necessary inputs.

NOTE: The first four parameters are required; the remaining nine parameters in square brackets are optional; use a # in place of skipped OPTIONAL parameters; enter a carriage return for defaults.

NOTE: If an index is not calculated, a dot (".") will be output to the "basename.patch", "basename.class", and "basename.land" files. The abbreviation "NA" will be output to the "basename.full" file.

Coverage {char}: The name of the input Arc/Info coverage. The coverage must be built for polygons and lines. Acceptable landscape formats are discussed in "FRAGSTATS Overview" (see fig. 2).

Out_file {char}: The basename for the output ASCII files. The extensions ".patch", ".class", ".land", and ".full" will be added to the basename. The output files contain the following information:

basename.patch: each record contains all the patch indices for a given patch separated by spaces.

basename.class: each record contains all the class indices for a given class separated by spaces.

basename.land: each record contains all the landscape indices for a given landscape separated by spaces.

basename.full: a file containing patch, class, and landscape indices for a given landscape. This file is formatted for displaying results.

NOTE: The "basename.patch", "basename.class", and "basename.land" files are in a format that should facilitate input to database management programs; they are not intended for viewing results (records are very long). Also note that if the files already exist, the information for a given landscape will be appended to the existing files.

Patchtype {char}: The name of the numeric attribute containing patch type codes (for example, an attribute "class" defined as 4,4,b that contains patch type codes ranging from 1 to 50). Polygons with patch type codes greater than or equal to zero are considered to be the landscape of interest. Polygons surrounding the landscape can be included so that indices requiring adjacency information can be calculated for polygons bordering the landscape boundary. These landscape border polygons should be set to a negative patch type value (see fig. 2).

Edge_dist {float}: The distance from patch edge in meters to use for determining core area (interior habitat). The core area of a patch is the area remaining after a buffer "edge_dist" wide is removed from the edge of a patch.

Background {integer}: Optional; the patch type (class) value of patches to be ignored in the input landscape [default is NONE]. Background polygons inside the landscape must have a positive patch type code. Background polygons in the landscape border must be set to the negative of the code used for the correponding interior background polygons.

Max_classes {integer}: Optional; the maximum number of patch types (classes) that could be present in the landscape [default is NONE]. This is needed for calculating relative patch richness. If a value is not provided, relate patch richness will not be calculated.

Weight_file {char}: Optional; the name of an ASCII file containing weights for each combination of patch types (classes) [default is NONE]. Each record should contain the numeric representation of two patch types and a weight, separated by commas or spaces. For example:

1,2,.25

1,3,.32

2,3,.45 and so forth.

Weights represent the magnitude of edge contrast between adjacent patch types and must range between 0 and 1 (0 = no contrast, 1 = maximum contrast). Edge contrast weights are used to calculate several edge contrast indices. If the weight file is not provided, these indices are not calculated. Background patch type codes should not be included in this file.

Patch_id {char}: Optional; the name of an attribute that contains unique ID's for each polygon [default is "coverage"#]. If an attribute is not provided, the "coverage"# attribute will be used.

Descriptor {char}: Optional; the name of an attribute that contains character descriptors for each patch type code (class) [default is NONE]. This attribute must be defined as 10 characters or less and may not contain spaces. If provided, the character descriptors will be written to the output files. Otherwise, the numeric patch type codes will be written to the output files.

Bound_wght {float}: Optional; what proportion (equivalent to contrast weight) of the landscape boundary and background class edges should be considered edge [default is 0]? This affects all edge indices.

(0) none; do not count any boundary/background as edge (weight = 0).

(1) all; count all boundary/background as maximum-contrast edge (weight = 1).

(2) other; specify a fraction between 0 and 1.
If you specify a fraction between 0 and 1, then that proportion of the total edge length involving the landscape boundary and any background class will be included as edge in the metrics based on edge length (for example, total edge, edge density). Also, that same fraction will be used as the edge contrast weight for all edge segments involving the landscape boundary and background class in the edge contrast metrics. See "FRAGSTATS Overview" for a more detailed discussion.

Write_patch {y/n}: Optional; should patch indices be written to the output files [default is YES]? If not, the "basename.patch" file will not be created and the patch indices will not be written to the "basename.full" file.

Write_class {y/n}: Optional; should class indices be written to the output files [default is YES]? If not, the "basename.class" file will not be created and the class indices will not be written to the "basename.full" file.

Path {char}: Optional; the name of the directory containing the FRAGSTATS AML's and C programs [default is the current directory]. If these are in a directory other than the one the user is running FRAGSTATS from, the user must set &AMLPATH prior to running FRAGSTATS.

Raster Version

Requirements and limitations—The raster version of the program was developed on a SUN workstation in the UNIX operating environment. It is written in C and compiled with the GNU C compiler and may not compile with other C compilers. In this version of FRAGSTATS the input landscape file and the patch ID file are stored as signed shorts (16 bits). A landscape, therefore, may not contain more than 32,767 different patch types (this shouldn't be a problem!). The input (or output) patch ID image is also limited to 32,767 unique ID's. On DEC or IBM machines, the option of inputting an Arc/Info SVF file (see below) does not work, owing to the different architectures of these machines and SUNs.

The UNIX raster version of FRAGSTATS also has been compiled to run in the DOS environment on a personal computer (PC). The PC version of FRAGSTATS will run only on a 386 or better machine. A math coprocessor also is required. It should run under DOS or Windows. FRAGSTATS will use disk space to allocate virtual memory. The environmental variable TEMP must be set to tell the program where to allocate the swap file (for example, SET TEMP=C:\tmp). Otherwise, the PC version of FRAGSTATS is run exactly the same way as the UNIX version (see guidelines below). Be aware that the PC version of FRAGSTATS may not run successfully on very large and complex landscapes owing to memory limitations of the PC.

Installation—To install FRAGSTATS from the DOS compatible diskette:

1. In DOS, load the FRAGSTATS diskette in your floppy drive, move to the directory you want to install FRAGSTATS in, then type:

pkunzip -d a:\frag.zip

where "a:" should be replaced with the name of your 3.5-inch floppy drive. If your system does not have a copy of the program "pkunzip," copy the program from the FRAGSTATS diskette, then issue the above command.

2. Three subdirectories will be created: vector, raster, and pcver. Move all the files in the raster directory to the UNIX environment by using FTP or some other file transfer utility.

3. In UNIX, move to the raster directory and rename the file fragstat.c to fragstats.c (mv fragstat.c fragstats.c). (DOS shortens file names to eight characters.)

4. In UNIX, rename the file fragstat.doc to fragstats.doc (mv fragstat.doc fragstats.doc). This file contains the user guidelines for the raster version of FRAGSTATS.

5. In UNIX, rename the file fragstat.mak to fragstats.make (mv fragstat.mak fragstats.make).

6. In UNIX, build FRAGSTATS with the command “make -f fragstats.make.”

NOTE: The DOS version of FRAGSTATS does not require any installation.

Running FRAGSTATS—To run FRAGSTATS there is a single command line, consisting of several arguments (each described below), issued from the prompt, as follows:

fragstats in_image out_file cellsize edge_dist data_type [rows] [cols] [background] [max_classes] [weight_file] [id_image] [desc_file] [bound_wght] [diags] [prox_dist] [nndist] [patch_stats] [class_stats]

NOTE: If fragstats is run without the command line arguments, the user will be prompted for all the necessary inputs.

NOTE: The first five parameters are required; the remaining 13 parameters in square parentheses are optional; use a $ in place of skipped OPTIONAL parameters.

NOTE: If an index is not calculated, a dot (“.”) will be output to the “basename.patch”, “basename.class”, and “basename.land” files. The abbreviation “NA” will be output to the “basename.full” file. For nearest neighbor distance, if a patch has no neighbors, “NONE” will be output to “basename.full” and a dot to the other files.

In_image {char}: The name of the input landscape file. File formats are discussed under data_type below and in “FRAGSTATS Overview” (see fig. 3). Patches outside the landscape boundary can be included so that indices requiring adjacency information can be calculated for patches bordering the landscape boundary; these landscape border patches should be set to a negative class value.

Out_file {char}: Basename for output ASCII files. The extensions .patch, .class, .land, and .full will be added to the basename. Note that in the PC version, the extensions have been shortened to .pat, .cla, .lnd (not .lan to avoid conflict with ERDAS file name extensions), and .ful to comply with DOS requirements. The output files contain the following information:

basename.patch: each record contains all the patch indices for a given patch separated by spaces.

basename.class: each record contains all the class indices for a given class separated by spaces.

basename.land: each record contains all the landscape indices for a given landscape separated by spaces.

basename.full: a file containing patch, class, and landscape indices for a given landscape. This file is formatted for displaying results.

NOTE: The “basename.patch”, “basename.class” and “basename.land” files are in a format that should facilitate input to database management programs; they are not intended for viewing results (records are very long). Also note that if the files already exist, the information for a given landscape will be appended to the existing files.

Cellsize {float}: The size of cells in meters in the input image. Cells must be square. The length of one side of a cell should be input.

Edge_dist {float}: The distance from patch edge in meters used to determine core area (interior habitat). The core area of a patch is the area remaining after a buffer “edge_dist” wide is removed from the edge of a patch.

Data_type {integer}: The type of input image file, as follows:

1. SVF file; this is a file created with the Arc/Info “gridsvf” command.

2. ASCII file, no header. Each record should contain one image row. Cell values should be separated by a comma or a space(s).

3. 8-bit binary file, no header.

4. 16-bit binary file, no header.

5. ERDAS image files (4, 8, or 16 bit), not IMAGINE images.

6. IDRISI image files.

Rows {integer}: Optional; the number of rows in the input image. This is only required if data_type is 2, 3, or 4.

Cols {integer}: Optional; the number of columns in the input image. This is only required if data_type is 2, 3, or 4.

Background {integer}: Optional; the value of background cells [default is NONE]. This is required only if there are cells interior or exterior to the landscape of interest that should be ignored (see fig. 3).

Background patch cells inside the landscape should have a positive patch type value. Background cells in the landscape border and outside the area of interest should be set to a negative patch type value (the negative of the value used for interior background patch cells). The user must enter a positive value for background even if the landscape contains only exterior (negative) background cells.

Sometimes this convention is difficult to follow. If only one type of background is found in the image (only interior [positive] or only exterior [negative]), FRAGSTATS will verify that each patch has been classified correctly. If FRAGSTATS finds that an interior background patch has been classified incorrectly as exterior background, it will be reclassified as interior background, and a message will be issued. Incorrectly classified exterior background patches also will be reclassified as exterior, if necessary. A warning will be issued about any questionable patches (for example, background patches along the landscape boundary).

If background patches along the landscape boundary are not classified correctly, the following class and landscape indices may not be calculated accurately: landscape shape index, total edge, edge density, contrast weighted edge density, and total edge contrast index.

Max_classes {integer}: Optional; the maximum number of patch types (classes) that could be present in the landscape [default is NONE]. This is needed for calculating relative patch richness. If a value is not provided, relative patch richness will not be calculated.

Weight_file {char}: Optional; the name of an ASCII file containing weights for each combination of patch types (classes) [default is NONE]. Each record should contain the numeric representation of two patch types and a weight, separated by commas or spaces. For example:

1,2,.25

1,3,.32

2,3,.45 and so forth.

Weights represent the magnitude of edge contrast between adjacent patch types and must range between 0 and 1 (0 = no contrast, 1 = maximum contrast). Edge contrast weights are used to calculate several edge contrast indices. If the weight file is not provided, these indices are not calculated. Background patch type codes should not be included in this file.

Id_image: Optional {char}; the method for assigning patch ID's to each patch in the landscape [default is 2]. Input 1, 2, or the name of a file, as follows:

1. Create and output an image that contains unique ID's for each patch. This allows the user to relate a set of patch statistics to a specific patch in the landscape, if another user-specified ID image is not specified (option 3). This file is named "in_image".ID and is the same "data_type" as "in_image".

2. Do not output an ID image (because it is not important to relate a set of patch statistics to a specific patch in the landscape).

3. The name of an ID image to read. The ID associated with each patch in this image will be written to the output files. The "data_type" of this file must be the same as "in_image".

Desc_file: Optional {char}; the name of an ASCII file containing character descriptors for each patch type (class) [default is NONE]. Each record in the file should contain a numeric patch type value and the character descriptor for that patch type, separated by a comma or space(s). For example:

1 shrubs

2 conifers

3 deciduous

Descriptive names cannot contain spaces. Use an underscore ("_") or a hyphen ("-") in place of blanks. The parameter *max_label_length*, in the file stats.h, controls the printed length of labels in the output files. FRAGSTATS is distributed with *max_label_length* set to 10. To change this, edit the file stats.h, change the parameter to the desired length, then rebuild FRAGSTATS. If *max_label_length* exceeds 22, the columns will not be aligned in the file "basename".full. If this descriptor file is provided, the character descriptors will be written to the output files. Otherwise, the numeric patch type codes will be written to the output files.

Bound_wght {float}: Optional; what proportion (equivalent to contrast weight) of the landscape boundary and background class edges should be considered edge [default is 0]? This affects all edge indices.

(0) none; do not count any boundary/background as edge (weight = 0).

(1) all; count all boundary/background as maximum-contrast edge (weight = 1).

(2) other; specify a fraction between 0 and 1.

If you specify a fraction between 0 and 1, then that proportion of the total edge length involving the landscape boundary and any background class will be included as edge in the metrics based on edge length (for example, total edge, edge density). Also, that same fraction will be used as the edge contrast weight for all edge segments involving the landscape boundary and background class in the edge contrast metrics. See “FRAGSTATS Overview” for a more detailed discussion.

Diags: Optional {y/n}; should diagonal neighbors be evaluated when finding the cells that make up a patch [default is YES]? If not, then the four cells (not eight) surrounding the cell of interest will be evaluated.

Prox_dist: Optional {float}; the search radius in meters to use for calculating the proximity indices [default is NONE]. If a value is not provided, the proximity indices will not be calculated. Note that “nndist” (below) must be “yes” if the proximity indices are to be calculated because they require the same calculations.

Nndist: Optional {y/n}; should indices based on nearest neighbor distance be calculated [default in YES]? This can be very time consuming for landscapes with hundreds of patches per class. This parameter must be “yes” if the proximity indices are to be calculated because they require the same calculations.

Patch_stats: Optional {y/n}; should patch indices be written to the output files [default is YES]? If not, the “basename.patch” file will not be created and the patch indices will not be written to the “basename.full” file.

Class_stats: Optional {y/n}; should class indices be written to the output files [default is YES]? If not, the “basename.class” file will not be created and the class indices will not be written to the “basename.full” file.

Appendix 3: Definition and Description of FRAGSTATS Metrics

In this section, each metric computed in FRAGSTATS is described. Metrics are grouped into patch, class, and landscape indices. Within each group, metrics are ordered in logical fashion according to the aspect of landscape structure measured. For example, the core area metrics (that is, those based on core area measurements) are grouped together. Each metric is defined in mathematical terms, and the measurement units and theoretical range in values are reported. The acronym for the metric given on the left side of the equation is the field name used in the ASCII output files. Where the vector and raster algorithms differ, we define both. A single notation scheme is used consistently for all metrics (table 2). 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 side of the equation is multiplied by 100 to convert a proportion to a percentage, or multiplied or divided by 10,000 to convert square meters 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. For each metric, the mathematical formula is described in narrative terms to facilitate interpretation of the formula.

Table 2—Notation used in FRAGSTATS algorithms

Term	Definition
Subscripts:	
i	1, ... , m or m′ patch types (classes)
j	1, ... , n patches
k	1, ... , m or m′ patch types (classes)
q	1, ... , p disjunct core areas
s	1, ... , n patches, within specified neighborhood
Symbols:	
A	Total landscape area (m^2)
a_{ij}	Area (m^2) of patch ij
a_{ijs}	Area (m^2) of patch ijs within specified neighborhood (m) of patch ij
a_{ij}^c	Core area (m^2) of patch ij based on specified buffer width (m)
a_{ijq}^c	Area (m^2) of disjunct core area q in patch ij based on specified buffer width (m)
p_{ij}	Perimeter (m) of patch ij
p_{ijk}	Length (m) of edge of patch ij adjacent to patch type (class) k
E	Total length (m) of edge in landscape; includes landscape boundary and background edge segments if the user decides to treat boundary and background as edge; otherwise, only boundary segments representing true edge are included

Table 2—Notation used in FRAGSTATS algorithms (continued)

Term	Definition
E'	Total length (m) of edge in landscape; includes entire landscape boundary and background edge segments regardless of whether they represent true edge
e_{ik}	Total length (m) of edge in landscape between patch types (classes) i and k; includes landscape boundary segments representing tree edge only involving patch type i
e'_{ik}	Total length (m) of edge in landscape between patch types (classes) i and k; includes all landscape boundary and background edge segments involving patch type i, regardless of whether they represent true edge
e''_{ik}	Total length (m) of edge in landscape between patch types (classes) i and k; includes the entire landscape boundary and background edge segments, regardless of whether they represent true edge
d_{ik}	Dissimilarity (edge contrast weight) between patch types i and k
N	Total number of patches in the landscape, excluding any background patches
N'	Total number of patches in the landscape that have nearest neighbors
$n = n_i$	Number of patches in the landscape of patch type (class) i
$n' = n'_i$	Number of patches in the landscape of patch type (class) i that have nearest neighbors
n_{ij}^{c}	Number of disjunct core areas in patch ij based on specified buffer width (m)
m	Number of patch types (classes) present in the landscape, excluding the landscape border if present
m'	Number of patch types (classes) present in the landscape, including the landscape border if present
m_{max}	Maximum number of patch types (classes) present in a landscape
h_{ij}	Distance (m) from patch ij to nearest neighboring patch of the same type (class), based on edge-to-edge distance
h_{ijs}	Distance (m) between patch ijs [located within specified neighborhood distance (m) of patch ij] and patch ij, based on edge-to-edge distance
g_{ik}	Number of adjacencies (joins) between pixels of patch types (classes) i and k
P_i	Proportion of the landscape occupied by patch type (class) i

Patch Indices

(P1) Landscape ID

The first field in the patch output file is landscape ID (LID). Landscape ID is set to the name of the input coverage (coverage) in the vector version and the name of the input image (in_image) in the raster version.

(P2) Patch ID

The second field in the patch output file is patch ID (PID). The vector version of FRAGSTATS contains an option (patch_id) to name an attribute that contains unique ID's for each patch. If an attribute is not specified, the "coverage" # attribute is used. Likewise, the raster version of FRAGSTATS contains an option (id_image) to name an image that contains unique ID's for each patch. If an image is not specified, FRAGSTATS will create unique ID's for each patch and optionally produce an image that contains patch ID's that correspond to the FRAGSTATS output.

(P3) Patch Type

The third field in the patch output file is patch type (TYPE). The vector version of FRAGSTATS contains an option (descriptor) to name an attribute that contains character descriptors for each patch type. Likewise, the raster version of FRAGSTATS contains an option (desc_file) to name an ASCII file that contains character descriptors for each patch type. In both versions, if the patch type options are not used, FRAGSTATS will write the numeric patch type codes to TYPE.

(P4) Area

Vector/Raster

$$\text{AREA} = a_{ij}\left(\frac{1}{10{,}000}\right)$$

Units: Hectares.

Range: AREA > 0, without limit.

The range in AREA is limited by the grain and extent of the image, and in a particular application, AREA may be further limited by the specification of a minimum patch size that is larger than the grain.

Description: AREA equals the area (m^2) of the patch, divided by 10,000 (to convert to hectares).

(P5) Landscape Similarity Index

Vector/Raster

$$\text{LSIM} = P_i = \frac{\sum_{j=1}^{n} a_{ij}}{A}(100)$$

Units: Percent.

Range: $0 < \text{LSIM} \le 100$.

LSIM approaches 0 when the corresponding patch type (class) becomes increasingly rare in the landscape. LSIM = 100 when the entire landscape consists of the corresponding patch type; that is, when the entire image is comprised of a single patch.

Description: LSIM equals total class area (m^2) divided by total landscape area (m^2), multiplied by 100 (to convert to a percentage); in other words, LSIM equals the percentage of the landscape comprised of the corresponding patch type. Note that LSIM is equivalent to %LAND at the class level.

(P6) Perimeter

Vector/Raster

$$PERIM = p_{ij}$$

Units: Meters.

Range: PERIM > 0, without limit.

Description: PERIM equals the perimeter (m) of the patch, including any internal holes in the patch.

(P7) Edge Contrast Index

Vector/Raster

$$EDGECON = \frac{\sum_{k=1}^{m'} (p_{ijk} \circ d_{ik})}{p_{ij}} (100)$$

Units: Percent.

Range: $0 \leq$ EDGECON ≤ 100.

EDGECON = 0 if the landscape consists of only 1 patch and either the landscape boundary contains no edge (when a border is present) or the boundary is not to be treated as edge (when a border is absent). Also, EDGECON = 0 when all the patch perimeter segments involve patch type adjacencies that have been given a zero-contrast weight in the edge contrast weight file. EDGECON = 100 when the entire patch perimeter is maximum-contrast edge (d = 1). EDGECON < 100 when a portion of the patch perimeter is less than maximum-contrast edge (d < 1). EDGECON is reported as "NA" in the "basename".full file and a dot "." in the "basename".patch file if a contrast weight file is not specified by the user.

Description: EDGECON 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). Any perimeter segment along the landscape boundary (if a border is absent) or bordering background is assigned the edge contrast weight specified by the user (see bound_wght option).

(P8) Shape Index

Vector

$$SHAPE = \frac{p_{ij}}{2\sqrt{\pi \circ a_{ij}}}$$

Raster

$$SHAPE = \frac{0.25\, p_{ij}}{\sqrt{a_{ij}}}$$

Units: None.

Range: SHAPE ≥ 1, without limit.

SHAPE = 1 when the patch is circular (vector) or square (raster) and increases without limit as patch shape becomes more irregular.

Description: SHAPE equals patch perimeter (m) divided by the square root of patch area (m^2), adjusted by a constant to adjust for a circular standard (vector) or square standard (raster).

(P9) Fractal Dimension

Vector

$$FRACT = \frac{2 \ln p_{ij}}{\ln a_{ij}}$$

Raster

$$FRACT = \frac{2 \ln (0.25\, p_{ij})}{\ln a_{ij}}$$

Units: None.

Range: $1 \le FRACT \le 2$.

A fractal dimension greater than 1 for a 2-dimensional patch indicates a departure from euclidean geometry (that is, an increase in shape complexity). FRACT approaches 1 for shapes with very simple perimeters such as circles or squares, and approaches 2 for shapes with highly convoluted, plane-filling perimeters. If patch area is 1 m^2 (thus, the denominator is 0) and the perimeter is 3.545 m in vector and 4 m in raster, then FRACT = 1; otherwise, FRACT is reported as "NA" in the "basename".full file and as a dot "." in the "basename".patch file.

Description: FRACT equals 2 times the logarithm of patch perimeter (m) divided by the logarithm of patch area (m^2); the raster formula is adjusted to correct for the bias in perimeter (Li 1990).

(P10) Core Area

Vector/Raster

$$CORE = a_{ij}^{c} \left(\frac{1}{10,000} \right)$$

Units: Hectares.

Range: $CORE \ge 0$, without limit.

CORE = 0 when every location within the patch is within the specified edge distance from the patch perimeter (that is, edge width). CORE approaches AREA as the specified edge distance decreases and as patch shape is simplified.

Description: CORE equals the area (m^2) within the patch that is further than the specified edge distance from the patch perimeter, divided by 10,000 (to convert to hectares). Note that raster version of FRAGSTATS employs the 4-neighbor approach when determining which cells are core and which are in the edge buffer.

(P11) Number of Core Areas

Vector/Raster

$$NCORE = n_{ij}^{c}$$

Units: None.

Range: $NCORE \ge 0$, without limit.

NCORE = 0 when CORE = 0 (that is, every location within the patch is within the specified edge distance from the patch perimeter [edge width]). NCORE > 1 when, because of shape, the patch contains disjunct core areas.

Description: NCORE equals the number of disjunct core areas contained within the patch boundary.

(P12) Core Area Index

Vector/Raster

$$CAI = \frac{a_{ij}^{c}}{a_{ij}} (100)$$

Units: Percent.

Range: $0 \leq CAI < 100$.

CAI = 0 when CORE = 0 (that is, every location within the patch is within the specified edge distance from the patch perimeter [edge width]); 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.

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.

(P13) Nearest Neighbor Distance

Raster

$$NEAR = h_{ij}$$

Units: Meters.

Range: NEAR > 0, without limit.

NEAR is reported as “None” in the “basename.full” output file and a dot in the “basename.patch” output file if no other patch of the same type exists in the landscape.

Description: NEAR equals the distance (m) to the nearest neighboring patch of the same type, based on shortest edge-to-edge distance.

(P14) Proximity Index

Raster

$$PROXIM = \sum_{s=1}^{n} \frac{a_{ijs}}{h_{ijs}^{2}}$$

Units: None.

Range: $PROXIM \geq 0$.

PROXIM = 0 if a patch has no neighbors of the same patch type within the specified search radius. PROXIM 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 and less fragmented in distribution. The upper limit of PROXIM is affected by the search radius and minimum distance between patches. PROXIM is reported as “NA” in the “basename”.full file and a dot “.” in the “basename”.patch file if a search radius is not specified by the user.

Description: PROXIM 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.

Class Indices

(C1) Landscape ID (LID)

The first field in the class output file is landscape ID (LID); it is defined as in the patch output file (see previous discussion).

(C2) Patch Type (TYPE)

The second field in the class output file is patch type (TYPE); it is defined as in the patch output file (see previous discussion).

(C3) Class Area

Vector/Raster

$$CA = \sum_{j=1}^{n} a_{ij} \left(\frac{1}{10,000} \right)$$

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.

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.

(C4) Total Landscape Area

Vector/Raster

$$TA = A \left(\frac{1}{10,000} \right)$$

Units: Hectares.

Range: TA > 0, without limit.

Description: TA equals the area (m^2) of the landscape, divided by 10,000 (to convert to hectares). TA excludes the area of any background patches within the landscape.

(C5) Percentage of Landscape

Vector/Raster

$$\%LAND = P_i = \frac{\sum_{j=1}^{n} a_{ij}}{A} (100)$$

Units: Percent.

Range: 0 < %LAND ≤ 100.

%LAND approaches 0 when the corresponding patch type (class) becomes increasingly rare in the landscape. %LAND = 100 when the entire landscape consists of a single patch type; that is, when the entire image is comprised of a single patch.

Description: %LAND 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, %LAND equals the percentage the landscape comprised of the corresponding patch type. Note that %LAND is equivalent to LSIM at the patch level.

(C6) Largest Patch Index

Vector/Raster

$$LPI = \frac{\max_{j=1}^{n}(a_{ij})}{A}(100)$$

Units: Percent.

Range: 0 < LPI ≤ 100.

LPI approaches 0 when the largest patch of the corresponding patch type becomes increasingly smaller. 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.

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.

(C7) Number of Patches

Vector/Raster

$$NP = n_i$$

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.

Description: NP equals the number of patches of the corresponding patch type (class).

(C8) Patch Density

Vector/Raster

$$PD = \frac{n_i}{A}(10{,}000)(100)$$

Units: Number per 100 hectares.

Range: PD > 0, without limit.

Description: PD equals the number of patches of the corresponding patch type (NP) divided by total landscape area, multiplied by 10,000 and 100 (to convert to 100 hectares).

(C9) Mean Patch Size

Vector/Raster

$$MPS = \frac{\sum_{j=1}^{n} a_{ij}}{n_i}\left(\frac{1}{10,000}\right)$$

Units: Hectares.

Range: MPS > 0, without limit.

The range in MPS is limited by the grain and extent of the image and the minimum patch size in the same manner as patch area (AREA).

Description: MPS equals the sum of the areas (m^2) of all patches of the corresponding patch type, divided by the number of patches of the same type, divided by 10,000 (to convert to hectares).

(C10) Patch Size Standard Deviation

Vector/Raster

$$PSSD = \sqrt{\frac{\sum_{j=1}^{n}\left[a_{ij} - \left(\frac{\sum_{j=1}^{n} a_{ij}}{n_i}\right)\right]^2}{n_i}}\left(\frac{1}{10,000}\right)$$

Units: Hectares.

Range: PSSD ≥ 0, without limit.

PSSD = 0 when all patches in the class are the same size or when there is only 1 patch (that is, no variability in patch size).

Description: PSSD equals the square root of the sum of the squared deviations of each patch area (m^2) from the mean patch size of the corresponding patch type, divided by the number of patches of the same type, divided by 10,000 (to convert to hectares); that is, the root mean squared error (deviation from the mean) in patch size. This is the population standard deviation, not the sample standard deviation.

(C11) Patch Size Coefficient of Variation

Vector/Raster

$$PSCV = \frac{PSSD}{MPS}(100)$$

Units: Percent.

Range: PSCV ≥ 0, without limit.

Description: PSCV equals the standard deviation in patch size (PSSD) divided by the mean patch size of the corresponding patch type (MPS), multiplied by 100 (to convert to percent); that is, the variability in patch size relative to the mean patch size. This is the population coefficient of variation, not the sample coefficient of variation.

(C12) Total Edge

Vector/Raster

$$TE = \sum_{k=1}^{m'} e_{ik}$$

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.

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 (that is, contrast weight > 0). 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 background edge segments involving the corresponding patch type.

(C13) Edge Density

Vector/Raster

$$ED = \frac{\sum_{k=1}^{m'} e_{ik}}{A} (10,000)$$

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.

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 (that is, contrast weight > 0). 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 background edge segments involving the corresponding patch type.

(C14) Contrast-Weighted Edge Density

Vector/Raster

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

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 none of the landscape boundary and background edge be treated as edge. CWED increases as the amount of class edge in the landscape increases or as the contrast in edges involving the corresponding patch type increases (that is, contrast weight approaches 1), or both. CWED is reported as "NA" in the "basename".full file and as a dot "." in the "basename".class file if a contrast weight file is not specified by the user.

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). If a landscape border is present, CWED includes landscape boundary segments involving the corresponding patch type and representing true edge only (that is, contrast weight > 0). If a landscape border is absent, all landscape boundary edge segments involving the corresponding patch type are assigned the edge contrast weight specified by the user (see bound_wght option). This is equivalent to treating the specified proportion of all boundary edge segments involving the corresponding patch type as maximum-contrast edge. Regardless of whether a landscape border is present or not, all background edge segments involving the corresponding patch type are assigned the edge contrast weight specified by the user. Again, this is equivalent to treating the specified proportion of all background edge segments involving the corresponding patch type as maximum-contrast edge.

(C15) Total Edge Contrast Index

Vector/Raster

$$TECI = \frac{\sum_{k=1}^{m'} (e_{ik} \circ d_{ik})}{\sum_{k=1}^{m'} e'_{ik}} (100)$$

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 none of the landscape boundary and background edge be treated as edge. TECI approaches 0 as the contrast in edges involving the corresponding patch type lessen (that is, contrast weight approaches 0). TECI = 100 when all class edge is maximum contrast (that is, contrast weight = 1). TECI is reported as “NA” in the “basename”.full file and as a dot “.” in the “basename”.class file if a contrast weight file is not specified by the user.

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). In the numerator, if a landscape border is present, all edge segments along the landscape boundary involving the corresponding patch type are treated according to their edge contrast weights as designated in the contrast weight file. If a landscape border is absent, all landscape boundary segments involving the corresponding patch type are assigned the edge contrast weight specified by the user (see bound_wght option). This is equivalent to treating the specified proportion of all boundary edge segments involving the corresponding patch type as maximum-contrast edge and the remainder as zero-contrast edge. Regardless of whether a landscape border is present or not, all background edge segments involving the corresponding patch type are assigned the edge contrast weight specified by the user. Again, note that this is equivalent to treating the specified proportion of all background edge segments involving the corresponding patch type as maximum-contrast edge and the remainder as zero-contrast edge. In the denominator, all edges involving the corresponding patch type are included, including the landscape boundary and background edge segments, regardless of whether they represent true edge or not or how the user chooses to handle boundary and background edges.

(C16) Mean Edge Contrast Index

Vector/Raster

$$MECI = \frac{\sum_{j=1}^{n} \left[\frac{\sum_{k=1}^{m'} (p_{ijk} \circ d_{ik})}{p_{ij}} \right]}{n_i} (100)$$

Units: Percent.

Range: 0 ≤ MECI ≤ 100.

MECI = 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. MECI approaches 0 as the contrast in edges involving the corresponding patch type lessen (that is, contrast weight approaches 0). MECI = 100 when all class edge is maximum contrast (that is, contrast weight = 1). MECI is reported as “NA” in the “basename”.full file and as a dot “.” in the “basename”.class file if a contrast weight file is not specified by the user.

Description: MECI equals the sum of the segment lengths (m) of each patches' perimeter multiplied by their corresponding contrast weights, divided by total patch perimeter (m), summed across all patches of the corresponding patch type, divided by the number of patches of the same type, multiplied by 100 (to convert to a percentage). If a landscape border is present, any patch perimeter segments along the landscape boundary are treated according to their edge contrast weights as designated in the contrast weight file. If a landscape border is absent, any patch perimeter segments along the landscape boundary are assigned the edge contrast weight specified by the user (see bound_wght option). Regardless of whether a landscape border is present or not, all patch perimeter segments bordering background are assigned the edge contrast weight specified by the user.

(C17) Area-Weighted Mean Edge Contrast Index

Vector/Raster

$$AWMECI = \sum_{j=1}^{n} \left(\left[\frac{\sum_{k=1}^{m'} (p_{ijk} \circ d_{ik})}{p_{ij}} \right] \left[\frac{a_{ij}}{\sum_{j=1}^{n} a_{ij}} \right] \right) (100)$$

Units: Percent.

Range: $0 \leq AWMECI \leq 100$.

AWMECI = 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. AWMECI approaches 0 as the contrast in edges involving the corresponding patch type lessen (that is, contrast weight approaches 0). AWMECI = 100 when all class edge is maximum contrast (that is, contrast weight = 1). AWMECI is reported as "NA" in the "basename".full file and as a dot "." in the "basename".class file if a contrast weight file is not specified by the user.

Description: AWMECI equals the sum of the segment lengths (m) of each patches' perimeter multiplied by their corresponding contrast weights, divided by total patch perimeter (m), multiplied by patch area (m^2) divided by the sum of patch areas, summed across all patches of the corresponding patch type, multiplied by 100 (to convert to a percentage). If a landscape border is present, any patch perimeter segments along the landscape boundary are treated according to their edge contrast weights as designated in the contrast weight file. If a landscape border is absent any patch perimeter segments along the landscape boundary are assigned the edge contrast weight specified by the user (see bound_wght option). Regardless of whether a landscape border is present or not, all patch perimeter segments bordering background are assigned the edge contrast weight specified by the user. AWMECI is similar to MECI except that each patch weighted by its size in computing the average patch edge contrast index.

(C18) Landscape Shape Index

Vector

$$LSI = \frac{\sum_{k=1}^{m} e''_{ik}}{2\sqrt{\pi \circ A}}$$

Raster

$$LSI = \frac{0.25\sum_{k=1}^{m} e''_{ik}}{\sqrt{A}}$$

Units: None.

Range: LSI ≥ 1, without limit.

LSI = 1 when the landscape consists of a single patch of the corresponding type and is circular (vector) or square (raster); LSI increases without limit as landscape shape becomes more irregular or as the length of edge within the landscape of the corresponding patch type increases, or both.

Description: LSI equals the sum of the landscape boundary (regardless of whether it represents true edge or not) and all edge segments (m) within the landscape boundary involving the corresponding patch type (including those bordering background), divided by the square root of the total landscape area (m^2), adjusted by a constant for a circular standard (vector) or square standard (raster).

(C19) Mean Shape Index

Vector

$$MSI = \frac{\sum_{j=1}^{n}\left(\frac{p_{ij}}{2\sqrt{\pi \circ a_{ij}}}\right)}{n_i}$$

Raster

$$MSI = \frac{\sum_{j=1}^{n}\left(\frac{0.25p_{ij}}{\sqrt{a_{ij}}}\right)}{n_i}$$

Units: None.

Range: MSI ≥ 1, without limit.

MSI = 1 when all patches of the corresponding patch type are circular (vector) or square (raster); MSI increases without limit as the patch shapes become more irregular.

Description: MSI equals the sum of the patch perimeter (m) divided by the square root of patch area (m^2) for each patch of the corresponding patch type, adjusted by a constant to adjust for a circular standard (vector) or square standard (raster), divided by the number of patches of the same type; in other words, MSI equals the average shape index (SHAPE) of patches of the corresponding patch type.

(C20) Area-Weighted Mean Shape Index

Vector

$$AWMSI = \sum_{j=1}^{n}\left[\left(\frac{p_{ij}}{2\sqrt{\pi \circ a_{ij}}}\right)\left(\frac{a_{ij}}{\sum_{j=1}^{n} a_{ij}}\right)\right]$$

Raster

$$AWMSI = \sum_{j=1}^{n}\left[\left(\frac{0.25p_{ij}}{\sqrt{a_{ij}}}\right)\left(\frac{a_{ij}}{\sum_{j=1}^{n} a_{ij}}\right)\right]$$

Units: None.

Range: AWMSI ≥ 1, without limit.

AWMSI = 1 when all patches of the corresponding patch type are circular (vector) or square (raster); AWMSI increases without limit as the patch shapes become more irregular.

Description: AWMSI equals the sum, across all patches of the corresponding patch type, of each patch perimeter (m) divided by the square root of patch area (m^2), adjusted by a constant to adjust for a circular standard (vector) or square standard (raster), multiplied by the patch area (m^2) divided by total class area (sum of patch area for each patch of the corresponding patch type). In other words, AWMSI equals the average shape index (SHAPE) of patches of the corresponding patch type, weighted by patch area so that larger patches weigh more than smaller patches.

(C21) Double Log Fractal Dimension

Vector/Raster

$$DLFD = \frac{2}{\left(\dfrac{\left[n_i \sum_{j=1}^{n} (\ln p_{ij} \cdot \ln a_{ij}) \right] - \left[\left(\sum_{j=1}^{n} \ln p_{ij} \right) \left(\sum_{j=1}^{n} \ln a_{ij} \right) \right]}{\left(n_i \sum_{j=1}^{n} \ln p_{ij}^2 \right) - \left(\sum_{j=1}^{n} \ln p_{ij} \right)^2} \right)}$$

Units: None.

Range: $1 \le DLFD \le 2$.

A fractal dimension greater than 1 for a 2-dimensional landscape mosaic indicates a departure from a euclidean geometry (that is, an increase in patch shape complexity). DLFD approaches 1 for shapes with very simple perimeters such as circles or squares, and approaches 2 for shapes with highly convoluted, plane-filling perimeters. DLFD employs regression techniques and is subject to small sample problems. Specifically, DLFD may greatly exceed the theoretical range in values when the number of patches is small (for example, <10), and its use should be avoided in such cases. In addition, DLFD requires patches to vary in size. Thus, DLFD is undefined and reported as “NA” in the “basename”.full file and as a dot “.” in the “basename”.class file if all patches are the same size or there is only 1 patch.

Description: DLFD 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).

(C22) Mean Patch Fractal Dimension

Vector

$$MPFD = \frac{\sum_{j=1}^{n} \left(\dfrac{2 \ln p_{ij}}{\ln a_{ij}} \right)}{n_i}$$

Raster

$$MPFD = \frac{\sum_{j=1}^{n} \left(\dfrac{2 \ln (0.25 p_{ij})}{\ln a_{ij}} \right)}{n_i}$$

Units: None.

Range: $1 \le MPFD \le 2$.

A fractal dimension greater than 1 for a 2-dimensional landscape mosaic indicates a departure from a euclidean geometry (that is, an increase in patch shape complexity). MPFD approaches 1 for shapes with very simple perimeters, such as circles or squares, and approaches 2 for shapes with highly convoluted, plane-filling perimeters.

Description: MPFD equals the sum of 2 times the logarithm of patch perimeter (m) divided by the logarithm of patch area (m^2) for each patch of the corresponding patch type, divided by the number of patches of the same type; the raster formula is adjusted to correct for the bias in perimeter (Li 1990).

(C23) Area-Weighted Mean Patch Fractal Dimension

Vector

$$AWMPFD = \sum_{j=1}^{n} \left[\left(\frac{2 \ln p_{ij}}{\ln a_{ij}} \right) \left(\frac{a_{ij}}{\sum_{j=1}^{n} a_{ij}} \right) \right]$$

Raster

$$AWMPFD = \sum_{j=1}^{n} \left[\left(\frac{2 \ln (0.25 p_{ij})}{\ln a_{ij}} \right) \left(\frac{a_{ij}}{\sum_{j=1}^{n} a_{ij}} \right) \right]$$

Units: None.

Range: $1 \le AWMPFD \le 2$.

A fractal dimension greater than 1 for a 2-dimensional landscape mosaic indicates a departure from a euclidean geometry (that is, an increase in patch shape complexity). AWMPFD approaches 1 for shapes with very simple perimeters, such as circles or squares, and approaches 2 for shapes with highly convoluted, plane-filling perimeters.

Description: AWMPFD equals the sum, across all patches of the corresponding patch type, of 2 times the logarithm of patch perimeter (m) divided by the logarithm of patch area (m^2), multiplied by the patch area (m^2) divided by total class area (sum of patch area for each patch of the corresponding patch type); the raster formula is adjusted to correct for the bias in perimeter (Li 1990). In other words, AWMPFD equals the average patch fractal dimension (FRACT) of patches of the corresponding patch type, weighted by patch area so that larger patches weigh more than smaller patches.

(C24) Core Area Percentage of Landscape

Vector/Raster

$$C\%LAND = \frac{\sum_{j=1}^{n} a_{ij}^{c}}{A} (100)$$

Units: Percent.

Range: $0 \le C\%LAND < 100$.

C%LAND approaches 0 when core area of the corresponding patch type (class) becomes increasingly rare in the landscape, because of smaller patches or more convoluted patch shapes, or both. C%LAND approaches 100 when the entire landscape consists of a single patch type (when the entire image is comprised of a single patch) and the specified edge width approaches 0.

Description: C%LAND 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, C%LAND equals the percentage of the landscape comprised of core area of the corresponding patch type.

(C25) Total Core Area

Vector/Raster

$$TCA = \sum_{j=1}^{n} a_{ij}^{c} \left(\frac{1}{10{,}000} \right)$$

Units: Hectares.

Range: TCA ≥ 0, without limit.

TCA = 0 when every location within each patch of the corresponding patch type is within the specified edge distance from the patch perimeters. TCA approaches CA as the specified edge distance decreases and as patch shapes are simplified.

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).

(C26) Number of Core Areas

Vector/Raster

$$NCA = \sum_{j=1}^{n} n_{ij}^{c}$$

Units: None.

Range: NCA ≥ 0, without limit.

NCA = 0 when TCA = 0 (that is, every location within patches of the corresponding patch type are within the specified edge distance from the patch perimeters). NCA > 1 when, because of patch shape complexity, a patch contains more than 1 core area.

Description: NCA 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 class.

(C27) Core Area Density

Vector/Raster

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

Units: Number per 100 hectares.

Range: CAD ≥ 0, without limit.

CAD = 0 when TCA = 0 (that is, every location within patches of the corresponding patch type are within the specified edge distance from the patch perimeters); in other words, when there are no core areas.

Description: CAD equals the sum of number of disjunct core areas contained within each patch of the corresponding patch type, divided by total landscape area, multiplied by 10,000 and 100 (to convert to 100 hectares).

(C28) Mean Core Area Per Patch

Vector/Raster

$$MCA1 = \frac{\sum_{j=1}^{n} a_{ij}^{c}}{n_i}\left(\frac{1}{10,000}\right)$$

Units: Hectares.

Range: MCA1 ≥ 0, without limit.

Ultimately, the range in MCA1 is limited by the grain and extent of the image and the minimum patch size in the same manner as mean patch size (MPS), but MCA1 is also effected by the specified edge width. MCA1 = 0 when total core area = 0 (every location within patches of the corresponding patch type are within the specified edge distance from the patch perimeters); in other words, when there are no core areas. MCA1 approaches MPS as the specified edge width decreases and as patch shapes are simplified.

Description: MCA1 equals the sum of the core areas of each patch (m^2) of the corresponding patch type, divided by the number of patches of the same type, divided by 10,000 (to convert to hectares). Note that MCA1 equals the average core area per patch, not the average size of disjunct core areas, as in MCA2.

(C29) Patch Core Area Standard Deviation

Vector/Raster

$$CASD1 = \sqrt{\frac{\sum_{j=1}^{n}\left[a_{ij}^{c} - \left(\frac{\sum_{j=1}^{n} a_{ij}^{c}}{n_i}\right)\right]^2}{n_i}}\left(\frac{1}{10,000}\right)$$

Units: Hectares.

Range: CASD1 ≥ 0, without limit.

CASD1 = 0 when all patches in the class have the same core area or when there is only 1 patch (that is, no variability in core area).

Description: CASD1 equals the square root of the sum of the squared deviations of each patch core area (m^2) from the mean core area per patch (MCA1) of the corresponding patch type, divided by the number of patches of the same type, divided by 10,000 (to convert to hectares); that is, the root mean squared error (deviation from the mean) in patch core area. This is the population standard deviation, not the sample standard deviation, and CASD1 represents the variation in core area among patches, not among disjunct core areas as in CASD2.

(C30) Patch Core Area Coefficient of Variation

Vector/Raster

$$CACV1 = \frac{CASD1}{MCA1}(100)$$

Units: Percent.

Range: CACV1 ≥ 0, without limit.

CACV1 = 0 when all patches in the class have the same core area or when there is only 1 patch (that is, no variability in core area).

Description: CACV1 equals the standard deviation in core area of patches (CASD1) divided by the mean core area per patch (MCA1) of the corresponding patch type, multiplied by 100 (to convert to percent); that is, the variability in core area relative to the mean core area. This is the population coefficient of variation, not the sample coefficient of variation, and CACV1 represents the variation in core area among patches, not among disjunct core areas as in CACV2.

(C31) Mean Area Per Disjunct Core

Vector/Raster

$$MCA2 = \frac{\sum_{j=1}^{n}\sum_{q=1}^{p} a_{ijq}{}^{c}}{\sum_{j=1}^{n} n_{ij}{}^{c}}\left(\frac{1}{10,000}\right)$$

Units: Hectares.

Range: MCA2 ≥ 0, without limit.

Ultimately, the range in MCA2 is limited by the grain and extent of the image and the minimum patch size in the same manner as mean patch size (MPS), but MCA2 is also effected by the specified edge width. MCA2 = 0 when total core area = 0 (every location within patches of the corresponding patch type are within the specified edge distance from the patch perimeters); in other words, when there are no core areas. MCA2 approaches MPS as the specified edge width decreases and as patch shapes are simplified.

Description: MCA2 equals the sum of the disjunct core areas of each patch (m^2) of the corresponding patch type, divided by the number of disjunct core areas of the same type, divided by 10,000 (to convert to hectares). Note that MCA2 equals the average size of disjunct core areas, not the average core area per patch, as in MCA1.

(C32) Disjunct Core Area Standard Deviation

Vector/Raster

$$CASD2 = \sqrt{\frac{\sum_{j=1}^{n}\sum_{q=1}^{p}\left[a_{ijq}{}^{c} - \left(\frac{\sum_{j=1}^{n}\sum_{q=1}^{p}a_{ijq}{}^{c}}{\sum_{j=1}^{n}n_{ij}{}^{c}}\right)\right]}{\sum_{j=1}^{n}n_{ij}{}^{c}}}\left(\frac{1}{10{,}000}\right)$$

Units: Hectares.

Range: CASD2 ≥ 0, without limit.

CASD2 = 0 when all disjunct core areas are the same size or when there is only 1 core area (that is, no variability in core area).

Description: CASD2 equals the square root of the sum of the squared deviations of each disjunct core area (m^2) from the mean size of disjunct core areas (MCA2) of the corresponding patch type, divided by the number of disjunct core areas of the same type, divided by 10,000 (to convert to hectares); that is, the root mean squared error (deviation from the mean) in the size of disjunct core areas. This is the population standard deviation, not the sample standard deviation, and CASD2 represents the variation in size of disjunct core areas, not patch core areas as in CASD1.

(C33) Disjunct Core Area Coefficient of Variation

Vector/Raster

$$CACV2 = \frac{CASD2}{MCA2}(100)$$

Units: Percent.

Range: CACV2 ≥ 0, without limit.

CACV2 = 0 when all disjunct core areas are the same size or when there is only 1 core area (that is, no variability in core area).

Description: CACV2 equals the standard deviation in the size of disjunct core areas (CASD2) divided by the mean size of disjunct core areas (MCA2) of the corresponding patch type, multiplied by 100 (to convert to percent); that is, the variability in core area relative to the mean core area. This is the population coefficient of variation, not the sample coefficient of variation, and CACV2 represents the variation in size of disjunct core areas, not patch core areas as in CACV1.

(C34) Total Core Area Index

Vector/Raster

$$TCAI = \frac{\sum_{j=1}^{n} a_{ij}^{c}}{\sum_{j=1}^{n} a_{ij}} (100)$$

Units: Percent.

Range: $0 \leq TCAI < 100$.

TCAI = 0 when none of the patches of the corresponding patch type contains any core area (CORE = 0 for every patch); that is, when the landscape contains no core area for the corresponding patch type. TCAI approaches 100 when the patches of the corresponding patch type, because of size, shape, and edge width, contain mostly core area.

Description: TCAI equals the sum of the core areas of each patch (m^2) of the corresponding patch type, divided by the sum of the areas of each patch (m^2) of the same type, multiplied by 100 (to convert to a percentage); that is, TCAI equals the percentage of a patch type in the landscape that is core area based on a specified edge width.

(C35) Mean Core Area Index

Vector/Raster

$$MCAI = \frac{\sum_{j=1}^{n} \left(\frac{a_{ij}^{c}}{a_{ij}} \right)}{n_i} (100)$$

Units: Percent.

Range: $0 \leq MCAI < 100$.

MCAI = 0 when none of the patches of the corresponding patch type contain any core area (CORE = 0 for every patch); that is, when the landscape contains no core area for the corresponding patch type. MCAI approaches 100 when the patches of the corresponding patch type, because of size, shape, and edge width, contain mostly core area.

Description: MCAI equals the sum of the proportion of each patch that is core area (core area of each patch [m^2] divided by the area of each patch [m^2]) of the corresponding patch type, divided by the number of patches of the same type, multiplied by 100 (to convert to a percentage); in other words, MCAI equals the average percentage of a patch of the corresponding patch type in the landscape that is core area based on a specified edge width.

(C36) Mean Nearest Neighbor Distance

Raster

$$MNN = \frac{\sum_{j=1}^{n'} h_{ij}}{n'_i}$$

Units: Meters.

Range: MNN > 0, without limit.

MNN is reported as “None” in the “basename”.full file and as a dot “.” in the “basename”.class file if there is only 1 patch of the corresponding patch type. Similarly, MNN is reported as “NA” in the “basename”.full file and a dot “.” in the “basename”.class file if the user chooses not to calculate nearest neighbor distance.

Description: MNN equals the sum of the distance (m) to the nearest neighboring patch of the same type, based on nearest edge-to-edge distance, for each patch of the corresponding patch type, divided by the number of patches of the same type.

(C37) Nearest Neighbor Standard Deviation

Raster

$$NNSD = \sqrt{\frac{\sum_{j=1}^{n'} \left[h_{ij} - \left(\frac{\sum_{j=1}^{n'} h_{ij}}{n'_i} \right) \right]^2}{n'_i}}$$

Units: Meters.

Range: NNSD ≥ 0, without limit.

NNSD = 0 when there are only 2 patches in the class or all patches have the same nearest neighbor distance (no variability in nearest neighbor distance). NNSD is reported as “NA” in the “basename”.full file and as a dot “.” in the “basename”.class file if there is only 1 patch of the corresponding patch type. Similarly, NNSD is reported as “NA” in the “basename”.full file and as a dot “.” in the “basename”.class file if the user chooses not to calculate nearest neighbor distance.

Description: NNSD equals the square root of the sum of the squared deviations of each patches’ nearest neighbor distance (m) from the mean nearest neighbor distance (MNN) 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 patch nearest neighbor distance. This is the population standard deviation, not the sample standard deviation.

(C38) Nearest Neighbor Coefficient of Variation

Raster

$$NNCV = \frac{NNSD}{MNN}(100)$$

Units: Percent.

Range: NNCV ≥ 0, without limit.

NNCV = 0 when there are only 2 patches in the class or all patches have the same nearest neighbor distance (no variability in nearest neighbor distance; NNSD = 0). NNCV is reported as "NA" in the "basename".full file and as a dot "." in the "basename".class file if there is only 1 patch of the corresponding patch type. Similarly, NNCV is reported as "NA" in the "basename".full file and as a dot "." in the "basename".class file if the user chooses not to calculate nearest neighbor distance.

Description: NNCV equals the standard deviation in nearest neighbor distances (NNSD) divided by the mean nearest neighbor distance (MNN) of the corresponding patch type, multiplied by 100 (to convert to percent); that is, the variability in nearest neighbor distance relative to the mean nearest neighbor distance. This is the population coefficient of variation, not the sample coefficient of variation.

(C39) Mean Proximity Index

Raster

$$MPI = \frac{\sum_{j=1}^{n}\sum_{s=1}^{n}\frac{a_{ijs}}{h_{ijs}^{2}}}{n_i}$$

Units: None.

Range: MPI ≥ 0.

MPI = 0 if all patches of the corresponding patch type have no neighbors of the same type within the specified search radius. MPI increases as patches of the corresponding patch type become less isolated and the patch type becomes less fragmented in distribution. The upper limit of MPI is determined by the search radius and minimum distance between patches. MPI is reported as "NA" in the "basename".full file and as a dot "." in the "basename".class file if the user chooses not to calculate the proximity index.

Description: MPI 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, summed across all patches of the same type and divided by the total number of patches in the class. In other words, MPI equals the average proximity index for patches in the class. When the search buffer extends beyond the landscape boundary for focal patches near the boundary, only patches contained within the landscape are considered in the computations.

(C40) Interspersion and Juxtaposition Index

Vector/Raster

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

Units: Percent.

Range: $0 < IJI \leq 100$.

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 (maximally interspersed and juxtaposed to other patch types). IJI is undefined and reported as “NA” in the “basename”.full file and as a dot “.” in the “basename”.class file if the number of patch types is less than 3.

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. IJI considers all patch types present on an image, including any present in the landscape border.

Landscape Indices

(L1) Landscape ID (LID)

The first field in the landscape output file is landscape ID (LID); it is defined as in the patch output file (see previous discussion).

(L2) Total Area

Vector/Raster

$$TA = A\left(\frac{1}{10{,}000}\right)$$

Units: Hectares.

Range: TA > 0, without limit.

Description: TA equals the total area (m^2) of the landscape, divided by 10,000 (to convert to hectares). TA excludes the area of any background patches within the landscape.

(L3) Largest Patch Index

Vector/Raster

$$LPI = \frac{\max_{j=1}^{n}(a_{ij})}{A}(100)$$

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 percent of the landscape.

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 percentage of the landscape that the largest patch comprises.

(L4) Number of Patches

Vector/Raster

$$NP = N$$

Units: None.

Range: NP ≥ 1, without limit.

NP = 1 when the landscape contains only 1 patch.

Description: NP equals the number of patches in the landscape. NP does not include any background patches within the landscape or patches in the landscape border.

(L5) Patch Density

Vector/Raster

$$PD = \frac{N}{A}(10{,}000)(100)$$

Units: Number per 100 hectares.

Range: PD > 0, without limit.

Description: PD equals the number of patches in the landscape divided by total landscape area, multiplied by 10,000 and 100 (to convert to 100 hectares).

(L6) Mean patch Size

Vector/Raster

$$MPS = \frac{A}{N}\left(\frac{1}{10{,}000}\right)$$

Units: Hectares.

Range: MPS > 0, without limit.

The range in MPS is limited by the grain and extent of the image and the minimum patch size in the same manner as patch area (AREA).

Description: MPS equals the total landscape area (m^2) , divided by the total number of patches, divided by 10,000 (to convert to hectares).

(L7) Patch Size Standard Deviation

Vector/Raster

$$PSSD = \sqrt{\frac{\sum_{i=1}^{m}\sum_{j=1}^{n}\left[a_{ij} - \left(\frac{A}{N}\right)\right]^2}{N}}\left(\frac{1}{10,000}\right)$$

Units: Hectares.

Range: PSSD $\geq$ 0, without limit.

PSSD = 0 when all patches in the landscape are the same size or when there is only 1 patch (no variability in patch size).

Description: PSSD equals the square root of the sum of the squared deviations of each patch area (m^2) from the mean patch size, divided by the total number of patches, divided by 10,000 (to convert to hectares); that is, the root mean squared error (deviation from the mean) in patch size. This is the population standard deviation, not the sample standard deviation.

(L8) Patch Size Coefficient of Variation

Vector/Raster

$$PSCV = \frac{PSSD}{MPS}(100)$$

Units: Percent.

Range: PSCV $\geq$ 0, without limit.

PSCV = 0 when all patches in the landscape are the same size or when there is only 1 patch (no variability in patch size).

Description: PSCV equals the standard deviation in patch size (PSSD) divided by the mean patch size (MPS), multiplied by 100 (to convert to percent); that is, the variability in patch size relative to the mean patch size. This is the population coefficient of variation, not the sample coefficient of variation.

(L9) Total Edge

Vector/Raster

$$TE = E$$

Units: Meters.

Range: TE $\geq$ 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.

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 (that is, contrast weight > 0). 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 background edge.

(L10) Edge Density

Vector/Raster

$$ED = \frac{E}{A}(10,000)$$

Units: Meters per hectare.

Range: ED ≥ 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.

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 (that is, contrast weight 0). 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 background edge.

(L11) Contrast-Weighted Edge Density

Vector/Raster

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

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 a single patch and the user specifies that none of the landscape boundary and background edge be treated as edge. CWED increases as the amount of edge in the landscape increases or as the contrast in edges increases (contrast weight approaches 1). CWED is reported as “NA” in the “basename”.full file and as a dot “.” in the “basename”.land file if a contrast weight file is not specified by the user.

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). If a landscape border is present, CWED includes landscape boundary segments representing true edge only (contrast weight > 0). If a landscape border is absent, all landscape boundary edge segments are assigned the edge contrast weight specified by the user (see bound_wght option). This is equivalent to treating the specified proportion of all boundary edge segments as maximum-contrast edge. Regardless of whether a landscape border is present or not, all background edge segments are assigned the edge contrast weight specified by the user. Again, this is equivalent to treating the specified proportion of all background edge segments as maximum-contrast edge.

(L12) Total Edge Contrast Index

Vector/Raster

$$TECI = \frac{\sum_{i=1}^{m'} \sum_{k=i+1}^{m'} (e_{ik} \circ d_{ik})}{E'} (100)$$

Units: Percent.

Range: $0 \leq TECI \leq 100$.

TECI = 0 when there is no edge in the landscape; that is, when the entire landscape and landscape border, if present, consist of a single patch and the user specifies that none of the landscape boundary and background edge be treated as edge. TECI approaches 0 as the contrast in edges lessen (contrast weight approaches 0). TECI = 100 when all edge is maximum contrast (contrast weight = 1). TECI is reported as “NA” in the “basename”.full file and as a dot “.” in the “basename”.land file if a contrast weight file is not specified by the user.

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). In the numerator, if a landscape border is present, all edge segments along the landscape boundary are treated according to their edge contrast weights as designated in the contrast weight file. If a landscape border is absent, all landscape boundary segments are assigned the edge contrast weight specified by the user (see bound_wght option). Note that this is equivalent to treating the specified proportion of the landscape boundary as maximum-contrast edge and the remainder as zero-contrast edge. Regardless of whether a landscape border is present or not, all background edge segments are assigned the edge contrast weight specified by the user. This is equivalent to treating the specified proportion of all background edge as maximum-contrast edge and the remainder as zero-contrast edge. In the denominator, all edges are included, including the landscape boundary and background edge segments, regardless of whether they represent true edge or how the user chooses to handle boundary and background edges.

(L13) Mean Edge Contrast Index

Vector/Raster

$$MECI = \frac{\sum_{i=1}^{m}\sum_{j=1}^{n}\left[\frac{\sum_{k=1}^{m'}(p_{ijk} \circ d_{ik})}{p_{ij}}\right]}{N}(100)$$

Units: Percent.

Range: 0 ≤ MECI ≤ 100.

MECI = 0 when there is no edge in the landscape; that is, when the entire landscape and landscape border, if present, consist of a single patch type and the user specifies that none of the landscape boundary and background edge be treated as edge. MECI approaches 0 as the contrast in edges lessen (contrast weight approaches 0). MECI = 100 when all edge is maximum contrast (contrast weight = 1). MECI is reported as “NA” in the “basename”.full file and as a dot “.” in the “basename”.land file if a contrast weight file is not specified by the user.

Description: MECI equals the sum of the segment lengths (m) of each patches' perimeter multiplied by their corresponding contrast weights, divided by total patch perimeter (m), divided by the total number of patches, multiplied by 100 (to convert to a percentage). If a landscape border is present, any patch perimeter segments along the landscape boundary are treated according to their edge contrast weights as designated in the contrast weight file. If a landscape border is absent, any patch perimeter segments along the landscape boundary are assigned the edge contrast weight specified by the user (see bound_wght option). Regardless of whether a landscape border is present or not, all patch perimeter segments bordering background are assigned the edge contrast weight specified by the user.

(L14) Area-Weighted Mean Edge Contrast Index

Vector/Raster

$$AWMECI = \sum_{i=1}^{m}\sum_{j=1}^{n}\left(\left[\frac{\sum_{k=1}^{m'}(p_{ijk} \circ d_{ik})}{p_{ij}}\right]\left[\frac{a_{ij}}{A}\right]\right)(100)$$

Units: Percent.

Range: 0 ≤ AWMECI ≤ 100.

AWMECI = 0 when there is no edge in the landscape; that is, when the entire landscape and landscape border, if present, consist of a single patch type and the user specifies that none of the landscape boundary and background edge be treated as edge. AWMECI approaches 0 as the contrast in edges lessen (contrast weight approaches 0). AWMECI = 100 when all edge is maximum contrast (contrast weight = 1). AWMECI is reported as “NA” in the “basename”.full file and as a dot “.” in the “basename”.land file if a contrast weight file is not specified by the user.

Description: AWMECI equals the sum of the segment lengths (m) of each patches' perimeter multiplied by their corresponding contrast weights, divided by total patch perimeter (m), multiplied by patch area (m^2), divided by total landscape area (m^2), summed across all patches in the landscape, multiplied by 100 (to convert to a percentage). If a landscape border is present, any patch perimeter segments along the landscape boundary are treated according to their edge contrast weights as designated in the contrast weight file. If a landscape border is absent, any patch perimeter segments along the landscape boundary are assigned the edge contrast weight specified by the user (see bound_wght option). Regardless of whether a landscape border is present or not, all patch perimeter segments bordering background are assigned the edge contrast weight specified by the user. AWMECI is similar to MECI except that each patch weighted by its size in computing the average patch edge contrast index.

(L15) Landscape Shape Index

Vector

$$LSI = \frac{E'}{2\sqrt{\pi \circ A}}$$

Raster

$$LSI = \frac{0.25\,E'}{\sqrt{A}}$$

Units: None.

Range: LSI $\geq$ 1, without limit.

LSI = 1 when the landscape consists of a single circular (vector) or square (raster) patch; LSI increases without limit as landscape shape becomes more irregular or as the length of edge within the landscape increases, or both.

Description: LSI equals the sum of the landscape boundary (regardless of whether it represents true edge) and all edge segments (m) within the landscape boundary (including those bordering background), divided by the square root of the total landscape area (m^2), adjusted by a constant for a circular standard (vector) or square standard (raster).

(L16) Mean Shape Index

Vector

$$MSI = \frac{\sum_{i=1}^{m}\sum_{j=1}^{n}\left(\frac{p_{ij}}{2\sqrt{\pi \circ a_{ij}}}\right)}{N}$$

Raster

$$MSI = \frac{\sum_{i=1}^{m}\sum_{j=1}^{n}\left(\frac{0.25p_{ij}}{\sqrt{a_{ij}}}\right)}{N}$$

Units: None.

Range: MSI $\geq$ 1, without limit.

MSI = 1 when all patches in the landscape are circular (vector) or square (raster); MSI increases without limit as the patch shapes become more irregular.

Description: MSI equals the sum of the patch perimeter (m) divided by the square root of patch area (m^2) for each patch in the landscape, adjusted by a constant for a circular standard (vector) or square standard (raster), divided by the number of patches (NP); in other words, MSI equals the average shape index (SHAPE) of patches in the landscape.

(L17) Area-Weighted Mean Shape Index

Vector

$$AWMSI = \sum_{i=1}^{m}\sum_{j=1}^{n}\left[\left(\frac{p_{ij}}{2\sqrt{\pi \cdot a_{ij}}}\right)\left(\frac{a_{ij}}{A}\right)\right]$$

Raster

$$AWMSI = \sum_{i=1}^{m}\sum_{j=1}^{n}\left[\left(\frac{0.25p_{ij}}{\sqrt{a_{ij}}}\right)\left(\frac{a_{ij}}{A}\right)\right]$$

Units: None.

Range: AWMSI ≥ 1, without limit.

AWMSI = 1 when all patches in the landscape are circular (vector) or square (raster); AWMSI increases without limit as the patch shapes become more irregular.

Description: AWMSI equals the sum, across all patches, of each patch perimeter (m) divided by the square root of patch area (m^2), adjusted by a constant to adjust for a circular standard (vector) or square standard (raster), multiplied by the patch area (m^2) divided by total landscape area. In other words, AWMSI equals the average shape index (SHAPE) of patches, weighted by patch area so that larger patches weigh more than smaller ones.

(L18) Double Log Fractal Dimension

Vector/Raster

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

Units: None.

Range: 1 ≥ DLFD ≥ 2.

A fractal dimension greater than 1 for a 2-dimensional landscape mosaic indicates a departure from a euclidean geometry (that is, an increase in patch shape complexity). DLFD approaches 1 for shapes with very simple perimeters such as circles or squares, and approaches 2 for shapes with highly convoluted, plane-filling perimeters. DLFD employs regression techniques and is subject to small sample problems. Specifically, DLFD may greatly exceed the theoretical range in values when the number of patches is small (<10), and its use should be avoided in such cases. In addition, DLFD requires patches to differ in size. Thus, DLFD is undefined and reported as “NA” in the “basename”.full file and as a dot “.” in the “basename”.land file if all patches are the same size or there is only 1 patch.

Description: DLFD equals 2 divided by the slope of the regression line obtained by regressing the logarithm of patch area (m^2) against the logarithm of patch perimeter (m).

(L19) Mean Patch Fractal Dimension

Vector

$$MPFD = \frac{\sum_{i=1}^{m} \sum_{j=1}^{n} \left(\frac{2 \ln p_{ij}}{\ln a_{ij}} \right)}{N}$$

Rastor

$$MPFD = \frac{\sum_{i=j}^{m} \sum_{j=1}^{n} \left(\frac{2 \ln (0.25 p_{ij})}{\ln a_{ij}} \right)}{N}$$

Units: None.

Range: 1 ≤ MPFD ≤ 2.

A fractal dimension greater than 1 for a 2-dimensional landscape mosaic indicates a departure from a euclidean geometry (an increase in patch shape complexity). MPFD approaches 1 for shapes with very simple perimeters, such as circles or squares, and approaches 2 for shapes with highly convoluted, plane-filling perimeters.

Description: MPFD equals the sum of 2 times the logarithm of patch perimeter (m) divided by the logarithm of patch area (m^2) for each patch in the landscape, divided by the number of patches; the raster formula is adjusted to correct for the bias in perimeter (Li 1990).

(L20) Area-Weighted Mean Patch Fractal Dimension

Vector

$$AWMPFD = \sum_{i=1}^{m} \sum_{j=1}^{n} \left[\left(\frac{2 \ln p_{ij}}{\ln a_{ij}} \right) \left(\frac{a_{ij}}{A} \right) \right]$$

Raster

$$AWMPFD = \sum_{i=1}^{m} \sum_{j=1}^{n} \left[\left(\frac{2 \ln (0.25 p_{ij})}{\ln a_{ij}} \right) \left(\frac{a_{ij}}{A} \right) \right]$$

Units: None.

Range: 1 ≤ AWMPFD ≤ 2.

A fractal dimension greater than 1 for a 2-dimensional landscape mosaic indicates a departure from a euclidean geometry (an increase in patch shape complexity). AWMPFD approaches 1 for shapes with very simple perimeters, such as circles or squares, and approaches 2 for shapes with highly convoluted, plane-filling perimeters.

Description: AWMPFD equals the sum, across all patches, of 2 times the logarithm of patch perimeter (m) divided by the logarithm of patch area (m^2), multiplied by the patch area (m^2) divided by total landscape area; the raster formula is adjusted to correct for the bias in perimeter (Li 1990). In other words, AWMPFD equals the average patch fractal dimension (FRACT) of patches in the landscape, weighted by patch area.

(L21) Total Core Area

Vector/Raster

$$TCA = \sum_{i=1}^{m} \sum_{j=1}^{n} a_{ij}^{c} \left(\frac{1}{10{,}000} \right)$$

Units: Hectares.

Range: TCA ≥ 0, without limit.

TCA = 0 when every location within every patch is within the specified edge distance from the patch perimeters. TCA approaches total landscape area as the specified edge distance decreases and as patch shapes are simplified.

Description: TCA equals the sum of the core areas of each patch (m^2), divided by 10,000 (to convert to hectares).

(L22) Number of Core Areas

Vector/Raster

$$NCA = \sum_{i=1}^{m} \sum_{j=1}^{n} n_{ij}^{c}$$

Units: None.

Range: NCA ≥ 0, without limit.

NCA = 0 when TCA = 0 (every location within every patch is within the specified edge distance from the patch perimeters).

Description: NCA 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.

(L23) Core Area Density

Vector/Raster

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

Units: Number per 100 hectares.

Range: CAD ≥ 0, without limit.

CAD = 0 when TCA = 0 (every location within every patch is within the specified edge distance from the patch perimeters); in other words, when there are no core areas.

Description: CAD equals the sum of number of disjunct core areas contained within each patch, divided by total landscape area, multiplied by 10,000 and 100 (to convert to 100 hectares).

(L24) Mean Core Area Per Patch

Vector/Raster

$$MCA1 = \frac{\sum_{i=1}^{m} \sum_{j=1}^{n} a_{ij}^{c}}{N} \left(\frac{1}{10{,}000} \right)$$

Units: Hectares.

Range: MCA1 ≥ 0, without limit.

Ultimately, the range in MCA1 is limited by the grain and extent of the image and the minimum patch size in the same manner as mean patch size (MPS), but MCA1 is also affected by the specified edge width. MCA1 = 0 when TCA = 0 (every location within every patch is within the specified edge distance from the patch perimeters); in other words, when there are no core areas. MCA1 approaches MPS as the specified edge width decreases and as patch shapes are simplified.

Description: MCA1 equals the sum of the core areas of each patch (m^2), divided by the number of patches, divided by 10,000 (to convert to hectares). Note that MCA1 equals the average core area per patch, not the average size of disjunct core areas, as in MCA2.

(L25) Patch Core Area Standard Deviation

Vector/Raster

$$CASD1 = \sqrt{\frac{\sum_{i=1}^{m}\sum_{j=1}^{n}\left[a_{ij}^{c} - \left(\frac{\sum_{i=1}^{m}\sum_{j=1}^{n}a_{ij}^{c}}{N}\right)\right]^2}{N}}\left(\frac{1}{10{,}000}\right)$$

Units: Hectares.

Range: CASD1 ≥ 0, without limit.

CASD1 = 0 when all patches in the landscape have the same core area or when there is only 1 patch (no variability in core area).

Description: CASD1 equals the square root of the sum of the squared deviations of each patch core area (m^2) from the mean core area per patch (MCA1), divided by the number of patches, divided by 10,000 (to convert to hectares); that is, the root mean squared error (deviation from the mean) in patch core area. This is the population standard deviation, not the sample standard deviation, and CASD1 represents the variation in core area among patches, not among disjunct core areas as in CASD2.

(L26) Patch Core Area Coefficient of Variation

Vector/Raster

$$CACV1 = \frac{CASD1}{MCA1}(100)$$

Units: Percent.

Range: CACV1 ≥ 0, without limit.

CACV1 = 0 when all patches in the landscape have the same core area or when there is only 1 patch (no variability in core area).

Description: CACV1 equals the standard deviation in core area (CASD1) divided by the mean core area per patch (MCA1), multiplied by 100 (to convert to percent); that is, the variability in core area relative to the mean core area. This is the population coefficient of variation, not the sample coefficient of variation, and CACV1 represents the variation in core area among patches, not among disjunct core areas as in CACV2.

(L27) Mean Area Per Disjunct Core

Vector/Raster

$$MCA2 = \frac{\sum_{i=1}^{m}\sum_{j=1}^{n}\sum_{q=1}^{p} a_{ijq}^{c}}{\sum_{i=1}^{m}\sum_{j=1}^{n} n_{ij}^{c}} \left(\frac{1}{10,000}\right)$$

Units: Hectares.

Range: MCA2 ≥ 0, without limit.

Ultimately, the range in MCA2 is limited by the grain and extent of the image and the minimum patch size in the same manner as mean patch size (MPS), but MCA2 is also effected by the specified edge width. MCA2 = 0 when total core area = 0 (every location within patches of the corresponding patch type are within the specified edge distance from the patch perimeters); in other words, when there are no core areas. MCA2 approaches MPS as the specified edge width decreases and as patch shapes are simplified.

Description: MCA2 equals the sum of the disjunct core areas of each patch (m^2), divided by the number of disjunct core areas, divided by 10,000 (to convert to hectares). MCA2 equals the average size of disjunct core areas, not the average core area per patch as in MCA1.

(L28) Disjunct Core Area Standard Deviation

Vector/Raster

$$CASD2 = \sqrt{\frac{\sum_{i=1}^{m}\sum_{j=1}^{n}\sum_{q=1}^{p}\left[a_{ijq}^{c} - \left(\frac{\sum_{i=1}^{m}\sum_{j=1}^{n}\sum_{q=1}^{p} a_{ijq}^{c}}{\sum_{i=1}^{m}\sum_{j=1}^{n} n_{ij}^{c}}\right)\right]^2}{\sum_{i=1}^{m}\sum_{j=1}^{n} n_{ij}^{c}}} \left(\frac{1}{10,000}\right)$$

Units: Hectares.

Range: CASD2 ≥ 0, without limit.

CASD2 = 0 when all disjunct core areas are the same size or when there is only 1 core area (no variability in core area).

Description: CASD2 equals the square root of the sum of the squared deviations of each disjunct core area (m^2) from the mean size of disjunct core areas (MCA2), divided by the number of disjunct core areas, divided by 10,000 (to convert to hectares); that is, the root mean squared error (deviation from the mean) in the size of disjunct core areas. This is the population standard deviation, not the sample standard deviation, and CASD2 represents the variation in size of disjunct core areas, not patch core areas as in CASD1.

(L29) Disjunct Core Area Coefficient of Variation

Vector/Raster

$$\text{CACV2} = \frac{\text{CASD2}}{\text{MCA2}}(100)$$

Units: Percent.

Range: CACV2 ≥ 0, without limit.

CACV2 = 0 when all disjunct core areas are the same size or when there is only 1 core area (no variability in core area).

Description: CACV2 equals the standard deviation in the size of disjunct core areas (CASD2) divided by the mean size of disjunct core areas (MCA2), multiplied by 100 (to convert to percent); that is, the variability in core area relative to the mean core area. This is the population coefficient of variation, not the sample coefficient of variation, and CACV2 represents the variation in size of disjunct core areas, not patch core areas as in CACV1.

(L30) Total Core Area Index

Vector/Raster

$$\text{TCAI} = \frac{\sum_{i=1}^{m}\sum_{j=1}^{n} a_{ij}^{c}}{A}(100)$$

Units: Percent.

Range: 0 ≤ TCAI < 100.

TCAI = 0 when none of the patches in the landscape contain any core area (CORE = 0 for every patch); that is, when the landscape contains no core area. TCAI approaches 100 when the patches, because of size, shape, and edge width, contain mostly core area.

Description: TCAI equals the sum of the core areas of each patch (m^2), divided by the total landscape area (m^2), multiplied by 100 (to convert to a percentage); that is, TCAI equals the percentage of the landscape that is core area.

(L31) Mean Core Area Index

Vector/Raster

$$\text{MCAI} = \frac{\sum_{i=1}^{m}\sum_{j=1}^{n}\left(\frac{a_{ij}^{c}}{a_{ij}}\right)}{N}(100)$$

Units: Percent.

Range: 0 ≤ MCAI < 100.

MCAI = 0 when none of the patches in the landscape contain any core area (CORE = 0 for every patch); that is, when the landscape contains no core area. MCAI approaches 100 when the patches, because of size, shape, and edge width, contain mostly core area.

Description: MCAI equals the sum of the proportion of each patch that is core area (that is, core area of each patch [m^2] divided by the area of each patch [m^2]), divided by the number of patches, multiplied by 100 (to convert to a percentage); in other words, MCAI equals the average percentage of a patch in the landscape that is core area.

(L32) Mean Nearest Neighbor Distance

Raster

$$MNN = \frac{\sum_{i=1}^{m} \sum_{j=1}^{n'} h_{ij}}{N'}$$

Units: Meters.

Range: MNN > 0, without limit.

MNN is reported as “None” in the “basename”.full file and as a dot “.” in the “basename”.land file if none of the patches have a nearest neighbor (every patch type consists of only 1 patch). MNN is reported as “NA” in the “basename”.full file and as a dot “.” in the “basename”.land file if the user chooses not to calculate nearest neighbor distance.

Description: MNN equals the sum of the distance (m) to the nearest patch of the same type, based on nearest edge-to-edge distance, for each patch in the landscape with a neighbor, divided by the number of patches with a neighbor.

(L33) Nearest Neighbor Standard Deviation

Raster

$$NNSD = \sqrt{\frac{\sum_{i=1}^{m} \sum_{j=1}^{n'} \left[h_{ij} - \left(\frac{\sum_{i=1}^{m} \sum_{j=1}^{n'} h_{ij}}{N'} \right) \right]^2}{N'}}$$

Units: Meters.

Range: NNSD ≥ 0, without limit.

NNSD = 0 when all patches have the same nearest neighbor distance (no variability in nearest neighbor distance). NNSD is reported as “NA” in the “basename”.full file and as a dot “.” in the “basename”.class file if none of the patches have a nearest neighbor. Similarly, NNSD is reported as “NA” in the “basename”.full file and as a dot “.” in the “basename”.land file if the user chooses not to calculate nearest neighbor distance.

Description: NNSD equals the square root of the sum of the squared deviations of each patches’ nearest neighbor distance (m) from the mean nearest neighbor distance (MNN), divided by the number of patches; that is, the root mean squared error (deviation from the mean) in patch nearest neighbor distance. This is the population standard deviation, not the sample standard deviation.

(L34) Nearest Neighbor Coefficient of Variation

Raster

$$NNCV = \frac{NNSD}{MNN}(100)$$

Units: Percent.

Range: NNCV ≥ 0, without limit.

NNCV = 0 when all patches have the same nearest neighbor distance (no variability in nearest neighbor distance; NNSD = 0). NNCV is reported as “NA” in the “basename”.full file and as a dot “.” in the “basename”.class file if none of the patches have a nearest neighbor. Similarly, NNCV is reported as “NA” in the “basename”.full file and as a dot “.” in the “basename”.land file if the user chooses not to calculate nearest neighbor distance.

Description: NNCV equals the standard deviation in nearest neighbor distances (NNSD) divided by the mean nearest neighbor distance (MNN), multiplied by 100 (to convert to percent); that is, the variability in nearest neighbor distance relative to the mean nearest neighbor distance. This is the population coefficient of variation, not the sample coefficient of variation.

(L35) Mean Proximity Index

Raster

$$MPI = \frac{\sum_{i=1}^{m}\sum_{j=1}^{n}\sum_{s=1}^{n}\frac{a_{ijs}}{h_{ijs}^{2}}}{N}$$

Units: None.

Range: MPI ≥ 0.

MPI = 0 if no patch has a neighbor of the same type within the specified search radius. MPI increases as patches become less isolated from patches of the same type and the patch types become less fragmented in distribution. The upper limit of MPI is determined by the search radius and minimum distance between patches. MPI is reported as “NA” in the “basename”.full file and as a dot “.” in the “basename”.land file if the user chooses not to calculate nearest neighbor distance.

Description: MPI equals the sum of patch area (m^2) divided by the squared nearest edge-to-edge distance (m) 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, summed across all patches in the landscape and divided by the total number of patches. In other words, MPI equals the average proximity index for patches in the landscape. When the search buffer extends beyond the landscape boundary for focal patches near the boundary, only patches contained within the landscape are considered in the computations.

(L36) Shannon's Diversity Index

Vector/Raster

$$SHDI = -\sum_{i=1}^{m} (P_i \circ \ln P_i)$$

Units: None.

Range: SHDI ≥ 0, without limit.

SHDI = 0 when the landscape contains only 1 patch (no diversity). SHDI increases as the number of different patch types (patch richness, PR) increases or the proportional distribution of area among patch types becomes more equitable, or both.

Description: SHDI equals minus the sum, across all patch types, of the proportional abundance of each patch type multiplied by that proportion.

(L37) Simpson's Diversity Index

Vector/Raster

$$SIDI = 1 - \sum_{i=1}^{m} P_i^2$$

Units: None.

Range: 0 ≤ SIDI < 1.

SIDI = 0 when the landscape contains only 1 patch (no diversity). SIDI approaches 1 as the number of different patch types (patch richness, PR) increases and the proportional distribution of area among patch types becomes more equitable.

Description: SIDI equals 1 minus the sum, across all patch types, of the proportional abundance of each patch type squared.

(L38) Modified Simpson's Diversity Index

Vector/Raster

$$MSIDI = -\ln \sum_{i=1}^{m} P_i^2$$

Units: None.

Range: MSIDI ≥ 0.

MSIDI = 0 when the landscape contains only 1 patch (no diversity). MSIDI increases as the number of different patch types (patch richness, PR) increases and the proportional distribution of area among patch types becomes more equitable.

Description: MSIDI equals minus the logarithm of the sum, across all patch types, of the proportional abundance of each patch type squared.

(L39) Patch Richness

Vector/Raster

$$PR = m$$

Units: None.

Range: PR ≥ 1, without limit.

Description: PR equals the number of different patch types present within the landscape boundary.

(L40) Patch Richness Density

Vector/Raster

$$PRD = \frac{m}{A}(10{,}000)(100)$$

Units: Number per 100 hectares.

Range: PRD > 0, without limit.

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).

(L41) Relative Patch Richness

Vector/Raster

$$RPR = \frac{m}{m_{max}}(100)$$

Units: Percent.

Range: 0 < RPR ≤ 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. RPR is reported as "NA" in the "basename".full file and as a dot "." in the "basename".land file if the maximum number of classes is not specified by the user.

Description: RPR equals the number of different patch types present within the landscape boundary divided by the maximum potential number of patch types based on the patch type classification scheme, multiplied by 100 (to convert to percent).

(L42) Shannon's Evenness Index

Vector/Raster

$$SHEI = \frac{-\sum_{i=1}^{m}(P_i \circ \ln P_i)}{\ln m}$$

Units: None.

Range: 0 ≤ SHEI ≤ 1.

SHDI = 0 when the landscape contains only 1 patch (no diversity) and approaches 0 as the distribution of area among the different patch types becomes increasingly uneven (dominated by 1 type). SHDI = 1 when distribution of area among patch types is perfectly even (proportional abundances are the same).

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.

(L43) Simpson's Evenness Index

Vector/Raster

$$SIEI = \frac{1 - \sum_{i=1}^{m} P_i^2}{1 - \left(\frac{1}{m}\right)}$$

Units: None.

Range: $0 \leq SIEI \leq 1$.

SIDI = 0 when the landscape contains only 1 patch (no diversity) and approaches 0 as the distribution of area among the different patch types becomes increasingly uneven (dominated by 1 type). SIDI = 1 when distribution of area among patch types is perfectly even (proportional abundances are the same).

Description: SIEI equals 1 minus the sum, across all patch types, of the proportional abundance of each patch type squared, divided by 1 minus the quantity 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.

(L44) Modified Simpson's Evenness Index

Vector/Raster

$$MSIEI = \frac{-\ln \sum_{i=1}^{m} P_i^2}{\ln m}$$

Units: None.

Range: $0 \leq MSIEI \leq 1$.

MSIDI = 0 when the landscape contains only 1 patch (no diversity) and approaches 0 as the distribution of area among the different patch types becomes increasingly uneven (dominated by 1 type). MSIDI = 1 when distribution of area among patch types is perfectly even (proportional abundances are the same).

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.

(L45) Interspersion and Juxtaposition Index

Vector/Raster

$$IJI = \frac{-\sum_{i=1}^{m'} \sum_{k=i+1}^{m'} \left[\left(\frac{e_{ik}}{E} \right) \circ \ln \left(\frac{e_{ik}}{E} \right) \right]}{\ln(½[m'(m'-1)])} (100)$$

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 (that is, maximum interspersion and juxtaposition). IJI is undefined and reported as “NA” in the “basename”.full file and as a dot “.” in the “basename”.land file if the number of patch types is less than 3.

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. IJI considers all patch types present on an image, including any present in the landscape border, if a border was included. 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.

(L46) Contagion Index

Raster

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

Units: Percent.

Range: $0 < CONTAG \leq 100$.

CONTAG approaches 0 when the distribution of adjacencies (at the level of individual cells) among unique patch types becomes increasingly uneven. CONTAG = 100 when all patch types are equally adjacent to all other patch types (that is, maximum interspersion and juxtaposition). CONTAG is undefined and reported as “NA” in the “basename”.full file and as a dot “.” in the “basename”.land file if the number of patch types is less than 2.

Description: CONTAG equals 1 plus the sum of the proportional abundance of each patch type multiplied by number of adjacencies between cells of that patch type and all other patch types, multiplied by the logarithm of the same quantity, summed over 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. CONTAG considers all patch types present on an image, including any present in the landscape border, and considers like adjacencies (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.

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McGarigal, Kevin; Marks, Barbara J. 1995. FRAGSTATS: spatial pattern analysis program for quantifying landscape structure. Gen. Tech. Rep. PNW-GTR-351. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 122 p.

This report describes a program, FRAGSTATS, developed to quantify landscape structure. FRAGSTATS offers a comprehensive choice of landscape metrics and was designed to be as versatile as possible. The program is almost completely automated and thus requires little technical training. Two separate versions of FRAGSTATS exist: one for vector images and one for raster images. The vector version is an Arc/Info AML that accepts Arc/Info polygon coverages. The raster version is a C program that accepts ASCII image files, 8- or 16-bit binary image files, Arc/Info SVF files, Erdas image files, and IDRISI image files. Both versions of FRAGSTATS generate the same array of metrics, including a variety of area metrics, patch density, size and variability metrics, edge metrics, shape metrics, core area metrics, diversity metrics, and contagion and interspersion metrics. The raster version also computes several nearest neighbor metrics.

Keywords: Landscape ecology, landscape structure, landscape pattern, landscape analysis, landscape metrics, spatial statistics.

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