Fragstats Landscape Metrics

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 using the population formula. In this case it would be appropriate to use the sample formula when calculating the variation among landscapes using the FRAGSTATS output for each landscape. The difference between the population and sample formulas is insignificant when sample sizes (i.e., number of patches) are large (e.g., > 20). However, when quantifying landscapes with a small number of 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, while 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. For example, at the landscape level *patch density* (PD) and *mean patch size* (MPS) will be perfectly correlated because they represent the same information. These redundant metrics are alternative ways of representing the same information; they are included in FRAGSTATS because the preferred form of representing a particular aspect of landscape structure will differ among applications and users. It behooves the user to understand these redundancies, because in most applications only 1 of each set of redundant metrics should be employed. It is important to note that in a particular application, some metrics may be empirically redundant; 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 metrics that are inherently redundant, but much can be learned about landscapes by interpreting metrics that are empirically redundant.

Many of the patch indices have counterparts at the class and landscape levels. For example, many of the class indices (e.g., mean shape index) represent the same basic information as the corresponding patch indices (e.g., patch shape index), but instead of considering a single patch, they consider all patches of a particular type simultaneously.

Likewise, many of the landscape indices are derived from patch or class characteristics. Consequently, many of the class and landscape indices are computed from patch and class statistics by summing or averaging over all patches or classes. Even though many of the class and landscape indices represent the same fundamental information, naturally the algorithms differ slightly (see Appendix C). Class indices represent the spatial distribution and pattern within a landscape of a single patch type; whereas, landscape indices represent the spatial pattern of the entire landscape mosaic, considering all patch types simultaneously. Thus, even though many of the indices have counterparts at the class and landscape levels, their interpretations may be somewhat different. Most of the class indices can be interpreted as fragmentation indices because they measure the fragmentation of a particular patch type; whereas, most of the landscape indices can be interpreted more broadly as landscape heterogeneity indices because they measure the overall landscape 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. For example, there is considerable evidence that bird species richness and the occurrence and abundance of some species are strongly correlated with patch size (e.g., Robbins et al. 1989). Thus, patch size information alone could be used to model species richness, patch occupancy, and species distribution patterns in a landscape given the appropriate empirical relationships derived from field studies.

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 a number of ecological applications. For example, an important by-product of habitat fragmentation is quantitative habitat loss. In the study of forest fragmentation, therefore, it is important to know how much of the target patch type (habitat) exists within the landscape. In addition, although many vertebrate species that specialize on a particular habitat have minimum area requirements (e.g., Robbins et al. 1989), not all species require that suitable habitat to be present in 1 contiguous patch. For example, northern spotted owls have minimum area requirements for late-seral forest that varies geographically; yet, individual spotted owls use late-seral forest that may be distributed among many patches (Forsman et al. 1984). For this species, late-seral forest area might be a good index of habitat suitability within landscapes the size of spotted owl home ranges (Lehmkuhl and Raphael 1993). In addition to its direct interpretive value, class area 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 with regards to evaluating landscape structure, but it is important because it defines the extent of the landscape. Moreover, total landscape area is used in the computations for many of the class and landscape metrics. 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.

For a categorized list of FRAGSTATS output metrics see the **FRAGSTATS Metrics List** document.

These metrics quantify area in absolute terms (hectares). It is often desirable to quantify area in relative terms as a percentage of total landscape area. Therefore, at the class level, FRAGSTATS computes the *percent of landscape* (%LAND) occupied by each patch type. At the patch level, the *landscape similarity index* (LSIM) equals the percent 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 (e.g., 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 3 patches extracted from a sample landscape that vary in size and landscape similarity. Roughly 50% of the landscape is similar to patch A (%LAND) and thus comprised of mixed, large sawtimber (MLS). In contrast, patches B and C represent relatively rare patch types because only 8% of the landscape is comprised of the respective 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. For example, 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 would probably contribute more to faunal species richness than patch A.

Class-Level Example.--Figure 5 depicts 3 sample landscapes that vary 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 than landscape A. Roughly 50% of landscapes B and C are mixed, large sawtimber, in contrast to only 5% of landscape A, according to the *percent 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. For example, populations of organisms associated with mixed, large sawtimber habitat 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 *percent of landscape* indicate that landscapes B and C are similar in composition with respect to mixed, large sawtimber habitat, other indices suggest that they vary greatly in configuration. For example, the *largest patch index* (LPI) represents the 3 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% of the landscape, whereas in landscape C it comprises 47% 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 3 sample landscapes that vary 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 > 25% 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 patch type that is highly subdivided may be more resistent to the propagation of some disturbances (e.g., disease, fire, etc.), and thus more likely to persist in a landscape than a patch type that is contiguous. Conversely, habitat fragments may suffer higher rates of disturbance for some disturbance types (e.g. windthrow) than 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 a index of spatial heterogeneity of the entire landscape mosaic. A landscape with a greater number of patches has a finer grain; that is, the spatial heterogeneity occurs at a finer resolution. Although the number of patches in a class or in the landscape may be fundamentally important to a number of ecological processes, often it does not have any interpretive value by itself because it conveys no information about 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, but fundamental, aspect of landscape structure. Patch density has the same basic utility as number of patches as an index, except that it expresses number of patches on a per unit area basis that facilitates comparisons among landscapes of varying size. Of course, if total landscape area is held constant, then patch density and number of patches convey the same information. 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. Holding class area constant, 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; relationships 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 2 indices represent slightly different aspects of class structure. For example, 2 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 landscapes. Alternatively, 2 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 selecting class metrics 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 ha could represent 1 or 100 patches and the difference could have profound ecological implications. Furthermore, mean patch size represents the average condition. Variation in patch size may convey more useful information. For example, a mean patch size of 10 ha could represent a class with 5 10-ha patches or a class with 2-, 3-, 5-, 10-, and 30-ha patches, and this difference could be important ecologically. For these reasons, mean patch size is probably best interpreted in conjunction with total class area, patch density (or number of patches), and patch size variability.

At the landscape level, mean patch size and patch density are both a function of number of patches and total landscape area. In contrast to the class level, these indices are completely redundant. Although both indices may be useful for "describing" 1 or more landscapes, they would never be used simultaneously in a statistical analysis of landscape structure. 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 that is not captured by mean patch size and other first-order statistics. For example, consider 2 landscapes with the same patch density and mean patch size, but with very different levels of variation in patch size. Greater variability indicates less uniformity in pattern either at the class level or landscape level and may reflect differences in underlying processes affecting the landscapes. Variability is a difficult thing to summarize in a single metric. FRAGSTATS computes 2 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 patch size among patches. Thus, although patch size standard deviation conveys information about patch size variability, it is a difficult parameter to interpret without doing so in conjunction with mean patch size because the absolute variation is dependent on mean patch size. For example, 2 landscapes may have the same patch size standard deviation, e.g., 10 ha; yet 1 landscape may have a mean patch size of 10 ha, while the other may have a mean patch size of 100 ha. In this case, the interpretations of landscape structure would be very different, even though absolute variation is the same. Specifically, the former landscape has greatly varying and smaller patch sizes, while the latter has more uniformly-sized and larger patches. For this reason, *patch size coefficient of variation* (PSCV) is generally preferable to standard deviation for comparing variability among landscapes. Patch size coefficient of variation measures relative variability about the mean (i.e., variability as a percentage of the mean), not absolute variability. Thus, it is not necessary to know mean patch size to interpret the coefficient of variation. Nevertheless, patch size coefficient of variation also can be misleading with regards to landscape structure in the absence of information on the number of patches or patch density and other structural characteristics. For example, 2 landscapes may have the same patch size coefficient of variation, e.g., 100%; yet 1 landscape may have 100 patches with a mean patch size of 10 ha, while the other may have 10 patches with a mean patch size of 100 ha. In this case, the interpretations of landscape structure could be very different, even though the coefficient of variation is the same. Ultimately, the choice of standard deviation or coefficient of variation will depend on whether absolute or relative variation is more meaningful in a particular application. Because these measures are not wholly redundant, it may be meaningful to interpret both measures in some applications.

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

Class-Level Example.--Figure 5 depicts 3 sample landscapes that vary 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 3 landscapes vary considerably in both amount and distribution of mixed, large sawtimber, *number of patches* and *patch density* alone do not 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 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 3 landscapes with respect to mixed, large sawtimber fragmentation (A being most fragmented, C being least). However, *mean patch size* is most informative 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, reflecting the smaller patch sizes in landscape A. However, according to *patch size coefficient of variation* (PSCV), these 2 landscapes have similar variability in patch sizes relative to their respective mean patch sizes (i.e., 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, it is apparent that 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 a 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, landscape 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 greater human disturbance in the form of timber management activities than landscape C. Differences in patch size variability suggest that the human-altered landscapes contain more uniformity in patch size than the unaltered landscape.

Landscape-Level Example.--Figure 6 depicts 3 sample landscapes that vary 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 3 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), in absolute terms, patch size in landscape A is much less variable than in landscape C. Sixty-five percent of the patches in landscape A are within 20 ha difference in size (± 1 standard deviation); whereas 65% of the patches in landscape C are within 100 ha difference in size. Therefore, based on standard deviation, the variation in patch size is much greater in Landscape C than 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 in landscape C. Hence, depending on whether you view variation in absolute (PSSD) or relative (PSCV) terms, you can reach very different conclusions regarding these landscapes. Ultimately, 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 relationships (Thomas et al. 1978 and 1979, Strelke and Dickson 1980, Morgan and Gates 1982, Logan et al. 1985). In landscape ecological investigations much of the presumed importance of spatial pattern is related to edge effects. The forest edge effect, for example, results primarily from differences in wind and light intensity and quality reaching a forest patch that alter microclimate and disturbance rates (e.g., Gratkowski 1956, Ranney et al. 1981, Chen and Franklin 1990). These changes, in combination with changes in seed dispersal and herbivory, can influence vegetation composition and structure (Ranney et al. 1981). The proportion of a forest patch that is affected in this manner is dependent, therefore, upon patch shape and orientation, and by adjacent land cover. A large but convoluted patch, for example, could be entirely edge habitat. It is now widely accepted that edge effects must be viewed from an organism-centered perspective because edge effects influence organisms differently; some species have an affinity for edges, some are unaffected, and others are adversely affected.

Early wildlife management efforts were focussed on maximizing edge habitat because it was believed that most species favored habitat conditions created by edges and that the juxtaposition of different habitats would increase species diversity (Leopold 1933). Indeed this concept of edge as a positive influence has guided land management practices until recently. Recent studies, however, have suggested 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 (e.g., Strelke and Dickson 1980, Kroodsma 1982, Brittingham and Temple 1983, Wilcove 1985, Temple 1986, Noss 1988, Yahner and Scott 1988, Robbins et al. 1989). 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 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 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 that involve comparing landscapes of varying size, this index may not be useful. *Edge density* (ED) standardizes edge to a per unit area basis that facilitates comparisons among landscapes of varying size. However, when comparing landscapes of identical size, total edge and edge density are completely redundant.

These edge indices are affected by the resolution of the image. Generally, the finer the resolution (i.e., the greater the detail with which edges are delineated), the greater the edge length. At coarse resolutions, edges may appear as relatively straight lines; whereas, at finer resolutions, edges may appear as highly convoluted lines. Thus, values calculated for edge metrics should not be compared among images with different resolutions. In addition, 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 with regards to 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. For example, microclimatic changes (e.g., wind, light intensity and quality, etc.) are likely to extend farther into a patch along an edge with high structural contrast than along an edge with low structural contrast (Ranney et al. 1981). Similarly, the adverse affects of brown-headed cowbird nest parasitism on some forest-dwelling neotropical migratory bird species are likely to be greatest along high-contrast forest edges (e.g., between mature forest patches and grassland), because cowbirds prefer to forage in early-seral habitats and parasitize nests in late-seral habitats (Brittingham and Temple 1983). 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 (e.g., 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 et al. 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 (Wiens et al. 1985, Hansen and di Castri 1992). For example, high-contrast edges may prohibit or inhibit some organisms from seeking supplementary resources in surrounding patches. Conversely, some species (e.g., great horned owl, Bubo virginianus) seem to prefer the juxtaposition of patch types with high contrast, as in the process of landscape complementation (Dunning et al. 1992).

Clearly, edge contrast can assume a variety of meanings for different ecological processes. Therefore, contrast can be defined in a variety of ways, but it always reflects the magnitude of difference between patches with respect to 1 or more ecological attributes at a given scale that are important to the phenomenon under investigation

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

FRAGSTATS 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. Thus, a patch with a 10% edge contrast index has very little contrast with its neighborhood; it has the equivalent of 10% of its perimeter in maximum-contrast edge. Conversely, a patch with a 90% edge contrast index has high contrast with its neighborhood. At the class and landscape levels, FRAGSTATS computes a *total edge contrast index* (TECI). Like its patch-level counterpart, this index quantifies edge contrast as a percentage of maximum possible. However, this index ignores patch distinctions; it quantifies edge contrast for the landscape as a whole, thereby focussing 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 affect 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 m or 1,000 m, is of high contrast, and vice versa. Note that these indices consider landscape boundary segments even if they have a contrast of zero (i.e., 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 (i.e., user-specified average edge contrast) could have significant affects on these indices, depending on the size and heterogeneity of the landscape. If a landscape border is present, this decision can still have significant affects 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 varying size. Unlike edge density, however, this index reduces the length of each edge segment proportionate to the degree of contrast. Thus, 100 m/ha of maximum-contrast edge (i.e., weight = 1) is unaffected; but 100 m/ha of edge with a contrast weight of 0.2 is reduced by 80% to 20 m/ha of contrast-weighted edge. This index measures the equivalent maximum-contrast edge density. For example, an edge density of 100 means that there are 100 meters of edge per hectare in the landscape. A contrast-weighted edge density of 80 for the same landscape means that there are the equivalent of 80 meters of maximum-contrast edge per hectare in the landscape. A landscape with 100 m/ha of edge and an average contrast weight of 0.8 would have twice the contrast-weighted edge density (80 m/ha) as a landscape with only 50 m/ha of edge but with the same average contrast weight (40 m/ha). Thus, both edge density and edge contrast are reflected in this index. For many ecological phenomena, edge types function differently. Consequently, comparing total edge density among landscapes may be misleading because of differences in edge types. This contrast-weighted edge density index attempts to quantify edge from the perspective of its functional significance. Thus, landscapes with the same contrast-weighted edge density are presumed to have the same total magnitude of edge effects from a functional perspective.

Edge contrast indices are limited by the considerations discussed above for metrics based on total edge length. These indices are only calculated and reported in the output files 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 3 patches extracted from a sample landscape that vary in edge contrast. According to the *edge contrast index* (EDGECON), patch A has the least contrast with its neighborhood, where contrast represents the degree difference in floristic and vegetation structure among patches. This is because patch A is a mixed, large sawtimber patch surrounded largely by conifer and hardwood, large sawtimber patches. Thus, the differences in vegetation composition and structure along the patch perimeter is 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/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% of its perimeter in maximum-contrast edge, whereas the perimeter of patch A has the equivalent of only 17% 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 3 sample landscapes that vary 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 vary. For example, the process of habitat fragmentation 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% to 0%. The total amount of class edge would be expected to peak at a *landscape similarity index* (LSIM) of approximately 50%, 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 *landscape similarity index*. In this case, although landscapes B and C have undergone the same amount of mixed, large sawtimber loss (i.e., similar LSIM 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 very 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 can also be measured in relative terms using the *total edge contrast index* (TECI), *mean edge contrast index* (MECI), and *area-weighted mean edge contrast index* (AWMECI). These 3 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 3 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 3 sample landscapes that vary 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 m/ha 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 in terms of the 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 inter-patch processes such as small mammal migration (Buechner 1989) and woody plant colonization (Hardt and Forman 1989), and may influence animal foraging strategies (Forman and Godron 1986). However, the primary significance of shape in determining the nature of patches in a landscape seems to be related to the "edge effect" (see discussion of edge effects for edge metrics).

Shape is a difficult parameter to quantify concisely in a metric. FRAGSTATS computes 2 types of shape indices; both are based on perimeter-area relationships. Patton (1975) proposed a diversity index based on shape for quantifying habitat edge for wildlife species and as a means for comparing alternative habitat improvement efforts (e.g., wildlife clearings). This *shape index* (SHAPE) measures the complexity of patch shape compared to a standard shape. 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. While there are other means of quantifying patch shape (e.g., 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 (i.e., 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 (i.e., landscape comprised of a single circular or square patch). Landscape shape index is identical to the shape index at the patch level (SHAPE), except that it treats the entire landscape as if it were 1 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 in order 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 and/or the actual shape of the landscape is of no particular interest. In this case, the total amount of true edge, or some other index based on edge, would probably be more meaningful. If the landscape boundary represents true edge or the shape of the landscape is particularly important, then the landscape shape index can be a useful index, especially when comparing among landscapes of varying 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 with regards to 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 vary 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 very 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 (e.g., 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 (Krummel et al. 1987, Milne 1988, Turner and Ruscher 1988, Iverson 1989, Ripple et al. 1991). The appeal of fractal analysis is that it can be applied to spatial features over a wide variety of scales. Mandelbrot (1977, 1982) introduced the concept of fractal, a geometric form that exhibits structure at all spatial scales, and proposed a perimeter-area method to calculate the fractal dimension of natural planar shapes. The perimeter-area method quantifies the degree of complexity of the planar shapes. The degree of complexity of a polygon is characterized by the fractal dimension (D), such that the perimeter (P) of a patch is related to the area (A) of the same patch by P » ÖA^{D} (i.e., log P » ½D log A). For simple Euclidean shapes (e.g., circles and rectangles), P » ÖA 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. Note that the value of the fractal dimension calculated in this manner is dependent upon patch size and/or the units used (Rogers 1993). Therefore, caution should be exercised when using this fractal dimension index as a measure of patch shape complexity.

Fractal analysis usually is applied to the entire landscape mosaic using the perimeter-area relationship $A = k\ P^{2/D}$, where k is a constant (Burrough 1986). If sufficient data are available, the slope of the line obtained by regressing log(P) on log(A) is equal to 2/D (Burrough 1986). Note, fractal dimension using this perimeter-area method is equal to 2 divided by the slope; D is not equal to the slope (Krummel et al. 1987) nor is it equal to 2 times the slope (e.g., O'Neill et al. 1988, Gustafson and Parker 1992) 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 (e.g., $n > 20$). 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 2 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 it may easily be used inappropriately.

Patch-Level Example.--Figure 4 depicts 3 patches extracted from a sample landscape that vary 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 2 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 the *shape index*.

Class-Level Example.--Figure 5 depicts 3 sample landscapes that vary 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 3 landscapes are greater than 1, indicating that the average patch shape in all 3 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 3 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 3 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 is therefore probably more reliable in this case.

Landscape-Level Example.--Figure 6 depicts 3 sample landscapes that vary in composition and pattern. In this case, even though the landscape boundary does not all represent 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 3 landscapes are greater than 1, indicating that the average patch shape in all 3 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 3 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. However, the index compares nicely 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 variability 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 of 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. In addition, it seems likely that edge effects would vary in relation to the type and nature of the edge (e.g., the degree of floristic and structural contrast and orientation). Unfortunately, in most cases, there is insufficient empirical support (or none) for designating separate edge widths for each unique edge type. Accordingly, in FRAGSTATS the user must specify a single edge width for all edge types.

In raster images, there are different ways to determine core area. FRAGSTATS employs a method in which a cell's 4 parallel neighbors are evaluated for similarity; diagonal neighbors are ignored. This method tends to slightly over-estimate the true core area.

Other methods can seriously under-estimate 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 percent 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 percent 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 affects of patch area, patch shape, and edge effect distance. Therefore, although they quantify landscape composition, they are affected by landscape configuration. For this reason, these metrics at the class level may be 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 percent 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 that summarize more than 1 feature (e.g., 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 actually contain several disjunct patches of suitable interior habitat, and it may be more appropriate to consider disjunct core areas as separate patches. For this reason, FRAGSTATS computes the *number of core areas* (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 with respect to 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. Conversely, this information can be represented as mean core area. Like their counterparts, note the difference between core area density and mean core area at the class level. Specifically, core area density is based on total landscape area; whereas, mean core area is based on total core area for the class. In contrast, at the landscape level, they are both based on total landscape area and are therefore completely redundant. Furthermore, mean core area can be defined in 2 ways. First, mean core area can be defined as the *mean core area per patch* (MCA1). Thus, patches with no core area are included in the average, and the total core area in a patch is considered together as 1 observation, regardless of whether the core area is contiguous or divided into 2 or more disjunct areas within the patch. Alternatively, mean core area can be defined as the *mean area per disjunct core* (MCA2). The distinction between these 2 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, regardless of whether it is 10 ha or 1,000 ha, 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. For example, 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. 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 (e.g., 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 3 conditions: (1) when there is only 1 core area in the landscape; (2) when there is more than 1 core area greater than 0 in size, but they are all the same size; and (3) when there is more than 1 patch, but none have any core area (CORE = 0). In all 3 cases, there is no variability in core area size, yet the ecological implications could be quite different.

All of the core area indices are affected by the interaction of patch size, patch shape, and the specified edge width. In particular, 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. Unfortunately, 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. Moreover, the utility of core area indices compared to their area-based counterparts depends on the resolution, minimum patch dimensions, and edge widths employed. For example, given a landscape with a resolution of 1 m^2 and minimum patch dimensions of 100 x 100 m, if an edge width of 1 m 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 3 patches extracted from a sample landscape that vary in core area based on a 100 m edge width for all edge types. Although patch A is almost 3 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. Note also that although patch B and C are almost equal in size, patch B has half the *core area* of patch C. This is a result of the interaction among patch size, patch shape, and edge width. With a 100 m 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 (e.g., 200 m) would result in both patches having 0 *core area* because of their small size, and a much smaller edge width (e.g., 10 m) would result in both patches having similar core areas. Thus, the affect of patch shape on *core area* is dependent on both patch size and edge width.

According to the *number of core areas* (NCORE), patches B and C both contain 1 core area because of their simple shapes. Patch A, however, contains 2 core areas because it is narrower than 200 m in the middle and then widens on both sides. Thus, under certain conditions it may be more meaningful to treat patch A as 2 separate patches. For example, if an organism avoids edge habitat up to a distance of 100 m, then from the organism's perspective, patch A may actually contain 2 separate suitable habitat patches. However, like *core area*, *number of core areas* is affected by the interaction of patch size, patch shape, and edge width. With a much larger edge width (e.g., 200 m) or much smaller edge width (e.g., 10 m), patch A would contain only 1 core area.

Although patch A is almost 3 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 2 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 3 sample landscapes that vary in the amount and pattern of mixed, large sawtimber habitat based on a 100 m edge width for all edge types. According to the *percent of landscape* (%LAND) in this patch type, roughly 50% of landscapes B and C are mixed, large sawtimber. According to the *core area percent of landscape* (C%LAND), however, only 10% of this habitat type in landscape B is core area, whereas 23% of this habitat type in landscape C is core area. Thus, the *core area percent of landscape* clearly indicates that landscape B is fragmented to a much greater degree than landscape C. Note, however, that inspection of this index alone does not indicate whether differences in the amount of core area are because of differences in total habitat area, habitat configuration, or both. Nevertheless, for an organism specialized on interior mixed, large sawtimber habitat, the *core area percent 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. Note that all core area indices are affected by the interaction of patch size, patch shape, and edge width. For example, with a much larger edge width (e.g., 200 m) or much smaller edge width (e.g., 10 m), the index values would 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 4 mixed, large sawtimber patches encompassing a total of 13 ha, there is no core area (i.e., no point in these patches is further than 100 m 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 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 3 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, 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. For example, although landscapes A and B have similar patch densities, *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 3 landscapes vary 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 3 landscapes with respect to 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). For example, it is difficult to tell from this index alone if the differences between landscapes B and C are because of differences in habitat area or habitat pattern. However, by interpreting both *class area* and *mean core area per patch* it becomes clear that the differences are due solely to pattern. *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.

Often, variation in the amount of core area per patch or disjunct core 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 6 times greater in landscape C than B. However, these indices alone do not say much about differences in structure among the 3 landscapes without simultaneously considering 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 coefficient of variation measures would depend 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% of the mixed, large sawtimber in landscape B is "interior" habitat; the remaining 80% 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 *landscape similarity index*, it becomes quite clear that landscapes B and C differ exclusively in habitat pattern 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 3 landscapes is highly fragmented (i.e., all have a high edge-to-interior ratio). 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. However, when the focus is on landscape structure, 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 3 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 mid-sized patch. This bias is characteristic of first-order statistics such 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 3 sample landscapes that vary in composition and pattern based on a 100 m edge width for all edge types. *Total core area* (TCA) indicates that landscapes A, B, C contain progressively more core area, and because *total landscape area* (TA) is similar, they represent a continuum from most to least patchy. Note that all core area indices are affected by the interaction of patch size, patch shape, and edge width. For example, with a much larger edge width (e.g., 200 m) or much smaller edge width (e.g., 10 m), the index values would 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 relationship between patch sizes and shapes in these landscapes and the designated edge width of 100 m. With a much larger edge width (e.g., 200 m) or much smaller edge width (e.g., 10 m), *number of core areas* would change 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 3 landscapes with respect to their spatial heterogeneity, *mean core area per patch* (MCA1) distinguishes among these landscape 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 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 mimic the results of *patch size standard deviation*. However, these indices alone do not tell us much about differences in structure among the 3 landscapes without simultaneously considering the *mean core area per patch* or *mean area per disjunct core*, respectively. *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. Among other things, 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 would depend on the particular application.

The *total core area index* (TCAI) represents the 3 landscapes along a continuum from most to least patchy. According to this index, only 10% of landscape A is "interior" habitat, the remaining 90% is "edge" habitat. Without any other information on landscape A, it could 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). 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 (Moore and Hooper 1975, Forman et al. 1976, Helliwell 1976, Whitcomb et al. 1981, Hayden et al. 1985, Dickman 1987). Opdam (1991) reviewed a number of studies that empirically demonstrated 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 (Levins 1970, Gilpin and Hanski 1991) and has been discussed in the context of conservation biology (e.g., Burkey 1989). The role of interpatch distance in metapopulations has had a preeminent role in recent conservation efforts for endangered species (e.g., Lamberson et al. 1992, McKelvey et al. 1992). Clearly, nearest-neighbor distance 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 1994, Gustafson et al. 1994, Whitcomb et al. 1981] and considers the size and proximity distance of all patches whose edges are within a specified search radius of the focal patch. The index is computed as the sum, over all patches of the corresponding patch type whose edges are within the search radius of the focal patch, of each patch size divided by the square of its distance from the focal patch. Note that we use the distance between the focal patch and each of the other patches within the search radius, similar to the isolation index of Whitcomb et al. (1981), rather than the nearest-neighbor distance of each patch within the search radius (which could be to a patch other than the focal patch), as in Gustafson and Parker (1992). 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, and/or closer patches than another patch will have a larger index value. Thus, the proximity index measures both the degree of patch isolation and the degree of fragmentation of the corresponding patch type within the specified neighborhood of the focal patch. The index is dimensionless (i.e., has no units) and therefore the absolute value of the index has little interpretive value; instead it is used as a comparative index.

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 (1994). 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 only be computed if there are at least 2 patches of the corresponding type. At the landscape level, mean nearest-neighbor distance considers only patches that have 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 2 patches of the same type. These 2 patches could be close together or far apart. In either case, the mean nearest-neighbor distance for this landscape may not characterize the entire landscape very well. For this reason, 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 that is 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, while the standard deviation does convey information about nearest neighbor variability, it is a difficult parameter to interpret without doing so in conjunction with the mean nearest-neighbor distance. For example, 2 landscapes may have the same nearest-neighbor standard deviation, e.g., 100 m; yet 1 landscape may have a mean nearest-neighbor distance of 100 m, while the other may have a mean nearest-neighbor distance of 1,000 m. In this case, the interpretations of landscape 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, while 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 (e.g., 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 (i.e., 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 with regards to landscape structure without also knowing the number of patches or patch density and other structural characteristics. For example, 2 landscapes may have the same nearest-neighbor coefficient of variation, e.g., 100%; yet 1 landscape may have 100 patches with a mean nearest-neighbor distance of 100 m, while the other may have 10 patches with a mean nearest-neighbor distance of 1,000 m. In this case, the interpretations of overall landscape 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 (i.e., 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. 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 insure 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 processes under consideration and the landscape is an "open" system relative to that organism or process, then nearest-neighbor results can be misleading. For example, consider a small subpopulation of a bird species occupying a patch near the boundary of a somewhat arbitrarily defined (from a bird's perspective) landscape. The nearest neighbor within the landscape boundary might be quite far away, yet in reality the closest patch might be very close, but just outside the designated landscape boundary. The magnitude of this problem is a function of scale. Increasing the size of the landscape relative to the scale at which the organism under investigation perceives and responds to the environment will decrease the severity of this problem. Similarly, the proximity 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 is of this problem is also a function of scale. Increasing the size of the landscape relative to the average patch size and/or decreasing the search radius will decrease the severity of this problem at the class and landscape levels. However, at the patch level, regardless of scale, individual patches located within the search radius of the boundary will have a biased proximity index. In addition, the proximity index 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 3 patches extracted from a sample landscape that vary in their neighborhood context. Patch A has the smallest *nearest-neighbor distance* (NEAR), followed by patch B and C. Similarly, patch A has the largest *proximity index* (PROXIM) based on a 200 m search radius, followed by patch 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 3 patches. Patch A contains a closer neighbor and a greater amount of similar habitat within its immediate neighborhood than either patch B or C. However, 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 3 sample landscapes that vary 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 m 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 C; yet, most other fragmentation indices indicate the converse. 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 3 sample landscapes that vary 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 m 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. There has been a proliferation of diversity indices and we will make no attempt to review them here. FRAGSTATS computes 3 diversity indices. These diversity measures are influenced by 2 components--richness and evenness. Richness refers to the number of patch types present; evenness refers to the distribution of area among different types. Richness and evenness are generally referred to as the compositional and structural components of diversity, respectively. Some indices (e.g., Shannon's diversity index) are more sensitive to richness than evenness. Thus, rare types have a disproportionately large influence on the magnitude of the index. Other indices (e.g., Simpson's diversity index) are relatively less sensitive to richness and thus place more weight on the common species. These diversity indices have been applied by landscape ecologists to measure 1 aspect of landscape structure--landscape composition (e.g., Romme 1982, O'Neill et al. 1988, Turner 1990a).

The most popular diversity index is *Shannon's diversity index* (SHDI) based on information theory (Shannon and Weaver 1949). The value of this index represents the amount of "information" per individual (or patch, in this case). Information is a somewhat abstract mathematical concept that we will not attempt to define. The absolute magnitude of Shannon's diversity index is not particularly meaningful; therefore, it is used as a relative index for comparing different landscapes or the same landscape at different times. *Simpson's diversity index* (SIDI) is another popular diversity measure that is not based on information theory (Simpson 1949). Simpson's index is less sensitive to the presence of rare types and has an interpretation that is much more intuitive than Shannon's index. Specifically, the value of Simpson's index represents the probability that any types selected at random would be different types. Thus, the higher the value the greater the likelihood that any 2 randomly drawn patches would be different patch types (i.e., greater 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 that belongs to a general class of diversity indices to which Shannon's diversity index belongs (Pielou 1975). Thus, the modified Simpson's and Shannon's diversity indices are similar in many respects and have the same applicability.

The use of diversity measures in community ecology has been heavily criticized because diversity conveys no information on the actual species composition of a community. Species diversity is a community summary measure that does not take into account the uniqueness or potential ecological, social, or economical importance of individual species. A community may have high species diversity yet be comprised largely of common or undesirable species. Conversely, a community may have low species diversity yet be comprised of especially unique, rare, or highly desired species. Although these criticisms have not been discussed explicitly with regards to the landscape ecological application of diversity measures, these criticisms are equally valid when diversity measures are applied to patch types instead of species. In addition, these diversity indices combine richness and evenness components into a single measure, even though it is usually 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. Therefore, 2 landscapes may have very different structure yet have the same richness. For example, 1 landscape may be comprised of 96% patch type A and 1% each of patch types B-E, whereas another landscape may be comprised of 20% each of patch types A-E. Although, patch richness would be the same, the functioning of these landscapes and the structure of the animal and plant communities would likely be greatly different. Because richness does not account for the relative abundance of each patch type, rare patch types and common patch types contribute equally to richness. Nevertheless, patch richness is a key element of landscape structure because the variety of landscape elements present in a landscape can have an important influence on a variety of ecological processes. Because many organisms are associated with a single patch type, patch richness often correlates well with species richness (McGarigal and McComb, unpubl. data).

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

Evenness measures the other aspect of landscape composition--the distribution of area among patch types. There are numerous ways to quantify evenness and most diversity indices have a corresponding evenness index derived from them. In addition, evenness can be expressed as its compliment--dominance (i.e., evenness = 1 - dominance). Indeed, dominance has often been the chosen form in landscape ecological investigations (e.g., O'Neill et al. 1988, Turner et al. 1989, Turner 1990a), although we prefer evenness because larger values imply greater landscape diversity. FRAGSTATS computes 3 evenness indices (*Shannon's evenness index*, SHEI; *Simpson's evenness index*, SIEI; *modified Simpson's evenness index*, MSIEI), corresponding to the 3 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 (i.e., equal distribution) for a given number of patch types represents the proportional reduction in the diversity index attributed to lack of perfect evenness. As the evenness index approaches 1, the observed diversity approaches perfect evenness.

Because evenness is represented as a proportion of maximum evenness, Shannon's evenness index does not suffer from the limitation of Shannon's diversity index with respect to interpretability. Nevertheless, it is important to note that 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.

<u>Landscape-Level Example</u>.--Figure 6 depicts 3 sample landscapes that vary in composition and pattern. *Shannon's diversity index* (SHDI), *Simpson's diversity index* (SIDI), and the *modified Simpson's diversity index* (MSIDI) largely 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 that there is a 79% probability that 2 randomly chosen patches would represent different patch types. According to *patch richness* (PR), the number of different patch types varies 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 3.5 different patch types within a 100-ha area and contains 37% 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 3 indices indicate that the distribution of area among patch types is 84-91% 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. Note that differences in evenness among landscapes based on *Simpson's evenness index* are less pronounced than the other 2 evenness indices, perhaps because Simpson's metric is less influenced by rare patch types.

Contagion and Interspersion Metrics

FRAGSTATS computes 2 indices representing patch interspersion and juxtaposition at the class and landscape levels, although 1 index applies only to the landscape level (Table 1). These metrics quantify landscape configuration. A contagion index was proposed first by O'Neill et al. (1988) and subsequently it has been widely used (Turner and Ruscher 1988, Turner 1989, Turner et al. 1989, Turner 1990a and b, Graham et al. 1991, Gustafson and Parker 1992). Li and Reynolds (1993) showed that the original formula was incorrect; they introduced 2 forms of an alternative contagion index that corrects this error and has improved performance. 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 1 of the contagion indices proposed by Li and Reynolds (1993). This *contagion index* (CONTAG) is applicable only to raster images at the landscape level and it is based on raster "cell" adjacencies, not "patch" adjacencies. This contagion index consists of the sum, over patch types, of the product of 2 probabilities: (1) the probability that a randomly chosen cell belongs to patch type i (estimated by the proportional abundance of patch type i), and (2) the conditional probability that given a cell is of patch type i, one of its neighboring cells belongs to patch type j (estimated by the proportional abundance of patch type i adjacencies involving patch type j). The product of these probabilities equals the probability that 2 randomly chosen adjacent cells belong to patch type i and j. This contagion index is appealing because of the straightforward and intuitive interpretation of this probability. Contagion measures both patch type interspersion (i.e., the intermixing of units of different patch types) as well as patch dispersion (i.e., the spatial distribution of a patch type). All other things being equal, a landscape in which the patch types are well interspersed will have lower contagion than a landscape in which patch types are poorly interspersed. According to the previous authors, contagion measures the extent to which landscape elements (patch types) are aggregated or clumped (i.e., dispersion); higher values of contagion may result from landscapes with a few large, contiguous patches, whereas lower values generally characterize landscapes with many small and dispersed patches. Thus, holding interspersion constant, a landscape in which the patch types are aggregated into larger, contiguous patches will have greater contagion than a landscape in which the patch types are fragmented into many small patches. Contagion measures dispersion in addition to patch type interspersion because cells, not patches, are evaluated for adjacency. Landscapes consisting of large, contiguous patches have a majority of internal cells with like adjacencies. In this case, contagion is high because the proportion of total cell adjacencies comprised of like adjacencies is very large and the distribution of adjacencies among edge types is very uneven. Moreover, 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 that are 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 can never 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 (i.e., equally adjacent to each other), whereas lower values characterize landscapes in which the patch types are poorly interspersed (i.e., disproportionate distribution of patch type adjacencies). The interspersion index is not directly affected by the number, size, contiguity, or dispersion of patches per se, as is the contagion index. Consequently, a landscape containing 4 large patches, each a different patch type, and a landscape of the same extent containing 100 small patches of 4 patch types will have the same index value if the patch types are equally interspersed (or adjacent to each other based on the proportion of total edge length in each edge type); whereas, the value of contagion would be quite different. Like the contagion index, the interspersion index is a relative index that represents the observed level of interspersion as a percentage of the maximum possible given the total number of patch types.

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 1 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.

It is important to note the differences between the contagion index and the interspersion and juxtaposition index. Contagion is affected by both interspersion and dispersion. The interspersion and juxtaposition index, in contrast, is affected only by patch type interspersion and 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 attempting to compare results from different studies.

Class-Level Example.--Figure 5 depicts 3 sample landscapes that vary 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. Note also that although landscapes A and C contain very 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% of the maximum possible equitable distribution in both landscapes, even though the absolutes amounts of edge and proportions associated with each edge type are clearly quite different.

Landscape-Level Example.--Figure 6 depicts 3 sample landscapes that vary 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 2 patch types that are present only in the landscape border and the amount of edge involving these 2 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.