FRAGSTATS USER GUIDELINES

Version 3

The main metrics (Connectivity)

**Background.** Connectivity refers to the degree to which a landscape facilitates or impedes ecological flows (e.g., the movement of organisms among habitat patches and therefore the rate of movement among local populations in a metapopulation). An abrupt change in the Connectivity of the landscape, for example, as might be caused by habitat loss and fragmentation, may interfere with dispersal success, such that formerly widespread populations may suddenly become fragmented into small, isolated populations. This may in turn lead to an abrupt decline in patch occupancy (metapopulation dynamics) and ultimately extinction of the population across the landscape (extinction thresholds).

Although Connectivity is considered a “vital element of landscape structure” (Taylor et al., 1993), it has eluded precise definition and has been difficult to quantify and implement in practice. In part, this is due to differences between the “structural connectedness” of patch types (or habitat) and the “functional connectedness” of the landscape as perceived by an organism or ecological process. Structural connectedness refers to the physical continuity of a patch type (or a habitat) across the landscape. Contiguous habitat is physically connected, but once subdivided, for example, as a result of habitat fragmentation, it becomes physically disconnected. Structural connectedness can be evaluated by a combination of measures of habitat extent, subdivision, and contagion. The notion of structural connectedness adopts an island biogeographic perspective because the focus is on the physical continuity of a single patch type. What constitutes "functional connectedness" between patches, on the other hand, clearly depends on the organism or process of interest; patches that are connected for bird dispersal might not be connected for salamanders, seed dispersal, fire spread, or hydrologic flow. As With (1999) notes, “what ultimately influences the Connectivity of the landscape from the organism’s perspective is the scale and pattern of movement (scale at which the organism perceives the landscape) relative to the scale and pattern of patchiness (structure of the landscape); ...i.e., a species’ gap-crossing or dispersal ability relative to the gap-size distribution on the landscape”(Dale et al. 1994, With and Crist 1995, Pearson et al. 1996, With et al. 1997). Functional connectedness, therefore, relates to the interaction of ecological flows (including organisms) with landscape pattern. Functional connections might be based on: (1) strict adjacency (touching) or some threshold distance (a maximum dispersal distance); (2) some decreasing function of distance that reflects the probability of connection at a given distance; or (3) a resistance-weighted distance function, e.g., where the distance between two patches is computed as the least cost distance on a resistance surface, where each intervening location between habitat patches is assigned a resistance value based on its permeability to movement by the focal organism. Then various indices of overall connectedness can be derived based on the pairwise connections between patches.

Connectivity -- Connectivity generally refers to the functional connections among patches. What constitutes a "functional connection" between patches clearly depends on
the application or process of interest; patches that are connected for bird dispersal might not be connected for salamanders, seed dispersal, fire spread, or hydrologic flow. Connections might be based on strict adjacency (touching), some threshold distance, some decreasing function of distance that reflects the probability of connection at a given distance, or a resistance-weighted distance function. Then various indices of overall connectedness can be derived based on the pairwise connections between patches. For example, one such index, connectance, can be defined on the number of functional joinings, where each pair of patches is either connected or not. Alternatively, from percolation theory, connectedness can be inferred from patch density or be given as a binary response, indicating whether or not a spanning cluster or percolating cluster exists; i.e., a connection of patches of the same class that spans across the entire landscape (Gardner et al. 1987). Connectedness can also be defined in terms of correlation length for a raster map comprised of patches defined as clusters of connected cells. Correlation length is based on the average extensiveness of connected cells. A map's correlation length is interpreted as the average distance one might traverse the map, on average, from a random starting point and moving in a random direction, i.e., it is the expected traversibility of the map (Keitt et al. 1997).

**FRAGSTATS Metrics.**—Although Connectivity can be evaluated using a wide variety of FRAGSTATS metrics that indirectly say something about either the structural or functional connectedness of the landscape, FRAGSTATS computes a few metrics whose sole purpose is to measure Connectivity. *Patch cohesion* (COHESION) was proposed by Schumaker (1996) to quantify the Connectivity of habitat as perceived by organisms dispersing in binary landscapes. Patch cohesion is computed from the information contained in patch area and perimeter. Briefly, it is proportional to the area-weighted mean perimeter-area ratio divided by the area-weighted mean patch shape index (i.e., standardized perimeter-area ratio). It is well known that, on random binary maps, patches gradually coalesce as the proportion of habitat cells increases, forming a large, highly connected patch (termed a percolating cluster) that spans the lattice at a critical proportion \( p_c \) that varies with the neighbor rule used to delineate patches (Staufer 1985, Gardner et al. 1987). Patch cohesion has the interesting property of increasing monotonically until an asymptote is reached near the critical proportion. Another index, connectance (CONNECT), can be defined on the number of functional joinings, where each pair of patches is either connected or not based on some criterion. FRAGSTATS computes connectance using a threshold distance specified by the user and reports it as a percentage of the maximum possible connectance given the number of patches. The threshold distance can be based on either Euclidean distance or functional distance, as described elsewhere (see Isolation/Proximity Metrics). Connectedness can also be defined in terms of correlation length for a raster map comprised of patches defined as clusters of connected cells. Correlation length is based on the average extensiveness of connected cells, and is computed as the area-weighted mean radius of gyration across all patches in the class or landscape. Correlation length is not included with the Connectivity metrics in the FRAGSTATS graphical user interface because it is already included as a distribution metric for patch radius of gyration (GYRATE_AM) under the Area/Density/Edge metrics. A map's correlation length is interpreted as the average
distance one might traverse the map, on average, from a random starting point and moving in a random direction, i.e., it is the expected traversability of the map (Keitt et al. 1997).

(C122) Connectance Index (class level)

\[
 CONNECT = \left( \frac{\sum_{j=1}^{n} c_{ijk}}{n_i (n_i - 1)} \right) (100) 
\]

where \( c_{ijk} = 0 \) if patch \( j \) and \( k \) are not within the specified distance of each other and \( c_{ijk} = 1 \) if patch \( j \) and \( k \) are within the specified distance.

\( n_i = \) number of patches in the landscape of the corresponding patch type (class).

**Description**
CONNECT equals the number of functional joinings between all patches of the corresponding patch type (sum of \( c_{ijk} \) where \( c_{ijk} = 0 \) if patch \( j \) and \( k \) are not within the specified distance of each other and \( c_{ijk} = 1 \) if patch \( j \) and \( k \) are within the specified distance), divided by the total number of possible joinings between all patches of the corresponding patch type, multiplied by 100 to convert to a percentage.

**Units**
Percent

**Range**
\( 0 \leq \text{CONNECT} \leq 100 \)

\( \text{CONNECT} = 0 \) when either the focal class consists of a single patch or none of the patches of the focal class are "connected" (i.e., within the user-specified threshold distance of another patch of the same type). \( \text{CONNECT} = 100 \) when every patch of the focal class is "connected."

**Comments**
Connectance is defined on the number of functional joinings between patches of the corresponding patch type, where each pair of patches is either connected or not based on a user-specified distance criterion. Connectance is reported as a percentage of the maximum possible connectance given the number of patches. Note, connectance can be based on either Euclidean distance or functional distance, as described elsewhere (see Isolation/Proximity Metrics), although this is not implemented yet. Also, note that Euclidean distances are calculated from cell center to cell center. Thus, two patches that have 10 10-m cells between them have a computed distance of 110 m, not 100 m.
**Connectance Index (landscape level)**

Connectance, denoted as $\text{CONNECT}$, is defined as the number of functional joinings between all patches of the same patch type divided by the total number of possible joinings, multiplied by 100 to convert to a percentage. The formula is given by:

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

where:
- $c_{ijk}$ is the joining between patch $j$ and $k$ based on a user-specified threshold distance, with 0 = unjoined and 1 = joined.
- $n_i$ is the number of patches in the landscape of each patch type ($i$).

**Description**

$\text{CONNECT}$ equals the number of functional joinings between all patches of the same patch type (sum of $c_{ijk}$ where $c_{ijk} = 0$ if patch $j$ and $k$ are not within the specified distance of each other and $c_{ijk} = 1$ if patch $j$ and $k$ are within the specified distance), divided by the total number of possible joinings between all patches of the same type, multiplied by 100 to convert to a percentage.

**Units**

Percent

**Range**

$0 \leq \text{CONNECT} \leq 100$

Connectance is defined as zero when either the landscape consists of a single patch, or all classes consist of a single patch, or none of the patches in the landscape are "connected" (i.e., within the user-specified threshold distance of another patch of the same type). Connectance equals 100 when every patch in the landscape is "connected."

**Comments**

Connectance is defined on the number of functional joinings between patches of the same type, where each pair of patches is either connected or not based on a user-specified distance criterion. Connectance is reported as a percentage of the maximum possible connectance given the number of patches. Connectance can be based on either Euclidean distance or functional distance, as described elsewhere (see Isolation/Proximity Metrics), although this is not implemented yet. Also, note that Euclidean distances are calculated from cell center to cell center. Thus, two patches that have 10 10-m cells between them have a computed distance of 110 m, not 100 m.
## Cohesion Index

### (C121) Patch Cohesion Index (class level)

<table>
<thead>
<tr>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>COHESION equals 1 minus the sum of patch perimeter (in terms of number of cell surfaces) divided by the sum of patch perimeter times the square root of patch area (in terms of number of cells) for patches of the corresponding patch type, divided by 1 minus 1 over the square root of the total number of cells in the landscape, multiplied by 100 to convert to a percentage. Note, total landscape area (A) excludes any internal background present.</td>
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<tr>
<th>Units</th>
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<tr>
<td>None</td>
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<table>
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<tr>
<th>Range</th>
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<tr>
<td>0 ≤ COHESION &lt; 100</td>
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COHESION approaches 0 as the proportion of the landscape comprised of the focal class decreases and becomes increasingly subdivided and less physically connected. COHESION increases monotonically as the proportion of the landscape comprised of the focal class increases until an asymptote is reached near the percolation threshold (see background discussion). COHESION is given as 0 if the landscape consists of a single non-background cell.

<table>
<thead>
<tr>
<th>Comments</th>
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<tbody>
<tr>
<td>Patch cohesion index measures the physical connectedness of the corresponding patch type. Below the percolation threshold, patch cohesion is sensitive to the aggregation of the focal class. Patch cohesion increases as the patch type becomes more clumped or aggregated in its distribution; hence, more physically connected. Above the percolation threshold, patch cohesion does not appear to be sensitive to patch configuration (Gustafson 1998)</td>
</tr>
</tbody>
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\[
COHESION = \left(1 - \frac{\sum_{i,j} p_{ij}}{\sum_{i,j} p_{ij} \sqrt{a_{ij}}}ight) \left(1 - \frac{1}{\sqrt{A}}\right)^{-1} \times 100
\]

- \( p_{ij} \) = perimeter of patch \( ij \) in terms of number of cell surfaces.
- \( a_{ij} \) = area of patch \( ij \) in terms of number of cells.
- \( A \) = total number of cells in the landscape.
### (L.121) Patch Cohesion Index (landscape level)

\[
\text{COHESION} = \left[ 1 - \frac{\sum_{i=1}^{n} \sum_{j=1}^{n} p_{ij}}{\sum_{i=1}^{n} \sum_{j=1}^{n} p_{ij} \sqrt{a_{ij}}} \right] \left[ 1 - \frac{1}{\sqrt{A}} \right]^{-1} \cdot 100
\]

- \( p_{ij} \) = perimeter of patch \( ij \) in terms of number of cell surfaces.
- \( a_{ij} \) = area of patch \( ij \) in terms of number of cells.
- \( A \) = total number of cells in the landscape.

**Description**

COHESION equals 1 minus the sum of patch perimeter (in terms of number of cells) divided by the sum of patch perimeter times the square root of patch area (in terms of number of cells) for all patches in the landscape, divided by 1 minus 1 over the square root of the total number of cells in the landscape, multiplied by 100 to convert to a percentage. Note, total landscape area (A) excludes any internal background present.

**Units**

None

**Range**

The behavior of this metric at the landscape level has not yet been evaluated.

**Comments**

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

**Limitations**

These metrics are limited in a variety of ways. First, patch cohesion is based on perimeter and area calculations and is therefore subject to the same limitations discussed elsewhere (see Area/Density/Edge Metrics) for edge calculations. Moreover, despite its appealing performance under certain conditions (e.g., Schumaker 1996), this index is plagued by the lack of a straightforward and intuitive interpretation. As a result, it remains largely untested in other ecological applications. Like all distance-based metrics, connectance suffers from the same limitations as nearest-neighbor distance (see Isolation/Proximity Metrics). Specifically, only patches within the landscape are considered when determining if a patch is connected or not, despite the fact that a patches’ nearest neighbor may be just outside the landscape boundary. Finally, like all functional metrics, the traversability index requires substantial knowledge of the organism or process under consideration in order to specify meaningful resistance coefficients. If the weighting scheme does not accurately represent the phenomenon under investigation, then the results will be spurious.

**The related metrics (Isolation)**

**Background**

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

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

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

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