Chapter 6. Landscape Analysis for Habitat Monitoring

Samuel A. Cushman
Kevin McGarigal
Kevin S. McKelvey
Christina D. Vojta
Claudia M. Regan

6.1 Objective

The primary objective of this chapter is to describe standardized methods for measuring and monitoring attributes of landscape pattern in support of habitat monitoring. This chapter describes the process of monitoring categorical landscape maps in which either selected habitat attributes or different classes of habitat quality are represented as different **patch** types, using maps produced by the modeling approaches described in chapter 5. Although many alternative models of landscape structure exist, such as landscape gradients (McGarigal and Cushman 2005) and graph models (Urban et al. 2009), we focus on categorical landscape maps because of their familiarity to managers, long history of use in landscape ecology, and the fact that land management agencies largely base planning and analysis on this kind of representation of landscape structure (McGarigal et al. 2009). The salamander habitat monitoring plan in chapter 10, however, provides an example of a graph model (i.e., a model of habitat connectivity for **metapopulation** structure).

This chapter focuses on landscape pattern analysis as part of monitoring habitat for emphasis species. To use landscape metrics for model development, see Cushman and McGarigal (2002), Grand et al. (2004), and Thompson and McGarigal (2002). This chapter presents key issues that should be addressed to ensure meaningful landscape analysis, and it reviews the steps to be followed in conducting and interpreting landscape analysis in the context of habitat monitoring. We emphasize the use of FRAGSTATS (McGarigal et al. 2012) as a primary tool to quantify the composition and structure of habitat in categorical maps, given that FRAGSTATS is freely available, widely used, user friendly, and well documented, and it provides comprehensive analysis ability for categorical landscape maps (http://www.umass.edu/landeco).

6.2 Key Concepts

6.2.1 Landscape Analysis and Adaptive Management

Adaptive management works by specifying resource goals, conducting management for the purpose of creating or maintaining these desired conditions, and monitoring results to confirm that the system is behaving as expected and that resources are moving toward the desired conditions (Holling 1978, Walters 1986). This approach presupposes that the state of the system is well known across time. For tracking the trajectories of ecological systems, monitoring provides the key data on condition and direction of the system necessary to guide incremental adjustments to management. As a result, monitoring resource condition and trend has greatly elevated importance under the adaptive management paradigm. Cost-effective, timely, representative, and broad-scale monitoring of multiple resources is the foundation on which adaptive management depends. Adaptive management literally cannot be adaptive without these data.

The adaptive management paradigm sets high priority on developing ongoing analyses, based on monitoring, to continually adjust or change land management planning decisions and thereby efficiently move toward desired conditions (Cushman and McKelvey 2010). Multiple resource monitoring is critical for establishing ecologically meaningful and appropriate desired conditions, evaluating current conditions relative to these objectives, and evaluating effects of management over time to guide adaptive changes to the management regime.

In the Forest Service, adaptive management is addressed through the land management planning process. The Land and Resource Management Plan (LRMP) provides a formal declaration of desired conditions that are implemented through goals, objectives, standards, and guidelines. LRMP objectives are measurable and can provide quantifiable threshold values for triggering a reevaluation of management. The LRMP monitoring plan enables managers to determine whether threshold values have been met. In the context of habitat for specific species, the LRMP might include objectives with specific habitat conditions, such as structural components, patch geometry (e.g., patch size and amount of edge versus core), and spatial context (adjacency to other habitat and connectivity). The LRMP monitoring plan would then use habitat attributes to quantify condition and trend relative to objectives and threshold values.

6.2.2 What Is a Landscape?

A landscape is a heterogeneous model of a region of the physical world in which certain attributes of the environment are represented spatially as linear features, patches, points, or continuously varying surfaces. Depending on the question of interest, a landscape may be of any size. For example, planning landscapes are usually watersheds and management zones measured at the scale of tens to thousands of acres. In contrast, ecological research focused on mycology or microorganisms might define landscapes of interest at the scale of a few square feet. The size and scale of a landscape are therefore direct functions of its purpose and, in the context of habitat monitoring, the landscape must also reflect a meaningful spatial extent and grain for the emphasis species.

Regardless of the size, landscapes are composed of elements—the spatial components that make up the landscape. A convenient and popular model for conceptualizing and representing the elements in a categorical map pattern is known as the **patch mosaic model** (Forman 1995). Patch boundaries represent discontinuities in environmental states that are large enough to be perceived by the organism of interest or that are relevant to the ecological phenomenon under consideration (Wiens 1976). Therefore, patches must be defined relative to the emphasis species being monitored.

The patch mosaic model is most powerful when heterogeneous environmental conditions can be clearly defined and accurately mapped as discrete patches and when the variation within a patch is deemed relatively insignificant and can be ignored. For example, breeding habitat for many pond-breeding amphibians can be clearly defined and delineated with relatively little uncertainty, and the variation in habitat quality within ponds is insignificant compared with differences among ponds or between uplands and ponds. Other applications of the patch mosaic model include forested woodlots embedded within a contrasting agricultural or urban landscape, fields in a forested landscape, and stands of deciduous trees within a coniferous forest. In general, whenever disturbances (natural or anthropogenic) either create discrete patches or leave behind discrete remnant patches, the patch mosaic model is likely to be useful.

An alternative to the patch mosaic model is the gradient landscape model, in which landscapes are viewed as spatially complex assemblages of elements that cannot be simply categorized into discrete patches, so that heterogeneity is represented instead as a continuous function (Cushman et al. 2009, Evans and Cushman 2009, McGarigal et al. 2009). For example, habitat for elk (*Cervus canadensis*) may be a function of the juxtaposition of different land cover types that provide forage and cover, influenced by the proximity of roads and human disturbance. These conditions likely vary across the landscape as continuous gradients rather than discrete patches, so a gradient mosaic model would be the more appropriate depiction of elk habitat. Unfortunately, quantitative methods for assessing gradient landscape structure are still under development (e.g., McGarigal et al. 2009) and are therefore not included in this technical guide. The gradient model of landscape structure offers exciting new opportunities to explore landscape pattern-process relationships, however, in potentially more meaningful methods than the traditional patch mosaic approach (McGarigal et al. 2009).

A third representation of landscape structure is connectivity across landscape elements, using network analysis (Urban et al. 2009). Network analysis portrays the functional relationships of nodes and links in a graph. In the context of habitat, graph nodes represent habitat patches or local populations, and links represent functional connections among habitat patches. A central task in network analysis is to find the shortest path between any pair of nodes in a graph (Urban et al. 2009), which can be used to characterize dispersal or migration pathways or connectivity among metapopulations.

In this chapter, we address landscape structure only in reference to the categorical patch mosaic model because of its familiarity to land managers, its ease of analysis with commonly available tools, and its appropriateness for representing patterns of habitat patches across landscapes. Simply put, habitat at the landscape level is typically represented as patches that are classified as habitat or nonhabitat, or as differing levels of habitat suitability. As mentioned previously, however, the salamander example in chapter 10 incorporates graph theory as part of the design for monitoring habitat connectivity.

6.2.3 What Is Habitat at the Landscape Level?

The habitats in which organisms live are spatially structured at multiple scales, and these patterns interact with organism perception and behavior to drive the processes of population dynamics and community structure (Johnson et al. 1992). For all species, habitat must have the following:

- Sufficient size and juxtaposition of resource patches to support reproduction.
- Sufficient size and proximity of habitat patches to facilitate dispersal.
- Sufficient size and proximity of patches to maintain metapopulation structure, if that is a characteristic of the species.

Each of these landscape functions operates at a different scale, but together, they define an organism's habitat at the landscape level.

At any scale, anthropogenic activities (e.g., urban development and timber harvest) can disrupt the structural integrity of landscapes through habitat loss and fragmentation. This disruption may reduce habitat area below critical occupancy thresholds and increase habitat fragmentation such that movements are impeded (Gardner et al. 1993) or unwanted movements of organisms are facilitated (e.g., predators or invasive species) (see chapter 7). The altered landscape structure can compromise the ability of a landscape to function as habitat at one or more scales. A full review of the implications of landscape pattern and habitat fragmentation on species' habitats and populations is beyond the scope of this chapter. Briefly, however, habitat fragmentation has been shown to decrease dispersal (deMaynadier and Hunter 2000, Gibbs 1998,), increase mortality (Carr and Fahrig 2001, Fahrig et al. 1995), and reduce genetic diversity of wildlife populations (Cushman 2006), thereby increasing extinction risk (Lande 1988, Tallmon et al. 2004).

Nonspatial habitat models are unable to reflect the major effects of landscape pattern in influencing the distribution and abundance of organisms. By contrast, landscape analyses allow for assessment of spatial pattern, isolation, and fragmentation of habitat patches relative to the ecological and demographic characteristics of the species.

6.2.3 The Importance of Scale

Scale is critical in defining a landscape, because pattern and its effect on process vary with scale. Thus, the scale of a landscape is inseparable from its definition. One cannot define a landscape without explicit consideration of its scale. At least two critical components of scale as it pertains to landscape definition exist: spatial scale and **thematic resolution**.

Spatial Scale

Several important considerations relating to spatial scale strongly influence results of landscape pattern analysis. The most important attributes are grain and extent (chapter 2, section 2.2.6). Both grain and extent affect landscape pattern analyses in fundamentally important ways. Many papers have investigated how changing spatial grain (Turner et al. 1989, Wickham and Riitters1995, Wu 2004, Wu et al. 2002) and landscape extent (Saura and Martinez-Millan 2001, Shen et al. 2003) affect landscape metrics. As a result of this rich body of work, extensive information is available about the scale dependency of landscape metrics in relation to grain, extent, and classification scheme of categorical landscape maps.

Grain sets a lower boundary on the range of detectable patterns. Extent sets an upper boundary on the extent of detectable pattern and defines the scope of inference of the analysis (see chapter 3, section 3.3.1). From the standpoint of habitat monitoring, the most important consideration of spatial scale relates to comparing analyses from different time periods. To be comparable, habitat maps from two or more analyses must share several characteristics, including (1) comparable thematic resolution (i.e., classification definitions are the same), (2) use of the same or highly similar data sources to provide comparable information (e.g., radiometric and spectral resolution in a remotely sensed imagery), and (3) comparable spatial scale in terms of both grain and extent. If any of these are inconsistent between analyses, then it is impossible to determine whether observed differences between habitat maps are because of differences in map characteristics or ecological differences. The issue of comparable data cannot be overstressed. Seemingly small differences in grain or classification definition can lead to widely divergent estimates of even simple attributes such as amount of forested area.

In general, studies conducted over large spatial extents tend to have coarse grain and low thematic resolution because of the difficulty of conducting fine grain analysis over large regions. Care must be taken to ensure that thematic resolution and spatial scale are appropriate for the emphasis species, however. These attributes are critical to the underlying habitat model (chapter 5) and must be specified correctly relative to the ecology of the particular organism or predictions will fail to reflect the true habitat conditions for the species (e.g., Thompson and McGarigal 2002). In addition, whenever comparing landscapes of different size, use area-normalized versions of landscape metrics.

Thematic Resolution

One of the biggest challenges in representing a categorical landscape mosaic is determining the appropriate thematic resolution**.** A number of papers have investigated how classification scheme and classification accuracy affect landscape metrics calculated from categorical patch mosaics (e.g., Shao et al. 2001, Wickham et al. 1997). Several well-known papers have evaluated the sensitivity and consistency of landscape metrics to variation in landscape pattern using controlled empirical sampling and neutral models (e.g., Cushman et al. 2008a, Hargis et al. 1998, Hess and Bay 1997, Neel et al. 2004, Riitters et al. 1995). The thematic resolution refers to what attributes of the underlying environment are represented in the habitat map and how finely they are resolved into categories.

Typically, the landscape has been classified into habitat patches based on properties of vegetation cover. This classification approach may be very meaningful for some organisms but not for others. For example, fossorial mammals are likely to be more sensitive to soil characteristics (e.g., depth, texture, wetness, organic matter, pH) than to aboveground vegetation. For these species, we might classify the landscape based on soil properties. Many other legitimate frameworks for classifying the landscape exist; the best thematic classification of the landscape ultimately depends on the habitat attributes identified for the emphasis species and the availability of data. In practice, data availability is often the limiting factor in determining the thematic resolution, because our desire to resolve thematic differences often exceeds our ability to do so with existing data. Thus, the selected thematic resolution is usually a compromise between the ideal number and types of classes from the perspective of the emphasis species and the number and types of classes that can be resolved accurately with existing data.

6.2.4 Effects of Map Error on Landscape Pattern Analysis

Landscape analysts must pay close attention to map error, because landscape metrics vary in their sensitivity to this unavoidable property of all classified maps. Some metrics, such as mean patch size and number of patches, can exhibit extreme sensitivity to even minor map error rates (Langford et al. 2006); therefore, they should be avoided in most cases. Other metrics, however, are relatively insensitive to misclassification errors involving small patches. For example, area-weighted metrics weight each patch proportionately to its area, and small patches have very little weight when computing the landscape metric. Thus, most of the problems associated with at least minor map errors can be avoided by choosing the most appropriate metrics. Of course, major map errors create insurmountable problems. Unfortunately, no general rule of thumb exists regarding how large the error rate can be before even the best metrics produce erroneous results.

6.3 Process Steps for Conducting a Landscape Analysis

6.3.1 Establish Objectives for the Landscape Analysis

The general objective of landscape pattern analysis is to quantify current area and configuration of habitat in a landscape of interest to compare it with desired conditions and previously measured conditions. For each emphasis species, create a specific objective that addresses the primary monitoring focus of the landscape pattern analysis. For example, a specific objective could be to measure changes in habitat patch proximity at the home range scale and compare this spatial distribution with historical conditions or desired future conditions. Another possible objective is to measure the extent to which habitat is well distributed across the plan area. A third objective might be to provide sufficient quantity and quality of habitat across an ecoregion to sustain metapopulation structure over long time frames.

Whatever the objective, it is critical to formally link it with the LRMP objectives and desired conditions that underlie the adaptive management cycle for the analysis area (section 6.2.1). Specifically, without detailed, specific guidance regarding what landscape elements to measure, what metrics to use, what the objectives are for monitoring, and what thresholds trigger a change in management, landscape analysis, at best, will be vaguely descriptive.

6.3.2 Define the Landscape

Choose a landscape extent that is meaningful from both an ecological perspective and a management perspective, given the scale at which the emphasis species operates and the specific objective of the landscape analysis. This choice might be the local range of an emphasis species or the extent of a local population, a metapopulation, or a group of species across an ecoregion. The extent may need to correspond to a specific project planning area (e.g., timber sale area), a timber or wildlife management unit, a watershed, or an administrative unit (e.g., ranger district or national forest), although these boundaries usually lack ecological context. If the landscape extent is small relative to the scale at which population processes for the species of interest act (e.g., emigration or dispersal), then it is likely that patterns in the broader surrounding landscape (i.e., the landscape context) will have as much (or more) effect on processes as patterns within the specified landscape. At a minimum, the scope and limitations of the analysis, given these scaling considerations, should be made explicit.

Next, define a relevant grain. Practically speaking, the grain of the data represents a balance between the desire for accurate calculations of landscape pattern, computational efficiency, and the desire to scale patterns appropriately for the organisms of interest and the chosen landscape extent (figure 6.1). The grain should be kept as fine as possible to ensure that small yet meaningful features of the landscape are preserved (figure 6.1). On the other hand, the grain should be large enough in relation to the extent so that unnecessary detail is not confused with the important coarse-scale patterns over large spatial extents. This clarity may be achieved by increasing the minimum mapping unit above the resolution set by the grain. In practice, these decisions are often guided by technical considerations owing to limited data sources and the availability of data-processing software. Again, the effects of scale on the scope and limitations of the analysis should be clearly addressed.

Ideally, the thematic resolution has been appropriately selected to match monitoring objectives. For example, suppose we chose to monitor the extent and pattern of cover type and seral stage classes as habitat attributes for a species. We might represent each cover type and seral stage combination as a separate class and consider each class as providing habitat of varying degrees of quality that differentially affect the connectivity of late-seral spruce-fir (*Picea* spp.-*Abies* spp.) habitat patches. In this context, the same high elevation landscape can be represented at different thematic resolutions. Although some organisms may perceive and respond to changes in the amount and distribution of late-seral spruce-fir forest, other organisms may exhibit more general associations with late-seral conifer forest of any species composition. If this situation is the case, we might represent the landscape at a broader thematic resolution (e.g., late-seral conifer forest) (figure 6.2).

Figure 6.1.—*Spatial grain should be appropriate for the organism of interest. For the American marten (*Martes americana*), a grain of 50 feet (ft) is finer than is needed, whereas a grain of 500 ft may ignore important aspects of landscape pattern.*

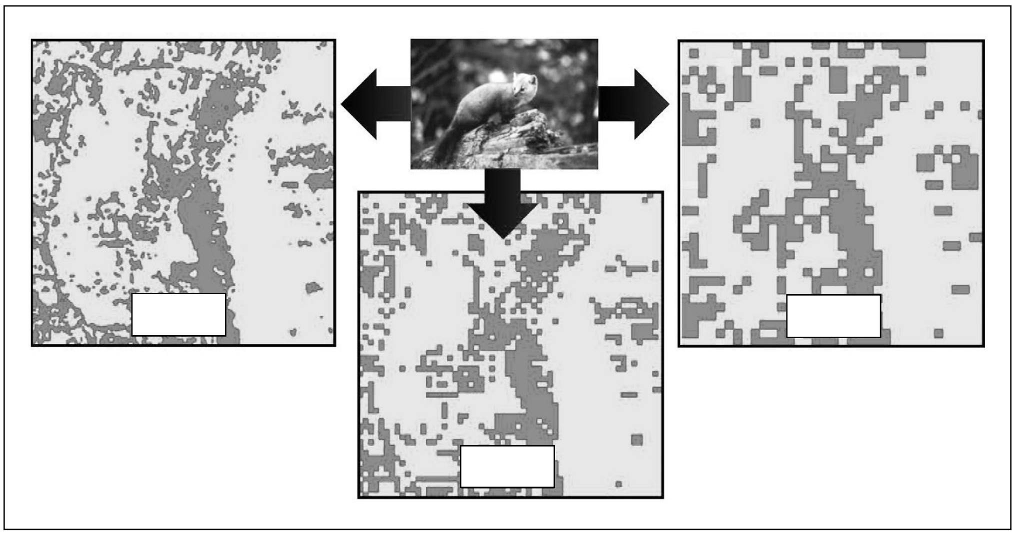
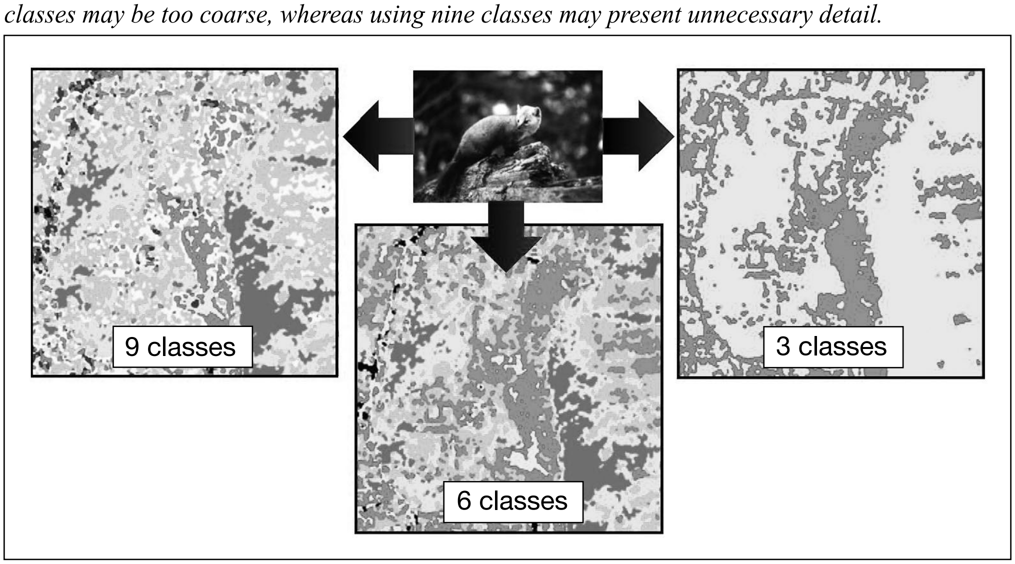


Figure 6.2.—*Ideally, the thematic resolution reflects the resolution at which organisms perceive the landscape. For the American marten (*Martes americana*), differentiating between only three cover classes may be too coarse, whereas using nine classes may present unnecessary detail.*



For yet other organisms, it might be more meaningful to classify with an even broader thematic resolution, treating all late-seral forest, including both deciduous and coniferous, or perhaps even all forested cover types as a single comprehensive class. Fundamentally, the same land area is viewed by different species at a different grain, which suggests an appropriate thematic resolution for each species.

If the objective of the landscape analysis is to quantify and monitor fragmentation, then decide which landscape elements will be viewed as fragmenting features. For example, does a small forest road bisecting contiguous forest constitute a fragmenting feature and split the forest into two distinct habitat patches? What if the road is an expressway? Is a small first order stream or a larger river a fragmenting feature? Linear landscape elements are often important features of the landscape; whether they function to disrupt the physical continuity of the landscape enough to warrant treatment as patch boundaries depends on the phenomenon under consideration and the specific capabilities of the species.

6.3.3 Identify the Larger Landscape Context

Ensure that the landscape defined for analysis is sufficiently bounded within a larger spatial extent to incorporate patterns and processes that operate at larger spatial scales. Landscapes, in general, are open systems; energy, materials, and organisms move into and out of the landscape. If the landscape of interest is too small, continuous landscape features important to animal movements will be truncated or not observable.

The larger landscape context is also essential to an analysis of habitat fragmentation because it is important to understand whether or not the habitat is both locally and regionally rare and fragmented. A larger extent of unfragmented habitat may offset any local fragmentation impacts. In addition, the larger landscape provides the context for discriminating between natural disturbance and succession processes operating to fragment habitat and anthropogenic activities that may be causing the system to move outside desired conditions (chapter 7 addresses human disturbance agents and processes). To address the influences of the surrounding landscape context, it is important to establish a **reference framework** that provides a description of regional landscape structure, range of variability, and other attributes of landscape context. This strategy is addressed in section 6.3.7.

6.3.4 Determine the Scope of Analysis

The scope of analysis pertains to the scale and/or focus of the monitoring program. In this chapter, we assume that the primary analysis tool is FRAGSTATS, because it is the most commonly used software for analyzing patch mosaics. Three levels of analysis in FRAGSTATS represent fundamentally different conceptualizations of landscape patterns and have important implications for the choice and interpretation of individual landscape metrics and the form of the results.

1. ***Focal patch analysis***. Under the patch mosaic model of landscape structure, the focus of monitoring is on the spatial character and/or context of individual **focal patches**. Results of a focal patch analysis are typically presented in table form, in which each row represents a separate patch and each column represents a separate patch metric, such as patch size.
2. ***Local landscape structure***. In many applications it is appropriate to assume that species experience landscape structure as local pattern gradients that vary through space according to their own perceptions and their ability to travel through or use different vegetation types. Thus, instead of analyzing global landscape patterns by conventional landscape metrics across the entire spatial extent, we use a moving window analysis to quantify the local landscape pattern because this approach more closely resembles the way that a species may perceive the landscape. A moving window analysis asks: From any given point, what is the composition and configuration of the landscape mosaic in the immediate vicinity? The window size should be selected to reflect the scale and manner in which the emphasis species perceives or responds to pattern. If this size is unknown, the user can vary the size of the window over several runs and empirically determine at which scale the organism is most responsive. The window moves over the landscape one cell at a time, thereby calculating this point-centered view for all locations on the landscape. The result is a continuous surface that is then combined with other such surfaces in multivariate models to predict, for example, the distribution and abundance of habitat continuously across the landscape. This approach is useful for evaluating changes in dispersal ability over time, given that the emphasis species may not be able to cross through certain vegetation types or land use types (see the salamander monitoring plan in chapter 10 as an example).
3. ***Global landscape structure***. The traditional application of landscape metrics involves characterizing the structure of the entire landscape with one or more landscape metrics. For example, traditional landscape pattern analysis would measure the total edge per unit area for the entire landscape. This global measure offers a landscape-centric perspective on landscape patterns using the entire patch mosaic in aggregate. The results of a global landscape structure analysis are typically presented in the form of a vector of measurements, in which each element represents a separate landscape metric.

6.3.5 Select Key Habitat Attributes of Landscape Pattern for Emphasis Species

Patches form the building blocks of landscape pattern. A patch is a delineated area that differs from adjacent areas in one or more attributes. Typically, after patches have been delineated on the basis of attributes and attribute values, the within-patch heterogeneity is ignored. Patches that share the same attributes or attribute values are grouped into a class.

Although the literature is replete with descriptors of landscape pattern, only two major components exist—composition and configuration. Landscape composition refers to features associated with the variety and abundance of patch types within the landscape, whereas spatial configuration is the spatial character, placement, or location of patches within the mosaic.

Principal Attributes of Landscape Composition

- Proportional abundance of each class—proportion of each habitat class relative to the entire map; one of the simplest and perhaps most useful pieces of information. All landscape analyses should calculate this metric because proportional abundance of each class is necessary for understanding future analyses.
- Richness—number of different habitat patch types.
- Evenness—the relative abundance of different patch types. Usually reported as a function of the maximum diversity possible for a given richness; i.e., evenness is 1 when the patch mosaic is perfectly diverse, given the observed patch richness, and approaches 0 as evenness decreases.
- Diversity—a composite measure of richness and evenness; can be computed in a variety of forms (e.g., Shannon and Weaver 1949, Simpson 1949), depending on the relative emphasis placed on these two components. Richness, evenness, and diversity are highly correlated, and none of them provide information on which patch types are contributing to the change in metric over time.

Principal Attributes of Spatial Configuration

- Patch size distribution and density—the simplest measure of configuration; represents a fundamental attribute of the spatial character of a patch. Most landscape metrics either directly incorporate patch size information or are affected by patch size. Patch size distribution can be summarized for a class or landscape(e.g., mean, median, max, and variance), or represented as patch density, which is simply the number of patches per unit area. Users should generally employ area-weighted patch size metrics to avoid large influence of small patches. Also, users should use patch density (and not number of patches) any time landscapes of different extents are compared.
- Patch shape complexity—relates to the geometry of patches; i.e., whether they tend to be simple and compact, or irregular and convoluted. Most common measures of shape complexity are based on the relative amount of perimeter per unit area, usually indexed in terms of a perimeter-to-area ratio and often standardized to a simple Euclidean shape (e.g., circle or square).
- **Core area**—the area unaffected by the edges of the patch; represents the interior area of patches after a user-specified edge buffer is eliminated. The edge-effect distance will vary depending on the phenomenon under consideration and can be treated as fixed or adjusted for each unique edge type. This metric integrates patch size, shape, and edge-effect distance into a single measure. All else being equal, smaller patches with greater shape complexity have less core area. Most metrics associated with size distribution (e.g., mean patch size and variability) can be formulated in terms of core area.

- Isolation/proximity—refers to the tendency for patches to be distant from other patches of the same or similar class. The original **proximity index** in landscape analysis was formulated to consider only patches of the same class within a specified neighborhood of patches. This binary representation of the landscape reflects an island biogeographic perspective on landscape pattern. Alternatively, this metric can be formulated to consider the contributions of all patch types to the isolation of the focal patch, reflecting a landscape mosaic perspective on landscape patterns.
- Contrast—relative difference among patch types. For example, mature forest next to younger forest might have a lower contrast edge than mature forest adjacent to open field, depending on how contrast is user defined. Can be computed as a **contrast-weighted edge density** in which each edge type (i.e., between each pair of patch types) is assigned a contrast weight.
- Dispersion—tendency for patch distribution to be either regular or clumped (i.e., contagious); a common approach is based on nearest neighbor distances between patches of the same type.
- Contagion and interspersion—contagion refers to the tendency of patch types to be spatially aggregated; that is, to occur in large, aggregated, or contagious distributions; ignores patches *per se* and measures the extent to which cells of a similar class are aggregated. By contrast, interspersion refers to the intermixing of patches of different types and is based entirely on patch (as opposed to cell) adjacencies. Several different approaches are available for measuring contagion and interspersion. One popular index that subsumes both dispersion and interspersion is the contagion index based on the probability of finding a cell of type *i* next to a cell of type *j* (Li and Reynolds 1995). This index summarizes the aggregation of all classes and thereby provides a measure of overall clumpiness of the landscape. McGarigal et al. (2012) suggest a complementary interspersion/juxtaposition index that increases in value as patches become more evenly interspersed in a salt and pepper mixture.
- Subdivision—degree to which a patch type is subdivided into separate patches (i.e., fragments), and not the size, shape, relative location, or spatial arrangement of those patches. Because these latter attributes are usually affected by subdivision, it is difficult to isolate subdivision as an independent component in landscape analysis. Subdivision can be evaluated using a variety of metrics already addressed; for example, the number, density, and average size of patches and the degree of contagion all indirectly evaluate subdivision. A suite of metrics, however, derived from the cumulative distribution of patch sizes, provides alternative and more explicit measures of subdivision (Jaeger 2000). When applied at the class level, these metrics can be used to measure the degree of fragmentation of the focal patch type. Applied at the landscape level, these metrics connote the graininess of the landscape.
- Connectivity—functional connections among patches, which clearly depend 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) of habitat patches, some threshold distance, a decreasing function of distance that reflects the probability of connection at a given distance, or a resistance-weighted distance function. Various indices of overall connectedness can be derived based on the pairwise connections between patches; i.e., **connectance** can be defined by the number of functional joinings, in which each pair of patches is either connected or not. Connectivity can also be defined in terms of **correlation length** for a raster map comprised of patches (defined as clusters of connected cells). A map's correlation length is the average distance an organism can traverse a map from a random starting point and moving in a random direction, while remaining in the same patch type (Keitt et al. 1997).

6.3.6 Selecting Landscape Metrics for Analysis

Landscape metrics are algorithms that quantify the specific spatial characteristics of patches, classes of patches, or entire landscape mosaics. *The proper indices to calculate are the ones that make ecological sense for the application at hand.* To select the appropriate suite of metrics, practitioners need detailed knowledge of the metrics, what they measure, and how they change. No substitute exists for this knowledge, and we strongly suggest that practitioners spend ample time studying the extensive documentation available on FRAGSTATS metrics (McGarigal et al. 2012). In general, however, all landscape analysis should include a measure of proportional abundance of the habitat classes of interest (PLAND in FRAGSTATS), and nearly always should include additional metrics on aggregation, edge, and other landscape structure attributes.

FRAGSTATS calculates all metrics for one or more of four major levels of the landscape mosaic.

1. ***Cell-level metrics*** are defined for individual cells, and characterize the spatial context or ecological neighborhood of each cell without explicit regard to any patch or class affiliation.
2. ***Patch-level metrics*** are defined for individual patches, and characterize the spatial character and context of patches. Individual patches possess relatively few fundamental spatial characteristics: size, perimeter, and shape.
3. ***Class-level metrics*** are integrated over all the patches of a given type (class). These metrics may be integrated by simple averaging, or through some sort of weighted-averaging scheme to bias the estimate to reflect the greater contribution of large patches to the overall index. Additional aggregate properties exist at the class level that result from the unique configuration of patches across the landscape. Class indices separately quantify the amount and spatial configuration of each patch type and thus provide a means to quantify the extent and fragmentation of each patch type in the landscape.
4. ***Landscape-level metrics*** are integrated over all patch types or classes over the full extent of the data (i.e., the entire landscape). Like class metrics, these metrics may

be integrated by a simple or weighted averaging or may reflect aggregate properties of the patch mosaic. In many applications, the primary interest is in the pattern (i.e., composition and configuration) of the entire landscape mosaic.

The two key concepts that will further help selecting landscape metrics for analysis include (1) gaining a theoretical and empirical understanding of metric behavior to guide interpretation, and (2) understanding redundancy among metrics to guide selection of a parsimonious suite of landscape metrics. In this chapter, we provide an overview and references to help move through the process of selecting landscape metrics for habitat monitoring.

The task of understanding the behavior and expected range of values of the landscape metrics has been a focus of research for more than 20 years (Cardille et al. 2005, Cushman et al. 2008a, Gustafson 1998, Hargis et al. 1998, Neel et al. 2004, Tischendorf 2001). Here, we distill the main points of metric selection. To select a proper set of landscape metrics for analysis it is essential that the monitoring team have a clear idea of (1) what attributes of landscape pattern are most important to meet the habitat monitoring objectives, and (2) which metrics are sensitive indicators of variability in these attributes within the context of the monitoring area. The first question (i.e., what attributes of landscape structure to measure) should be determined before analysis, through review of current scientific literature regarding the effects of landscape pattern on ecosystem and population processes and which aspects of landscape pattern are strongly related to which processes (see McGarigal et al. 2012). The second question of which metrics sensitively reflect these landscape patterns can be addressed partly by reviewing technical literature on landscape pattern analysis (Gustafson 1998, Hargis et al. 1998, McGarigal et al. 2012, Neel et al. 2004). The task of selecting a parsimonious suite from the pool of relevant metrics identified in the process steps described in chapters 2 and 5 can be facilitated by reviewing pertinent technical papers (Cushman et al. 2008a, McGarigal and McComb 1995, Riitters et al. 1995).

The best approach is to select relatively few metrics of both landscape composition and configuration at each of the class and landscape levels that measure the spatial attributes of interest and are not redundant with each other. Generally speaking, analysts will always want to choose one or more measures of landscape composition at the class and landscape levels (see section 6.3.5). In addition, analysts will generally select one or more class- and landscape-level metrics measuring contagion and interspersion, core area, contrast, patch size distribution, and isolation. We suggest analysts carefully study the FRAGSTATS user's guide and other documentation (available at http://www.umass.edu/landeco.) This review will provide information on how to obtain and use FRAGSTATS software, as well as detailed description of the different landscape metrics available to quantify different aspects of landscape composition and configuration.

6.3.7 Use an Existing or Establish a New Reference Framework of Landscape Processes and Patterns

The absolute value of any given landscape metric is often not directly interpretable without knowing the likely range of values represented by a relevant reference range of conditions, which we will refer to as the reference framework. Meaningful evaluation of contemporary conditions requires comparison with a reference to determine status and change, and to design management to provide sustainable yield of resources while also maintaining ecosystem heath (Hessburg et al. 1999, Swetnam et al. 1999). It is critical that the reference framework represent the dynamics of ecosystems as they vary over time and across landscapes (Swanson et al. 1994). One important reference framework is the historic range of variability (HRV; Cissel et al. 1994, Wiens et al. 2012, Swanson et al. 1994). HRV provides a spatial and temporal foundation for adaptive management (Keane et al. 2009, Landres et al. 1999). Some of the key attributes of a reference framework are the type, frequency, and severity of disturbance under a natural disturbance regime and mean and variation of patch size, extent, and pattern among the cover types represented in the map being analyzed (either selected habitat attributes or patches representing categories of predicted habitat quality).

When possible, use a quantitative approach to construct the reference framework. This approach may involve the use of retrospective studies of past landscape conditions (e.g., historical reconstructions of landscape patterns and dynamics) or the use of computer simulation models to simulate landscape changes based on the best understanding of the processes that drive landscape change (Keane et al. 2009). When habitat monitoring begins, the sequential reanalysis over time will augment the temporal reference framework.

A reference framework should include a much broader spatial extent than the landscape under consideration for habitat monitoring to provide a context to evaluate the broader regional significance of landscape pattern. For example, if the analysis objective is to monitor changes in habitat fragmentation, it is necessary to understand whether the habitat of interest was either locally or regionally rare and whether it was fragmented in the past (see chapter 10, greater sage-grouse [*Centrocercus urophasianus*] case example, for use of a reference framework). The broader landscape extent defined in section 6.3.3 might serve as a suitable spatial extent for a reference framework. It is beyond the scope of this technical guide to fully describe a process for creating a reference framework, and the task is challenging. Yet ultimately, it may be essential for interpreting landscape metrics and for evaluating changes in landscape pattern for an emphasis species.

6.3.8 Analyze and Interpret Landscape Pattern Through Comparison With the Reference Framework and Desired Conditions

A land management plan may contain desired condition statements that include specific reference to landscape pattern for one or more emphasis species. If the desired condition for landscape pattern is worded broadly, for example, "maintain large patches of habitat that are well distributed across the plan area," rephrase these statements in terms of specific landscape metrics and the range of acceptable values for each metric based on the reference framework and on the conceptual model of the species' habitat. As addressed in section 6.1, it is essential to integrate landscape analysis of wildlife habitat into an adaptive management framework that includes detailed and specific objectives and quantitative **triggers** expressed in terms of the landscape metrics analyzed. This approach will provide clearly interpretable information that directly guides management decisions.

If an adequate reference framework exists, it will be straightforward to evaluate current conditions. The value of each landscape metric measured for the current landscape can be directly compared with the range of values in the reference framework and with the values described as acceptable in the desired conditions statements. This comparison is made in terms of departure in the value of each metric from either a threshold or the range of desired conditions and expressed as graphs and tables of percentage differences between existing, reference, and desired conditions. In this form, the analysis provides a directly interpretable evaluation of conditions in comparison with management goals and indicates which attributes are at variance with desired conditions and to what degree.

For example, an effort to monitor habitat for greater sage-grouse might include monitoring the number of habitat patches larger than some minimal size. The monitoring program may specify a minimum number of patches of a certain size that would serve as a trigger point for reassessing management (chapter 10, sage-grouse case example).

6.3.9 Monitoring Landscape Attributes Over Time

A monitoring team can retrospectively monitor changes in landscape attributes by using a series of two or more maps that represent vegetation types or land use categories at different points in time. To be comparable, the maps must represent the same thematic resolution at the same scale, be derived from a comparable data source, and use comparable methodology, such as using the same neighbor rule (e.g., 4- or 8-neighbor rule) to define patches. Changes in the maps will still occur because of improvements in data quality and methodology, but these changes will not have the adverse impact on comparability that would result from changes in grain, extent, or number of cover classes.

Betts et al. (2003) used a set of comparable maps for monitoring changes in habitat of seven forest-associated species in the Fundy Model Forest (1,700 square miles) in New Brunswick, Canada, from 1993 to 1999. The authors obtained Landsat-5 and Landsat-7 images from 1992, 1995, 1997, 1998, and 1999 and then used a local classified image of vegetation types from 1993 as the basis for classifying habitat. Using habitat capability models for each of the seven species, the authors collapsed the original vegetation map into cover type classes and focused on five cover types that constituted habitat of the indicator species. The authors also used the habitat models to identify a minimum patch size and maximum interpatch distance for each species so that patches that did not meet the minimum or that were too isolated from other habitat would not be included in the total amount of habitat. The authors calculated changes in three landscape metrics—total habitat area, mean patch size, and nearest neighbor distance—and found that the rate of habitat fragmentation (reduction in mean patch size and increase in interpatch distance) exceeded the rate of habitat loss (total patch area).

The most important consideration for ensuring that results of a landscape pattern analysis for habitat monitoring are consistent and comparable over time is consistency in map definition (e.g., habitat classification method, grain, and extent). An inherent challenge exists in attaining this consistency, as, over time, our ability to map habitat features and the quality of habitat models will improve (chapter 5). These changes in spatial data will necessarily change map definitions, making it difficult to distinguish between changes because of methodology and changes in the true area and configuration of habitat. This dilemma is unavoidable, and we recommend using the best available models and maps of habitat and habitat attributes. Moreover, it is essential that the details of the data sources, their accuracy and definition, and the models used in previous analyses are well documented, to at least qualitatively consider the differences in methodology between measurement dates.

Finally, to be useful in monitoring changes in amount and pattern of habitat over time, a landscape analysis must be tied explicitly to a formal decisionmaking framework, such as a land management plan. In the context of adaptive management, the management plan will include desired conditions that are formally and quantitatively expressed in terms of landscape metric values and will include threshold values that specify the amount of departure from desired conditions that would trigger a change in management. Such formal and quantitative targets and thresholds, when coupled with a consistent and comparable landscape analysis, provide a direct means to evaluate change in spatial patterns in habitat over time and information to guide the adaptive management cycle. We recommend comparing the monitoring results to a threshold over statistically comparing two time periods. Compounded map error makes a statistical comparison difficult (Remmel and Csillag 2003), whereas comparing each time period with a predefined threshold is more tractable and more biologically meaningful.

6.4 Conclusion

Landscape analyses are an important part of habitat monitoring because the habitats in which organisms live are spatially structured at multiple levels and generally include a landscape level. In this chapter, we describe habitat as patches in a landscape mosaic, although we acknowledge and describe other approaches to characterize landscapes. Scale is critical in defining a landscape because the size and scale of a landscape is directly related to how it is used by a species. Moreover, pattern and its effect on process vary with spatial scale and thematic resolution.

To be effective, a landscape analysis must be directly tied to the objectives and desired conditions of a planning document such as an LRMP. Ideally, the LRMP provides a formal declaration of desired conditions, provides a quantitative description of current departure from desired conditions, and specifies a quantifiable threshold value or set of values that can be used to trigger a change in management toward desired conditions. We offer numerous approaches to quantify landscape pattern in terms of composition and spatial configuration, for use in quantifying desired conditions, and in establishing thresholds.

The nine process steps for conducting a landscape analysis outlined in this chapter are (1) establish objectives for the landscape analysis, (2) define the landscape, (3) identify the larger landscape context, (4) determine the scope of analysis, (5) select key habitat attributes of landscape pattern for emphasis species, (6) select landscape metrics for analysis, (7) use an existing or establish a new reference framework of landscape processes and patterns, (8) analyze and interpret landscape pattern regarding the reference framework and desired conditions, and (9) monitor landscape attributes over time.