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Landscape Ecology

A Spatial and Human-Oriented Ecology

During the eighteenth and nineteenth centuries, many scientists developed the basis for what would become the science of *ecology* (Forman and Godron 1986). Haeckel introduced the term ecology in 1866, originally meaning "knowledge of the house (hold)" (Capra 1996), as a sister science of economy, which is literally "the management (and counting) of the house (hold)" (Zonneveld 1995).

Ecology is concerned with the interactions between organisms and their environment and how those interactions determine the distribution of both plants and animals (O'Callaghan 1996).

Ecology focuses on the study of ecosystems, and on the vertical relationships (topology) between the different components of ecosystems, such as climate, water, soil, bedrock, flora, and fauna.

1.1. Foundations of Landscape Ecology

Landscape ecology emerged in Europe in the 1950s and shares its heritage with the related disciplines of biogeography and ecology. One of the principal distinctions between landscape ecology and other branches of ecology is the emphasis and focus on the spatial patterning of multiple ecosystems in heterogeneous landscapes.

Landscape ecology introduced several perspectives and principles that have become fundamental for planners. One such perspective is the spatial dimension of ecological processes. Vertical (topological) relationships are considered together with horizontal (chorological) relationships between the ecosystems that comprise a landscape. Landscape ecology offers theory and empirical evidence that enables scientists and planners to understand and compare different spatial configurations of land cover types (Forman 1995), and enables planners to anticipate and manage the ecological consequences of a plan.

A second fundamental perspective is the focus of landscape ecology on human ecology, and on the application in planning and management. In landscape ecology, human activities are considered part of ecosystems, not as a separate component.

A third perspective consists of adopting the landscape as the principal unit of study. Together with a systemic, holistic approach, landscape ecology provides an integrated analysis of the complex, human-made landscapes that are fast becoming dominant worldwide.

In nature, form and function constitute a unity because they are reciprocally influential in a closely integrated relationship responsible for landscape evolution. In this context, the form and function principle is particularly useful to planning since it allows one to relate physical characteristics of the landscape and the spatial configuration of a plan with landscape functions and the processes that shape and alter those same characteristics. Although these might have slightly different meanings, land use, land cover, spatial structure, and pattern are fundamental concepts for both landscape ecologists and planners (Antrop 2001). Landscape ecologists focus on detecting structure where planners work on creating new structures. The former look at spatial patterns to learn about landscape processes and functions, the latter focus on guiding these according to planning goals (Antrop 2001).

1.2. A Landscape Perspective

There is enormous global diversity in landscape types, from grasslands and deserts, to forests and tundra, with many gradations between these types and the level of human activity occurring within them—activities such as agriculture, urban and suburban development, forestry, and mining. Each of these landscape types has several dimensions: ecological, economic, social, cultural, and aesthetic. Depending on one's professional or disciplinary viewpoint, landscapes can be seen from multiple perspectives. One perspective views the visible component of the landscape, the so-called "phenosystem" (González Bernáldez 1981), primarily as an aesthetic phenomenon as in the seventeenth century landscape painting. Another perspective views landscapes as "closer to the eyes than to the mind, more related to the heart, the soul, the moods than to the intellect" (Hardt 1970 cited in Bastian 2001, 758). Others view landscape as a socio-spatial entity (Linehan and Gross 1998), or as landscape products (Taborda 2000). Others perceive landscapes as geographic surface units, focused on their natural components including: water, hills, fields, and forests (Wascher 2000). Since the beginning of the twenty-first century, the landscape concept has been evolving towards a transdisciplinary perspective (Naveh 1991; Tress and Tress 2001) (see Box 1.1).

Box 1.1. Landscapes as Multidimensional Entities

Landscape ecology originally focused on three landscape characteristics: structure, function, and change. And respectively on (1) the distributional patterns of landscape elements or ecosystems, (2) the flows of animals, plants, energy, mineral nutrients, and water between these elements, and (3) the ecological changes in the landscape mosaic over time. Forman and Godron (1986) defined three fundamental elements of landscape structure: patches, corridors, and the matrix. Together these constitute the widely accepted "patch-corridor-matrix" or mosaic model (Forman 1995).

However, landscapes are more than biophysical elements. Both nature and culture interact to produce patterns, to influence functions and to effect change. Some argue that if we are to promote an integration of biophysical and cultural approaches, we should be focusing on commonalities instead of focusing on differences (Botequilha Leitão 2001). So what do natural sciences (e.g., ecology) have in common with social sciences (e.g., sociology), or humanities (e.g., history)?

Marcucci (2000) argues that a historical model is best to integrate a spatial, geographical dimension and to allow cultural systems to be represented as sequential phenomena related to place. He also emphasizes the significance of geography in history that, by accounting for the profound impact of ecological flows on landscape evolution, helps place it in a regional context and supports the recreation of ecological stages of the land. According to Cronon (1990 cited in Marcucci 2000, 75) "landscape ecology is that form of ecology which is credited with bringing ecology and history together." Other authors found social system variables to have a clear influence on spatial differentiation of ecological impacts (Pickett et al. 1997; Grove and Burch 1997).

Thus it seems that the spatial dimension could provide for a common linkage among several disciplines. Spatially-explicit landscape models can articulate the linkages between natural and cultural variables. As Brandt (2000) states, it is not a matter of opposing the human mind to nature, but to stress the important and special dynamics between them (Brandt 2000). Close cooperation is needed to transcend the realms of natural sciences and reach out to human and social sciences, which are connected with

(*continues*)

Box 1.1. *Continued*

human land uses (Naveh 1998 and 2001; Marcucci 2000). Although the transdisciplinary challenge is being addressed by different disciplines, a truly integrative approach is yet to be fully developed and achieved, one that would consider the different landscape dimensions equitably, in one single model, and that should prove to be operational and applicable to planning. Recently a transdisciplinary landscape model was proposed by Tress and Tress (2001), which considers five landscape dimensions: spatial, temporal, mental, as the nexus of nature and culture, and as a complex system. Although promising, this approach is at an early stage of development.

The message to take home is that nature and culture are complementary, not counterparts, and the landscape represents the very point of contact between them (Naveh 1998;Tress and Tress 2001).

1.3. Main Characteristics of Landscape Ecology

To use landscape pattern metrics appropriately, it is important to understand their scientific context. While the range of applications for landscape metrics may be diverse, most metrics were developed and adapted specifically for landscape ecological research applications. Therefore, the more knowledge planners possess about landscape ecology principles and concepts, the easier it becomes for them to use landscape metrics appropriately.

In this handbook we have adopted a widely accepted definition of landscape: a kilometer-wide mosaic over which particular local ecosystems and land uses recur (Forman and Godron 1986; Forman 1995). A landscape mosaic is comprised of spatial elements (e.g., patches, corridors, and matrices, described below), and landscape metrics help to measure, describe, and understand the significance of these elements or their spatial pattern. Although we focus on a spatial approach to understand landscapes, we acknowledge the need to perceive landscapes as multidimensional entities that can be understood from a transdisciplinary perspective (see Box 1.1). Additionally, we find the spatial approach to understanding landscapes to be compatible with other approaches from other disciplines including: anthropology, sociology, history, and economics.

Landscape ecology focuses on the relationship between landscape structure and function and the ways landscapes change over time. To introduce this we will first examine the conceptual fundamentals of landscape structure and function. Then we will examine fundamental conceptions of landscape change, focusing on issues that are highly relevant for planning.

1.3.1. *Landscape Structure*

Landscape structure is a description of the spatial relationships among ecosystems, or more specifically the distribution of energy, materials, and species in relation to the size, number, types, and configurations of ecosystems.

There are several principal ways to describe the structure of landscapes, each using different kinds of data. With point data, the property of interest is usually the geographic location of each point, although measured attributes at each location may also be of interest. Linear networks within a landscape may be useful in the study of hydrologic systems (such as rivers and streams), wildlife corridors, or transportation and energy networks. Surficial, or continuous surface data is useful to address landscape variability as gradients (McGarigal and Cushman 2005). Categorical data assumes a patchy landscape structure, as commonly seen in soil or land cover maps. In this handbook the categorical data model is used, which has been widely adopted by planners.

Forman and Godron (1986) use three fundamental landscape elements to define landscape structure: patches, corridors, and the matrix. With these three elements any landscape (e.g., urban, agricultural, forested) can be described. According to Forman (1995, 7), the model that coalesces these landscape elements, the *mosaic model*, has analogies in other disciplines such as art, architecture, urban planning, and medicine. In the circulatory system of the human body, an organ (heart) and tubes (veins, arteries) together form a structure that allows blood to move (flow) and transport oxygen (function) within an overall context of other systems in the body (matrix). Over time body shape and size changes, thus altering body functions. Another example of this analogy is provided by Kevin Lynch's typology of urban form including: districts, edges, nodes (patches), paths (corridors), and landmarks (Lynch 1960).

In addition to landscape elements *per se*, it is important to account for the spatial relationships among the elements that make up a landscape. Are they clustered and adjacent to one another, or dispersed and far apart? In a landscape ecological approach, landscape elements can only be fully understood by understanding their context. The ecological significance of spatial characteristics (size, shape, or spatial distribution) of landscape elements is given not by these characteristics *per se*, but by considering the effect of those characteristics on each other and on other elements of the landscape. All landscape elements, regardless of their specific land cover type, influence landscape functions through their spatial characteristics. This is a fundamental interrelationship applicable to any landscape type—urban, rural, or natural (see Box 1.2).

Box 1.2. Structure as a Holistic Property of Landscapes

Many contemporary landscape ecologists argue that a holistic conception of landscapes is needed to understand how landscape elements relate to each other (Naveh and Lieberman 1994; De Leo and Levin 1997; Antrop 1998; Tress and Tress 2001). By definition, holism states that the sum is more than the mere sum of their parts (Figure 1.1). Holism provides a new way to analyze; it argues that landscape elements receive their meaning or significance by their context, or their position within the whole (Antrop 1998, 157).

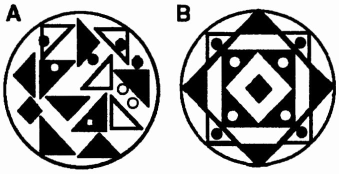

Figure 1.1. *Holism.* The significance of spatial structure and relationships between components in a given system, e.g., landscape elements in a given landscape. B is not the mere sum of the components in A due to different interactions across system components, changed by an alteration on the spatial organization of the elements, i.e., structure. *With permission from Bòlos 1992*

Additionally "systems thinking is a method of scientific enquiry that allows one to understand and investigate complex realities" such as landscapes (Tress and Tress 2001, 149). Holistic thinking "provides the basis for studying certain wholes or systems, without knowing all the details of its internal functions" (Zonneveld 1988, 8).

The modelling approach used to study the dynamic interactions between landscape spatial structure and functions is similar to those so-called black box models, which are useful to model complex systems. In these we know both the inputs (change in structure, e.g., shape of a patch), and the outputs (change in a certain function, e.g., increase in movement of a certain species of interest, or an ecological process), but we do not comprehend entirely the mechanisms of this relationship (what is behind what happens between input and output) (Figure 1.2).

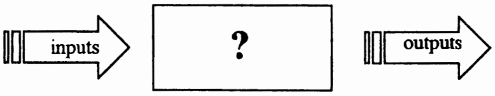

Figure 1.2. *"Black box" modelling approach.* Both input and output are known, but often the mechanisms or the causal relationships that operate between inputs and outputs are not well understood.

Isolation is a landscape characteristic emerging from a given landscape structure, measurable by particular landscape metrics. Ecological significance of isolation of a certain patch only has meaning if the patch is considered within its landscape context. For example, what is the relationship of the patch to other patches in its neighborhood? (Figure 1.3).

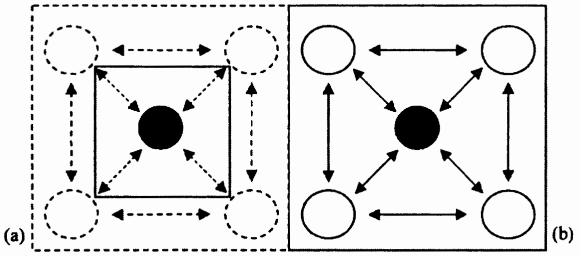

Figure 1.3. The concept of isolation is understood differently at the patch and landscape (context). The box represents the focus of the analysis, i.e., our landscape; circles represent landscape spatial elements, and the arrows represent landscape flows between elements. Solid lines represent elements and flows that are being considered, dashed lines represent those that are disregarded. Note that in the left diagram (a) the focus is on the central patch. Landscape context, including all other patches around it and the relationships between these, is ignored. Thus the ecological significance of the isolation of the central patch in (a) only makes sense if we consider what is going on outside of the solid line box, as in (b). Landscape elements are not islands; to understand their dynamics, one needs to consider the context, as proposed by R.H. MacArthur and E.O. Wilson in *The Theory of Island Biogeography* (1967).

According to McGarigal et al. (2002) "isolation deals explicitly with the spatial and temporal *context* of habitat patches, rather than the spatial character of the patches themselves." 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, or isolation from, other subpopulations of the same or competing species. 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; Helliwell 1976; Whitcomb et al. 1981; Hayden et al. 1985; Dickman 1987; in McGarigal et al. 2002, 45). Therefore, the importance of a given patch for habitat conservation is dependent on the relationships with other patches of a similar nature (landscape context). Isolation metrics such as the ***nearest neighbor distance*** or the ***proximity index*** provide ways to quantify these structural characteristics.

LANDSCAPE STRUCTURAL ELEMENTS: PATCH, CORRIDOR, AND MATRIX

A patch is defined as a relatively homogeneous nonlinear area that differs from its surroundings (Forman 1995). Patches provide multiple functions including wildlife habitat, aquifer recharge areas, or sources and sinks for species or nutrients. A parcel of native forested land surrounded by farm fields is a patch, as is a large asphalt parking lot surrounded by golf courses. Thus, there are many kinds of patches: agricultural fields, wood lots, or villages (Figure 1.4). What constitutes a patch ultimately depends on the application and what is deemed meaningful as a way of representing the landscape mosaic in the context of that application.

A corridor is defined as a linear area of a particular land cover type that is different in content and physical structure from its context (Forman 1995). Corridors serve many functions within the landscape including habitat for wildlife, pathways or conduits for the movement of plants, animals, nutrients, and wind, or as a barrier to such movement. There are many types of corridors, ranging from riparian or river corridors, to interstate highway systems, to canals within an agricultural landscape (Figure 1.5).

The matrix is the dominant land cover type (LCT) in terms of area, degree of connectivity and continuity, and control that is exerted over the dynamics of the landscape (Forman 1995) (Figure 1.6). Examples of

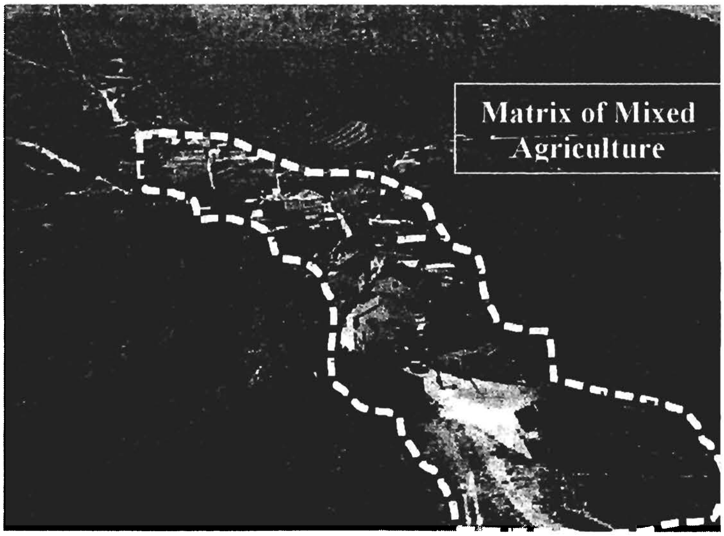

Figure 1.4. A village (urban patch) embedded in a matrix of mixed agriculture in Portugal. *Courtesy of A. Silva*

Figure 1.5. Corridors in the landscape can be either natural (the river corridor), or human made (the road or the bridge). *Courtesy of A. Silva*

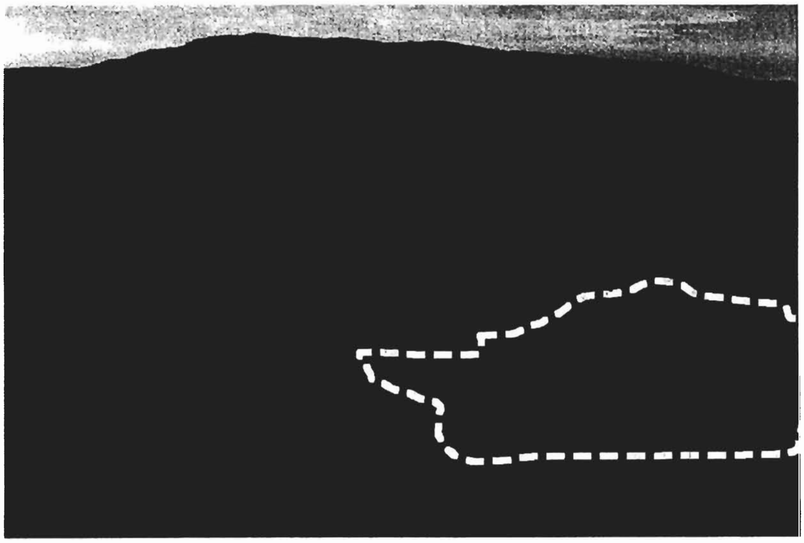

Figure 1.6. A forest matrix that surrounds a village with its agricultural fields, in plateaus (maize fields and vineyards).

matrices include: a city with patches of parkland, forest with patches created by timber harvesting, agricultural fields with occasional small woodlots, or an agricultural landscape with a dense network of hedgerows and riparian vegetation (Figure 1.4). In the last example, hedgerows may exert significant control over the functioning of the landscape by controlling the movement of nutrients, wind, water, and wildlife across the landscape, as well as controlling the movement of people in the landscape. This control is accomplished without being the proportionately dominant land cover type—spatial arrangement of the hedgerow is key.

The spatial arrangement of patches, corridors, and matrices, and their profound interactions are, in a sense, the hallmarks of landscape ecology.

1.3.2. *Landscape Function*

Landscape function can refer to the broad categories of "services" that landscapes provide: production, protection, and regulation. Production services support the human needs for food, wood, recreation, and transport. Landscape protection provides for natural functions, such as rainfall infiltration, oxygen production and absorption of carbon dioxide, water cleansing by soils and wetlands, nutrient buffering by riparian corridors, and maintenance of biological diversity. Landscape regulation provides negative feedback loops that assure the overall stability of a landscape (Naveh 1994; 1998, 9; 1999).

Landscape function can also refer specifically to the flows of energy, materials, nutrients, species, people, and finally to ecological processes such as the production of biomass or the infiltration and percolation of rainfall. Materials like water or nutrients like carbon, phosphorus, and nitrogen either cycle within or flow through ecosystems, either between air and organisms (carbon), soil and organisms (phosphorus), or between air, soil, and organisms (nitrogen) (Forman 1995).

1.3.3. *Relationships Between Landscape Structure and Function*

Structure and function relationships are illustrated by the form and function principle, which states that the interaction between two objects is proportional to their common boundary surface (or edge) (Forman and Godron 1986, 177). The size and shape of patches determines to a large degree their ecological and functional characteristics. Large agricultural fields, for example, have greater evapotranspiration rates per unit of area than small fields. This is due in part to the greater expanse of vegetation (crops) that the wind may travel over, and the large proportion of topsoil exposed to wind and sunlight. Large forests, on the other hand, may serve to protect water and soil resources by providing vegetative cover for an entire aquifer, and by limiting the amount of soil that is exposed to weathering forces of wind and sunlight.

Large patches of native ecosystems are more likely to possess a greater variety of habitats than small patches, and therefore are more likely to support greater biodiversity (Dramstad et al. 1996). More food, fiber, and biochemical products are likely to be found in large patches (Forman 1995). Ecosystem services such as moderating fluctuations in surface water levels, the recycling of minerals and nutrients, and the removal of toxins from circulation in the environment are also more likely to be achieved as the size of the patches is increased. In addition, the inspirational and aesthetic experiences of the public may be greater when experienced in larger patches, such as wide-open spaces, spacious urban parks or gardens, or even urban neighborhoods of high aesthetic quality.

Variation in the size and shape of patches and corridors, and the area of the matrix, has a strong influence on the resulting landscape pattern. Size and shape determine the amount of boundary shared with other patches, corridors, and the matrix. Linear patches and corridors have greater amounts of boundary than compact, rounded patches. And complex, convoluted patch shapes have greater amounts of boundary than simple patch shapes. The boundaries between landscape elements are termed "edge" by ecologists, and they have significant implications for how a patch, corridor, or matrix ecosystem will function. For example, Hardt and Forman (1989) found that natural succession of a reclaimed strip mine site or other open area could be managed by manipulating the boundary (edge) shape at the scale of tens of meters. Planting trees and shrubs to form concavities along a straight forest boundary proved to effectively enhance the colonization of a mine. In fact, reclaimed mine areas where forest patch perimeters were characterized by concavities experienced more colonization than those by straight boundaries or convexities.

Spatial distribution, the relative location of patches and corridors within the matrix, matters as well. Each type of land cover has distinct physical characteristics. For example, a parking lot or a pasture exposed in the sun is hotter than the adjacent woods or a pond. Flows are created by measurable differences, such as those in pressure and temperature, across the landscape (Forman and Godron 1986). Wind is caused by a differential of air pressure, flowing from high pressure to low pressure areas. Landscape flows behave and move differently throughout the landscape depending on what land cover types (LCTs) are adjacent or near to one another.

LANDSCAPE CONNECTIVITY

Connectivity is a landscape property that nicely illustrates the relationship between landscape structure and function. In general, connectivity refers to the degree to which the landscape facilitates or impedes the flow of energy, materials, nutrients, species, and people across the landscape. Connectivity is an emergent property of the landscape that results from the interaction between landscape structure (i.e., the composition and configuration of the landscape mosaic) and landscape function (e.g., water flow, nutrient cycling, maintenance of biological diversity). Because connectivity is essential to proper ecosystem functioning, it is of great relevance in conservation planning and management (Naveh 1994; Forman 1995; Bennett 1999). For example, the greenway concept recognizes connectivity as key to providing multifunctional corridors for hydrological management, species movement, recreation, and cultural landscape preservation (Ahern 2004).

The concept of connectivity is perhaps easiest to understand in the context of plant and animal movement. In this context, connectivity refers to the degree to which the landscape facilitates or impedes movement of individuals among habitat patches. Connectivity affects the rate of movement among local populations in a spatially-structured population (or metapopulation) and is therefore critical to the persistence of populations in fragmented landscapes (Forman and Godron 1986; McDonnell and Pickett 1988; Opdam 1991; Opdam et al. 1993; Naveh 1994; Forman 1995; Bennett 1999). By affecting movement rates and patterns, connectivity also affects gene flow, which is essential for the long-term survival of populations (Selman and Doar 1992). An abrupt change in the connectivity of the landscape 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 and ultimately to the extinction of the population in the landscape. Thus, connectivity is often a critical issue regarding the conservation of populations.

Connectivity for populations may be achieved in many ways. The size, number, and distribution of habitat patches influence the physical connectedness of habitat across the landscape, and may be the primary determinant of connectivity for some species (Fritz 1979; Opdam 1988 cited in Selman and Doar 1992). This is most likely when there is a discrete patch structure in which the landscape is comprised of habitat and nonhabitat—at least as perceived by the species. In this situation, when habitat is abundant and widespread, connectivity is virtually assured. Habitat loss results in a simple loss of suitable habitat and the effect on landscape structure is a quantitative one: a reduction in the proportion of habitat on the landscape. A qualitative change in landscape structure and connectivity occurs at a critical threshold, beyond which any additional loss of habitat produces a fragmented landscape in which habitat is dissected into multiple small, isolated patches. The pattern of habitat destruction and the dispersal capabilities of the species determine the level of habitat loss at which this threshold in landscape connectivity occurs.

Physical connections between habitat patches via corridors may also affect connectivity for populations (Baudry and Merriam 1988). Corridors have different functions with respect to connectivity: (1) they may provide breeding habitat for individuals and thus serve to connect larger population units by maintaining gene flow, (2) they may provide only dispersal habitat and thus serve only to facilitate movement among larger habitat patches, and (3) they may serve as barriers or filters that prevent or impede the movement of organisms across the corridor (Forman and Godron 1986). Empirical evidence that corridors actually facilitate landscape connectivity is equivocal (Simberloff and Cox 1987; Simberloff et al. 1992; Hobbs 1993; Mann and Plummer 1995; Rosenburg et al. 1997). Nevertheless, in conservation practice it is generally assumed that corridors mitigate the effects of habitat fragmentation by facilitating connectivity between habitat patches, and therefore have an important role in the maintenance of biological diversity (Forman 1995; Linehan et al. 1995; Bennett 1999; Jongman and Pungetti 2004) and ecosystem functioning (Chapin et al. 1998; Bennett 1999).

Lastly, the character of the intervening matrix between habitat patches may also affect connectivity for populations. Organisms do not restrict their movement to suitable habitat and the physical connections (e.g., corridors) among those patches, but move throughout the entire landscape mosaic to find suitable habitat. The matrix is often a composite of patches with varying levels of permeability. Consequently, as with corridors, conditions in the matrix may affect movement rates and patterns, and therefore they are the ultimate criterion of successful movement among habitat patches. Unfortunately, like corridors, the evidence in support of the matrix concept is not based on extensive experimental support.

Ultimately, 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)."

The concept of connectivity also applies to other flows across the landscape. Water flow is arguably the most important flow in any landscape. It is important by itself, as a source of water to all life in the landscape, and for the transport of materials, nutrients, and species, including humans, across a landscape. Consequently, disruption of hydrologic connectivity is a major concern when planning for sustainability. Human land use activities that disrupt the flow of water are a major concern for planners. For example, dams disrupt the flow of water and, as a result, can serve as traps for nutrients, pollutants, and sediments, and can impair the movement of fish downstream and upstream during migrations. In the same manner that dams disrupt surface water flows, underground developments (e.g., basements, underground parking, and subways) constitute barriers to groundwater flows.

1.3.4. *Landscape Change*

The surface of the earth is constantly undergoing change resulting from the cumulative effect of a variety of disturbances, and the growth and development of ecosystems and human culture. Landscape change can be understood as the alteration of landscape structure and function over time. The most effective manner for landscape planners to deal with landscape change is to develop a basic understanding of it, and to understand options and consequences associated with alternative plans for the future.

In many landscapes that are relatively untouched by human management, it has long been observed that the vegetation present at individual locations in the landscape changes in response to disturbance and succession, but, if averaged over a sufficiently long time or large area, the proportion of the landscape in each stage of development remains relatively constant. This "shifting mosaic" concept of landscape change emphasizes that even systems with a high disturbance frequency could be in a steady state or equilibrium if the creation of new patches is balanced by the maturation of old ones (i.e., a balance between disturbance and succession on a larger scale). Aubreville was one of the first (1938) to describe and conceptualize this process, using as an example the forest in (what was then) French West Africa (Remmert 1991). These forests normally do not uniformly pass from one stage of development to another in one developmental direction. Instead, different portions of the forest are in different stages of growth and decline. As one portion of the forest is reaching a mature state, another portion may only be starting its development after a disturbance. The result is a landscape with different patches in differing stages of development at any point in time, and in which the spatial distribution of stages shifts over time, but the overall composition (in terms of the proportional representation of stages) remains relatively constant.

Watt (1947) referred to any patch mosaic exhibiting this property as the "unit pattern," which he defined as the full representation of the pattern in all its stages. Moreover, Watt suggested that the stages should be present in relative abundances corresponding to the duration of each stage. This is often heralded as one of the earliest and most lucid translations of temporal dynamics into spatial pattern.

There have been several other variations on this theme, most notably the "climax pattern" of Whittaker (1953) and the "shifting mosaic steady-state" of Borman and Likens (1979). Importantly, this form of landscape change is not limited to forests or other unmanaged landscapes. Portions of grasslands in many parts of the world may burn periodically, thus creating a mosaic of differently-aged plant communities. Selective harvesting or replanting of trees in forests may also create a shifting mosaic pattern. And a predominantly agricultural landscape in which farmers practice crop rotation could be seen as a shifting mosaic as well.

Many landscapes, especially those substantially altered by human intervention, do not exhibit shifting mosaic tendencies. Instead, landscapes may undergo a major transformation from one dominant land use to another. A forested landscape can be transformed into an agricultural landscape by human intervention. However, as human populations recognize the benefits associated with forested areas, some of these agricultural systems now incorporate woodlands or even large tracts of forest. This is true in many European forests such as the Veluwe in the central Netherlands. Some landscapes have reverted back to largely forested landscapes, as in New England. The same changes can occur between predominantly mixed agro-forest systems and suburban-urban areas, but in this case the reverse process is more difficult due to the frequently permanent and almost irreversible changes related to urbanization.

Disturbances are important drivers of landscape change. A disturbance is any relatively discrete event (natural or anthropogenic) in time that disrupts an ecosystem, community, or population structure, and changes resources, substrate availability, or the physical environment, including both destructive, catastrophic events as well as less notable, natural environmental fluctuations (White and Pickett 1985). Typically, a disturbance causes a significant change in the system under consideration (Forman 1995, 351). Fires, hurricanes, floods, insect outbreaks, volcanic eruptions, landslides, and land clearing for development can all be considered disturbances because they cause a change in the system.

Natural disturbances can be localized, such as small fires and storms, or cover large areas, such as insect defoliations and hurricanes. Some elements of the landscape may be resistant to certain natural disturbances, such as water being resistant to fire. Other landscape elements may facilitate certain disturbances, revealing an actual ecosystem dependency upon periodic disturbance, such as the chaparral in California where dry vegetation accumulates as fuel for wildfires. These ecosystems have evolved in response to fire, taking advantage of the release of nutrients after a fire occurs. Species may adapt reproductive and physiological strategies in order to survive and take advantage of environmental conditions created by the disturbance.

Anthropogenic disturbances can assume many forms, e.g., pollution, alteration of the rate of ecological processes, habitat destruction and fragmentation. In this handbook we emphasize fragmentation as an important landscape process that affects wildlife habitat. Some forms of anthropogenic disturbance may be linear in form, such as roads, railway lines, foot trails, and canals. Such transportation corridors, in addition to inhibiting movement of wildlife and nutrients, may represent a chronic form of disturbance where noise, litter, and chemical pollutants are introduced into the adjacent landscape elements (Forman and Deblinger 2000; Forman et al. 2003).

Disturbance is a normal part of every landscape that must be taken into account when plans are developed. Complete suppression of natural disturbances is, by definition, impossible. Understanding the disturbance regime, the spatial and temporal characteristics of disturbances (both natural and anthropogenic), is critical to the ecological and cultural success of a proposed plan. Landscapes should be managed to maintain ecosystem processes and the range of natural variability across scales. Events that characterize the variability found in natural ecosystems should be present and functioning. Resource managers often attempt to reduce the probability of events that are considered destabilizing to a landscape, such as floods and fires. Unfortunately, these attempts often lead to undesirable outcomes, namely dramatic changes in the natural cycles. These changes can be the cause of impacts much more damaging in the long term than the events themselves (De Leo and Levin 1997). For instance, flooding holds important consequences for nutrient inputs to surface water, as well as the social and cultural costs incurred when flooding displaces people. Also, disturbance can be critical to enhancing biodiversity by presenting opportunities for a variety of species to colonize a landscape. The suppression of disturbance, therefore, can have several deleterious effects, the most important of which may be the development of a homogenous landscape that is less resistant to future disturbance.

LAND TRANSFORMATION, HABITAT LOSS AND FRAGMENTATION

To provide for basic human needs like food, fuel, and housing, natural ecosystems are converted either to managed forest systems, agricultural systems, or residential systems. In fact, humans have converted 95% of the earth's terrestrial ecosystems to managed forest, agricultural, rural, and urban landscapes (Kim and Weaver 1994).

Loss and fragmentation of habitat is a typical process of landscape change and is one of the greatest threats to biodiversity worldwide (Sorrell 1998). In the last decades of the twentieth century, suburbanization around major cities occurred with significant impacts on forested areas and wildlife habitat. Suburbanization is spreading dramatically and affecting rural landscapes (Antrop 2000). Life-support systems are basically formed by agricultural systems and natural systems; the former providing food, the latter providing other physiological needs by purifying and recycling the air and water, and by stabilizing the climate (Odum 1989). Since cities are highly dependent on their surrounding countryside (Odum 1971; Rees 2003), it is crucial to acknowledge the importance of rural landscape conservation for human society. Even in urban planning *per se*, planners must acknowledge the relationships with the surrounding countryside and its multiple resources, and plan it as a whole unit, as illustrated by Ribeiro Telles' (1998) Global Landscape Concept.

During land transformation three main stages can be identified (Figure 1.7). *Dissection* and *perforation* dominate in the first stage. The construction of roads, power lines, corridors, or other linear features *dissect* the landscape. *Perforation* is caused by the introduction of nonlinear patches (e.g., agricultural fields, houses) within the matrix. In the second stage, the processes of *fragmentation* and *shrinkage* dominate, and the former processes decrease in importance. Fragmentation occurs when continuous natural areas are broken up or subdivided into disjunct fragments as development progresses. Shrinkage is the gradual reduction in area and increased isolation of remaining fragments as development increasingly dominates the landscape. In the third and final stage, *attrition*, i.e., the gradual loss of remaining fragments, leads to a new matrix of a developed land cover type (LCT), such as agricultural or urban residential.

Consider a binary landscape with only two land cover types: (1) forest, and (2) urban. In a simple land transformation process, forest is slowly replaced by urban development (Figures 1.8 and 1.9). In the relatively intact landscape, the majority of the landscape is occupied by forest. During the initial stages of land transformation, small amounts of forest are

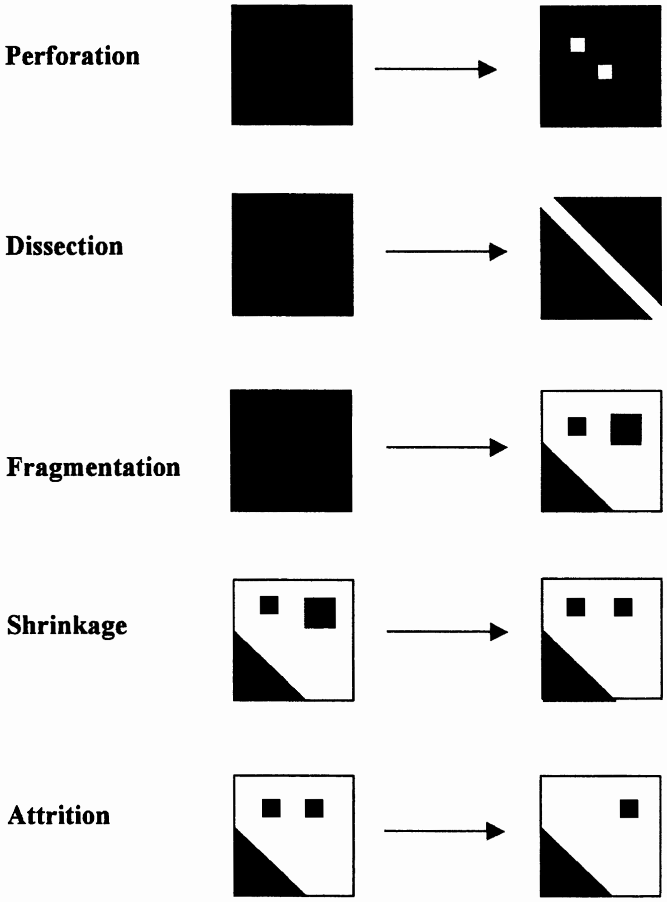

Figure 1.7. Forman's spatial stages of landscape transformation: perforation, dissection, fragmentation, shrinkage, and attrition. Forest habitat cover is represented in black; urban areas, including roads, are represented in white. *Forman 1995, 407*

incrementally lost. As perforation and dissection continue, individual patches of forest begin to appear (fragmentation). As development continues, the distance between forest patches increases. The forest patches then begin to diminish in size (shrinkage) and eventually disappear altogether (attrition) (Figures 1.7, 1.8, and 1.9).

Fragmented landscape patterns hold consequences for many aspects of the environment and human culture. Landscapes that are highly fragmented may have increased rates of soil erosion via wind and water, as well as increased rates of stream and river sedimentation. Fragmented landscapes are less likely to possess long tracts of land suitable for public

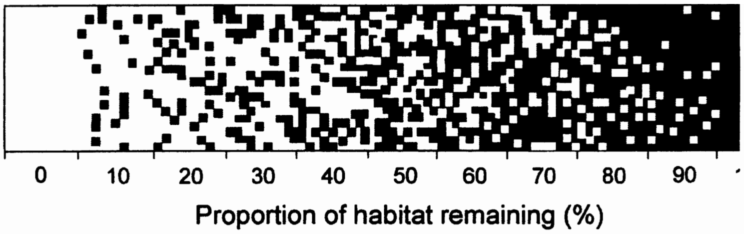

Figure 1.8. Depiction of habitat fragmentation and loss in a simulated landscape. Forest habitat cover is represented in black; urban areas, including roads, are represented in white. *Adapted from Andrén 1994*

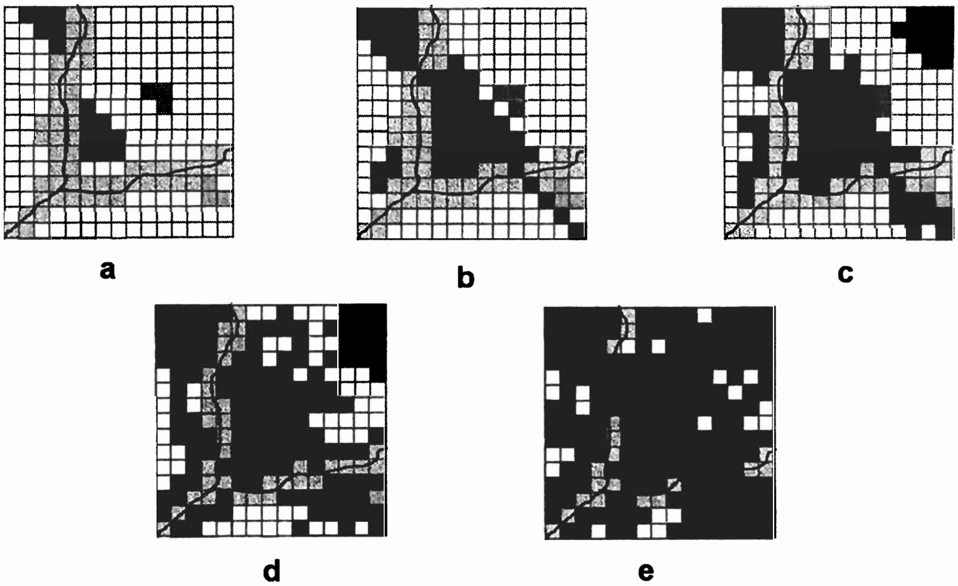

Figure 1.9. Hypothetical landscape transformation associated with agricultural and urban development. The landscape is composed of seven land cover types: road (black), urban (dark gray), agriculture (medium gray), riparian (light gray), forest (white), wetland (stipple), and meadow (cross hatch). The sequence illustrates a typical transformation in which the landscape changes from a forested landscape (a) to an agricultural/urban landscape (e).

recreation, such as riparian corridors. Wildlife populations are likely to suffer dramatic effects in fragmented landscapes (Andrén 1994). Human activities such as agriculture and urban development are obvious causes of habitat loss and fragmentation. Roads can also be a significant fragmenting factor, because they create access for humans to engage in extraction, recreational, or residential development activities. Roads can have several effects, namely the isolation of wildlife species that depend on core area habitat and/or are unwilling to cross open areas (Garland and Bradley 1984; Mader 1984 cited in Sorrell 1998). Roads also create artificial edges that opportunistic wildlife species exploit, and can be a major cause of mortality when individuals attempt to cross roads.

Forman (2000) and Forman and Deblinger (2000) estimate that transportation infrastructure in the U.S.A. affects one third of its total mainland. A similar impact exists in Europe where roads, waterways, and railways have been affecting landscapes for centuries, resulting in loss of habitats, fauna casualties, disturbance (noise and light), and local pollution influencing many animal species (IENE 1997, Ministry of Water Traffic Management, cited in Jongman 2002, 215).

1.4. Quantifying Landscape Structure

1.4.1. *What Are Landscape Metrics?*

Landscape metrics measure and describe the spatial structure of patches, classes of patches, or entire patch mosaics (i.e., landscapes). Metrics provide useful information about the composition or configuration of a landscape, e.g., the proportion of each land cover type present, or the size or shape of landscape elements. A major value of landscape metrics lies in their usefulness for comparing alternative landscape configurations, e.g., comparing different landscapes mapped in the same manner, evaluating the same landscape at different times, or comparing the same landscape under alternative scenarios (Gustafson 1998).

Landscape metrics measure two fundamental aspects of landscape structure: composition and configuration. *Landscape composition* refers to the variety and abundance of patch types without regard to their spatial character or arrangement. Composition metrics measure the number of patch types (i.e., patch richness), the proportional abundance of each patch type (i.e., class area proportion), and the overall diversity of patch types (e.g., Shannon's and Simpson's diversity indices). Although composition metrics are not spatially explicit, they still have important spatial effects (Gustafson 1998). *Landscape configuration*, in contrast, refers to the spatial character and arrangement, position, or orientation of landscape elements. Configuration metrics measure things such as patch shape and compactness, the distance between patches of the same class (i.e., nearest neighbor distance), the clumping of patches and patch types, and the degree of contrast along patch edges. Landscape composition and configuration affect ecological processes independently and interactively. Therefore it is especially important to understand what component of landscape pattern is being quantified by a particular metric (McGarigal et al. 2002).

1.4.2. *Patch, Class, and Landscape-Level Metrics*

Landscapes can be analyzed at four levels depending upon the desired emphasis: cell (available only when using raster, or grid, data), patch, class, and landscape (Figure 1.10). Cell-level metrics have not yet been well-developed or applied in landscape ecology, so we will limit our concern to the other three levels:

1. Patch level: a patch is a relatively homogeneous area that differs from its surroundings. In vector data, a patch is a polygon, classified as a specific land cover type. In raster or grid data, a patch is a cluster of like-valued cells based on either a four or eight neighbor adjacency rule. Patch-level metrics quantify characteristics of individual patches, such as size, shape, and nearest neighbor distance, and return a unique value for each patch (i.e., one record per patch). In many applications, patch-level characteristics are not interpreted directly, and instead they function simply as the basis for computing characteristics of an entire class of patches (i.e., land cover types) or of the entire patch mosaic. However, in some cases, a planner may be interested in the patch-level characteristics themselves. For example, one could be interested in identifying the largest single patch in a landscape to prioritize for biodiversity conservation.

2. Class level: a class is a set of patches of the same type (i.e., a land cover type). In vector data, a class is a set of polygons classified as the same patch type. In raster or grid data, a class is a set of like-valued cells, regardless of their patch affiliation (i.e., all cells with the same cell value). Class-level metrics quantify characteristics of an entire class (i.e., patch type), such as total extent, average patch size and degree of aggregation or clumping, and return a unique value for each class (i.e., one record per class). Most of the class-level metrics can be interpreted as fragmentation indices (in the broadest sense) because they measure the configuration of a particular patch type. In most applications, class-level characteristics are the primary focus because

the extent and fragmentation of a particular class (or classes) is the principal concern. For example, a planner may be interested in knowing the total area of forest, the average size of forest patches, the average distance between forest patches, or in comparing the total area of forest to the total area of other cover types (e.g., residential or urban). Note that many of the class-level metrics are derived from the patch-level metrics by summing or averaging over all patches of the corresponding class. For example, mean patch size is based on the size of individual patches of the corresponding class.

3. Landscape level: a landscape is a set of all patches within the area of interest. In vector data, a landscape is the entire collection of polygons, regardless of patch type. In raster or grid data, a landscape is the entire collection of cells, regardless of class value. Landscape-level metrics quantify characteristics of the entire patch mosaic, such as the diversity of patch types, average patch size and degree of clumping, and return a unique value for the entire landscape (i.e., one record per landscape). Landscape-level metrics characterize the overall composition and configuration of the patch mosaic without reference to individual patches or patch types. Most of the landscape-level metrics can be interpreted broadly as landscape heterogeneity indices because they measure the overall landscape pattern. Like class-level metrics, many of the landscape-level metrics are derived from patch or class-level metrics by summing or averaging over all patches or classes.

There are a few important caveats regarding the patch-class-landscape hierarchy. First, because all patch-level metrics can also be summarized at the class and landscape levels, it is important to interpret each metric in a manner appropriate to the level. For example, at the patch level, patch area describes the size of a patch in isolation, but denotes nothing of fragmentation *per se*; whereas, at the class level, mean patch area (in conjunction with total class area or number of patches) describes an important aspect of fragmentation of the corresponding class. Similarly, at the landscape level, mean patch area (in conjunction with total landscape area or number of patches) describes the overall patchiness or heterogeneity of the landscape, but denotes nothing of fragmentation *per se*, which is a class-level phenomenon. Thus, the same basic metric (patch area) has a different interpretation at each level of the hierarchy.

Second, not all metrics have counterparts at all three levels of the hierarchy. In particular, some metrics are unique to the class or landscape levels. For example, the number of different patch types (i.e., patch richness)

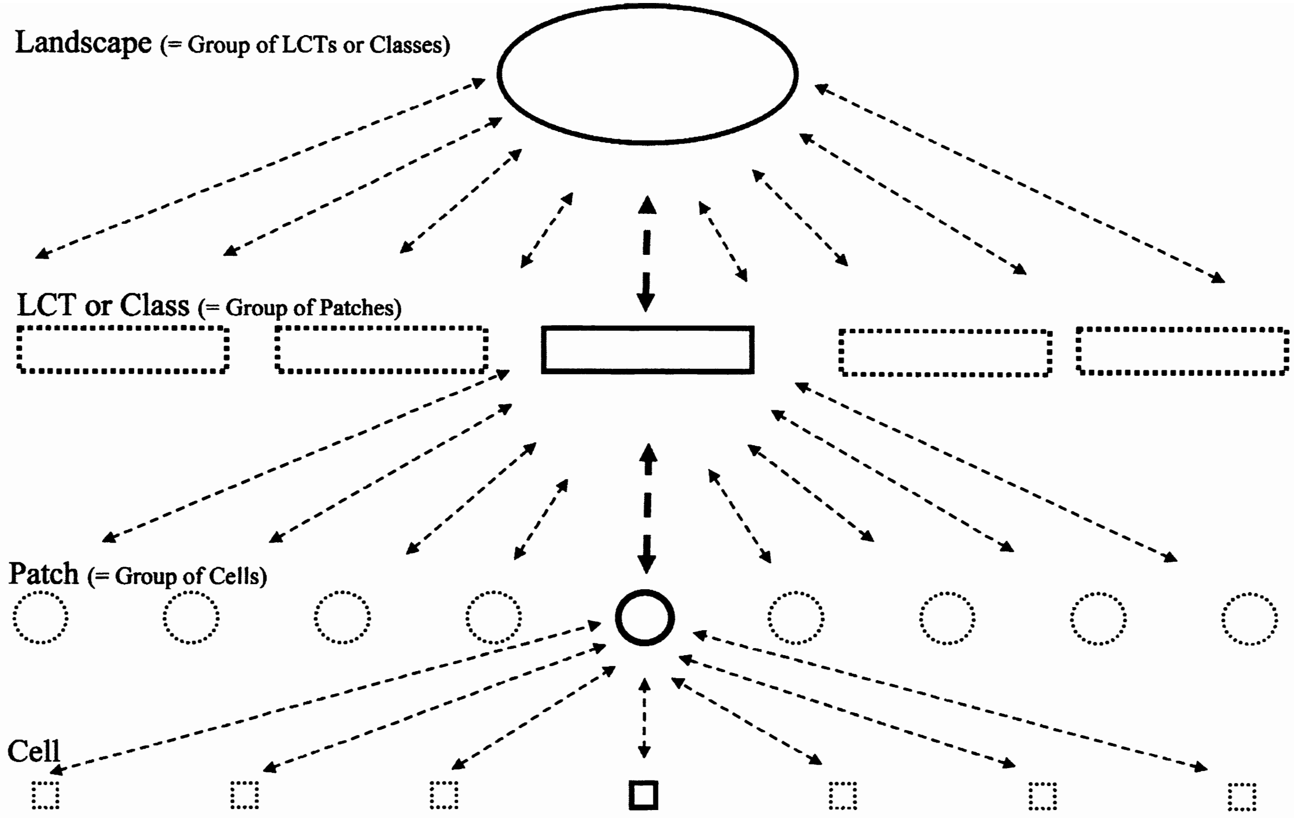

Figure 1.10. Conceptual diagram of the four levels of analysis provided in the metrics included in the handbook: cell, patch, class/land cover type (LCT), and landscape.

and their degree of clumping (i.e., contagion) are only relevant at the landscape level. Similarly, the proportion of the landscape comprised of a particular class (i.e., class area proportion) is only relevant at the class level.

Lastly, despite the use of the patch-class-landscape hierarchy for organizing the quantification of landscape structure, not all metrics are inherently patch based. That is, not all metrics are derived from the spatial properties of patches *per se*, which are aggregated into classes and then into the landscape. For example, the total length of edge or the degree of contrast along those edges does not depend explicitly on the patch structure *per se*; the same total edge length could be derived from wildly varying numbers and shapes of patches. In addition, with raster or grid data, it is possible to derive characteristics from the spatial properties of individual cells, regardless of their patch affiliations. For example, the degree of clumping at the landscape level (i.e., contagion) is derived from the matrix of cell adjacencies, which shows the frequency with which different pairs of patch types (including like adjacencies between the same patch type) appear side-by-side on the map. Thus, while all metrics are tied to one or more levels of the patch-class-landscape hierarchy for purposes of reporting, they are not all formulated based on the patch mosaic organization on which the hierarchy is based.

1.4.3. *Variability*

In many 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. Measuring variability is useful since averaging statistics can camouflage important phenomena, such as an uneven distribution of values and the occurrence of outliers (e.g., very small or very large patches). For example, consider two landscapes with the same patch density and mean patch size, but with very different levels of variation in patch size. Greater variability indicates less uniformity in pattern, either at the class level or landscape level, and may reflect differences in underlying processes affecting the landscapes. However, even second order statistics such as the variance can be difficult to interpret as they mask the details of the exact underlying distribution. Ultimately, it may be most informative to evaluate the actual distribution itself.

1.4.4. *Computing Landscape Metrics*

In the last two decades significant advances have been made in computing, mathematical theory, and systems analysis. These theories and tools are promising for addressing the level of complexity associated with sustainability. As the scale of planning moves from the site or ecosystem level, to the landscape or regional level, data volume increases exponentially. Holism and systems theory have become central paradigms in ecologically-based planning to address the horizontal dimensions and hierarchical (vertical) levels inherent in natural systems. To address the huge volumes of data, the complexity of planning issues, data visualization requirements, and public involvement in the planning process, tools such as Geographic Information Systems (GIS), Artificial Intelligence Systems, and Spatial Decision Support Systems have become more and more common in planning.

In landscape planning, GIS has become a fundamental tool not only for the storage and management of information (cartographic and alphanumeric) that results from spatial analysis, but also in the processing of this information to construct and analyze alternative future landscape scenarios (Burrough 1986; Steinitz 1993; Haynes-Young et al. 1994; Hulse et al. 1997; Steinitz et al. 1998; Ahern et al. 1999; Hanna 1999; Theobald et al. 2000; Botequilha Leitão 2001; Botequilha Leitão and Ahern 2002; Hulse et al. 2002; Steinitz et al. 2003). GIS can play an important role in all phases of planning and decision making:

Data Input, Storage and Management: creating and updating spatial data layers (e.g., topography, land cover, etc.) and managing the spatial database.

Analysis: analyzing spatial relationships within or among data layers (e.g., terrain analysis, landscape pattern analysis, etc.).

Modeling/Simulation: modeling/simulating spatial relationships (e.g., creating alternative planning scenarios, simulating visual impacts of proposed projects, etc.).

Outputs: creating maps to facilitate the planning and decision-making process and to communicate results (e.g., public presentations).

In this handbook, we use the software FRAGSTATS for computing landscape metrics (McGarigal et al. 2002). We adopted FRAGSTATS for several reasons: (1) it contains the most relevant landscape metrics, (2) it supports distribution statistics such as median, average, range, standard deviation, etc., (3) it includes a complete user's guide with a description of the theoretical and mathematical basis for each metric, (4) inputs/outputs are compatible with a wide range of GIS software including ArcGIS (ESRI), and (5) it is available online as freeware at the FRAGSTATS web site at the University of Massachusetts, Amherst (http://www.umass.edu/landeco/research/fragstats/fragstats.html). In addition, FRAGSTATS is the tool of choice in basic and applied ecological literature as in Diaz (1996), Zorn and Upton (1997), Hargis et al. (1998), Tinker et al. (1998), Tischendorf (2001) and others.

GIS has several imbedded functions that support the gauging of some of the ten metrics without the use of FRAGSTATS. The computation of polygon area (patch size) and perimeter length (patch edge), and the number of polygons (patch number), either disaggregated by land cover type, or computed for the entire landscape map, is relatively easy to compute in most GIS software. They are the basis for computing an entire range of metrics included in the FRAGSTATS software, for example:

- Patch Richness (PR) is readily available in GIS maps, either in raster or vector format, as the number of LCTs or land use classes that show up in a legend of a particular mapped landscape.
- Class Area Proportion (CAP) is calculated by averaging the area of all polygons (patches) of a same LCT.
- Patch Number (PN) is simply the number of patches of an LCT, or for all patches, of all LCTs, across the entire landscape.
- Mean Patch Size (AREA_MN) is computed by calculating the average of polygon areas for a specific LCT.
- Euclidean Nearest Neighbor Distance (ENN) is usually a built-in option in standard spatial analysis GIS software menus.
- The remaining five metrics proposed in this handbook, shape (SHAPE), radius of gyration (GYRATE), proximity index (PROX), edge contrast (ECON) and contagion (CONTAG), are not readily available in most GIS software packages, but are calculated by FRAGSTATS.