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Sustainability at Landscape and Regional Scales

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Many of the important threats to sustainability of the biosphere involve changes in patterns of land use as a result of an expanding human population. Loss of habitat, decreased biodiversity, tropical deforestation, and desertification all involve changes in the extent and patterning of natural systems on the landscape. Reversing current trends requires a new emphasis on the interaction between spatial patterning and ecological function. This chapter recommends a number of measures of landscape pattern, based primarily on remote sensing, and suggests critical research areas needed to address sustainability of heterogeneous spatial systems.

For decades, ecology has focused on paradigms that assume spatial homogeneity. Heterogeneity and pattern were invariably observed in field studies, but results were nevertheless averaged across space. The dominant paradigms held that the critical regularities were contained in the means. Heterogeneity was the "nasty bit" left over and relegated to unexplained variance.

Today, as we discuss the sustainable biosphere, it is impossible to ignore spatial pattern: 5.5 billion humans are carving the terrestrial biosphere into a mosaic of land uses that threaten the subsidies provided by intact ecosystems on intact landscapes.[1] For purposes of this chapter, we define the landscape scale as involving 10,000 to 10 million hectares, with each spatial unit or pixel involving 1 to perhaps 100 hectares.

Landscape and regional changes are implicated in all of the problems identified in the Sustainable Biosphere Initiative (Lubchenco and others 1991). The primary terrestrial contributor to global change in atmospheric carbon is the disruption of tropical forest landscapes (Dale 1990a, forthcoming; Dale, Houghton, and Hall 1991). The primary risk to biodiversity comes from landscape fragmentation and loss (Wilson 1988). An important threat to sustainable ecological systems is the isolation of natural systems on the landscape, which affects the spread of and ability to recover from disturbances (Turner and others 1989, 1991). In fact, most of the phenomena we label as disturbance—from the eruption of Mount St. Helens, to invasions of the Gypsy Moth, to damage from hurricanes in the Everglades, to fires in Yellowstone—are spatial disruptions at the landscape and regional scale.

Tropical deforestation provides a strong motivation for considering landscape and regional scales. The Brazilian Amazon has the largest tract of moist tropical rain forest in the world (Molofosky, Hall, and Myers 1986). Remotely sensed imagery reveals that by 1987, 41,000 square kilometers had been cleared in Rondonia for colonization (Booth 1989; Malingreau and Tucker 1988; Stone, Brown, and Woodwell 1989). At current rates, the forest in Rondonia will be gone by 2000. The ecological effects of changing tropical forest landscapes include decreased biodiversity (Wilson 1988), disruption of hydrological regimes (Shukla, Nobre, and Sellers 1990), degradation of soil (Hecht 1981), and changes in greenhouse gases that could induce changes in climate (Houghton and others 1983; Post and others 1990).

Problems such as deforestation lead us to ask how sustainability is related to the mosaic of ecological systems at landscape and regional scales. Basically, these large scales are relevant to sustainability insofar as the arrangement of systems in space influences (1) the intrinsic stability of ecosystems and (2) the ability of ecosystems to provide a variety of human subsidies, including food, fiber, water, and recreation. Factors influencing intrinsic stability include increase in the frequency or extent of disturbances, significant loss of species, and decreased ability to recover from disturbances. Factors influencing sustained services to humans include erosion, water quality, and loss of wildlife.

Given the importance of changes in land use, it is providential that three technological breakthroughs have made the study of large-scale spatial changes practical. First, advances in satellite imagery (Dale 1990b; Tucker and others 1986) provide large-scale data sets. Second, developments in geographic information systems facilitate manipulation of data (Dearstone and others, forthcoming). Third, rapid developments in landscape ecology are providing the theory (Graham and others 1991; Hunsaker and others 1990) and models (Dale and others 1993; Southworth, Dale, and O'Neill 1991a, 1991b) for regional applications.

The purpose of this chapter is to suggest how landscape ecology can be applied to monitoring large geographic areas for sustainability. We offer a variety of elementary measures of landscape pattern that are both practical (based on current technology) and interpretable (based on current ecological understanding). We also recommend areas of research that must be addressed if we are to assure the sustainability of heterogeneous spatial systems.

Measuring pattern at landscape scales

Measurements at the landscape scale must satisfy four criteria. They must (1) be practical, (2) capture significant aspects of pattern, (3) be sensitive to changes through time or across systems, and (4) be interpretable in terms of ecological processes (O'Neill, Hunsaker, and Levine 1992).

Habitat coverage

The simplest landscape measure is the number of pixels (the smallest spatial units on the map) that change land use. Changes in natural vegetative cover, for example, reflect loss of habitat and can be directly translated into increased risk to wildlife species. O'Neill, Gardner, and Turner (1992) present a list of rare and endangered species in southeastern United States that are uniquely dependent on a particular type of habitat. In specific regions, such as the sandy scrub of central Florida, the list permits an immediate interpretation of habitat loss.

Attention can also be focused on specific transitions from one land cover to another. These include loss of rare land covers (such as wetlands), loss of windbreaks, or formation of contiguous agriculture adjacent to a stream or lake. We would also be concerned with connectivity between landscapes as reflected in corridors between patches of natural habitat (Forman and Godron 1986; Harris and Scheck 1991).

Ecotones

The length of ecotones or edges can also be related to suitability of the landscape for wildlife (Gardner and others 1991). In general, loss of edge can be related to decreased biodiversity since ecotones normally have higher species diversity. Ecotones often form unique habitats that are associated with rare and endangered species (O'Neill, Gardner, Turner, and Romme 1992).

It is also relevant to examine the relationship of edges to sizes of patches. For example, cowbirds on forest edges are nest predators on warblers. Forest patches have to be sufficiently large so that nest sites are far enough away from edges that cowbirds cannot find them. If patches get too small, warbler populations start to decline.

Patch configurations

Much of what we understand about the influence of landscape pattern on ecological processes is based on the configuration of patches. For example, the frequency distribution of patches by size can be important because some species require a minimal size of patch. The largest patch may also serve as a reservoir that maintains a population on the landscape. Fragmentation of a landscape into many isolated patches has been shown to reduce biodiversity (Bierregard 1990; Lovejoy, Bierregard, and Rylands 1986; Saunders, Hobbs, and Margules 1991).

It would also be possible to consider the frequency distribution of distances between patches. These nearest-neighbor distances are related to the difficulty experienced by wildlife moving across the landscape. Some spatial arrangements

of patches are particularly vulnerable to fragmentation. Isolated habitat is often configured in a longitudinal pattern, like a string of pearls. Examples include alpine tundra along ridge tops of the Rockies, dune vegetation along beaches, and granite outcrops. Removing a single patch from this configuration may split the entire habitat in two if the gap exceeds the ability of the populations to disperse.

Attention does not need to be limited to patches of natural vegetation. It is also possible to interpret changes in the extent and pattern of clearing relative to risk of erosion. Erosion is significantly increased on long slopes of uninterrupted, unvegetated surfaces. On this basis, clearings might be weighted by slope, size, and proximity to other clearings.

Weighting change in habitat

Interpretations of change in landscape can be enhanced by weighting the transition of individual pixels. For example, a transition to agriculture might be weighted by distance to water to evaluate the impact on water quality. Greater weight might be given to a transition that fragments a large patch. Similarly, a transition could be weighted by the probability of forming a barrier to the movement of animals or the break up of a corridor. It would be important to distinguish between 100 pixels scattered randomly and 100 pixels in a line, forming a new barrier to the movement of animals.

Individual transitions can also be weighted by characteristics of the entire landscape. In an area with very little wetland (or riparian or critical habitat), loss of a pixel is more important than in a region where the habitat is abundant.

Many possibilities emerge through the use of ancillary data, such as agricultural censuses, human population numbers, or forest surveys. As an example, loss of a pixel of forest with recreational value would be weighted more heavily in regions with large urban populations.

Calculated landscape indexes

Dealing with changes in all types of land cover can be a daunting task, and some consideration must be given to reducing the amount of data. For example, the "U" index (O'Neill and others 1988a) is a simple measure of overall impact of humans. The index is calculated as the number of pixels in types of natural land cover divided by the pixels in human land uses, such as agriculture and urbanization.

Percolation theory (Gardner and others 1987) provides a framework for relating pattern of landscape to the ability of an organism to move across the landscape. Rates of diffusion can be calculated and interpreted in terms of wildlife use or spread of fires. The percolation backbone defines the fewest steps needed to traverse the landscape.

Percolation theory also defines critical values of habitat coverage (Gardner and O'Neill 1991). On a random square lattice, the critical value is 59.28 percent. If the percentage of cover for habitat is less than this value, the landscape becomes dissected into isolated patches. The resource utilization scale measures the scale at which an organism must operate to use the resources on a landscape (O'Neill and others 1988b). Similarly, epidemiology theory can be combined with percolation theory to calculate the probability that a disturbance or pest will spread or become endemic (O'Neill, Gardner, Turner, and Romme 1992).

Several other landscape indexes have been developed in recent studies. Dominance is an information theoretic index that indicates the extent to which the landscape is dominated by a single land use (O'Neill and others 1988a). Empirical studies confirm that the fractional dimension of patches indicates the extent to which humans have reshaped the structure of the landscape (Krummel and others 1987; O'Neill and others 1988a). Humans prefer simple shapes; nature generates complex configurations. Contagion (Haban Li and Reynolds, forthcoming; O'Neill and others 1988a) expresses the probability that land uses are more clumped than the random expectation.

One method to assess a land cover would be to ask, "How well is the land being used, compared with its potential?" This suggests an index that compares each pixel with an overlying map of potential vegetative cover and calculates the percentage difference. Another index might compare present land use with suitability for various human applications, such as agriculture.

Similarly, it should be possible to devise a measure of landscape suitability for animals. Consider a square "window" of pixels, the size of an organism's home range. Within the window, we could consider a variety of habitat requirements, such as mixture of vegetation and availability of water. We could then place the window over a corner of the map and calculate a correlation between the existing landscape and the habitat requirements. The window could then be moved systematically over the map to obtain an

overall score that indicates the suitability of the landscape for this organism. We could design a suite of windows for insects, birds, mammals, and so forth. This approach provides a simple, easily interpreted method to compare two landscapes or to evaluate the impact on animals of a change in landscape pattern.

Indicators of economic activity

We must be careful not to miss obvious measures of potential human impact. One of these is simply the number of miles of roads. Vehicles that use roads kill wildlife. Road surfaces alter hydrologic pathways and, when they intersect streams, affect the quality of water. Roads also provide pathways that accelerate the dispersal of pests.

It is well established in economic theory that the number of miles of new roads (and their quality) indicates future development and economic activity (Jones and O'Neill n.d.). In simplest terms, products must be transported to market. As the distance to market increases, transportation costs eat into profits. At some distance, profits reach zero, and there is no motivation for farming, logging, or mining (Jones and O'Neill 1993a, 1993b, and forthcoming). Distance to market can also determine the motivation of farmers to employ conservation measures in their farming activities (Jones and O'Neill n.d.).

It would also be of interest to evaluate landscapes by distance to the nearest urban pixel. One could calculate the average distance for a scene or just draw an area of urban influence. Given global trends toward urban sprawl, this could be taken as a measure of risk for development or overuse.

Hierarchical scales of landscape pattern

Empirical studies (O'Neill and others 1991a, 1991b) have confirmed the prediction from hierarchy theory (O'Neill and others 1986; O'Neill 1988, 1989; O'Neill, Johnson, and King 1989) that landscapes should show pattern at distinct scales. This approach uses statistical analysis of transect data to identify multiple scales of pattern (Turner and others 1991). The number of scales is a unique index that focuses on the ecological processes that influence landscape pattern.

Disruptions of this scaled structure mean that ecological processes determining a particular scale have been disrupted. Although the detailed relationship between processes and scaled patterns is still a matter of research, we have hierarchical neutral models that are suitable for testing hypotheses in the field (O'Neill, Hunsaker, and Levine 1992).

Landscape pattern and water quality

It is also possible to assess the risk of water quality degradation due to changes in terrestrial landscapes (Hunsaker and others, forthcoming). Across a region, increase in agricultural and urban land uses or decreases in natural vegetation indicate a risk of future problems with water quality. The changes in basic cover could be weighted by distance to water, soil type, and slope calculated from digital elevation models. Essentially, the same data set can be used with the Universal Soil Loss Equation to estimate erosion. A second type of indicator might focus on the risks of undesirable hydrologic events. For example, a flood indicator could include vegetative cover, wetlands that modify peak flows, and surficial geology.

Riparian zones are important buffers for maintaining the quality of water in streams. Changes in the width of buffers, weighted by slope, are an important indicator. The actual index might be average width or miles of riparian zone that are narrower than desirable. The *Canadian Timber Management Guide* (Ontario Ministry of Natural Resources 1988) sets standards for the width of buffer zones that range from 30 meters on slopes of 0°–15° to 90 meters on slopes above 45°. This standard could be applied by counting pixels that encroach on the recommended buffers.

Research needs in landscape and regional studies

The research agenda for landscape studies can be stated simply: How do ecological processes interact with the environment to create patterns, and how do the patterns influence ecological function? Basically, there is a need to develop measures of spatial pattern and to correlate pattern with ecological processes in field studies. Without attempting to be all-inclusive, several areas of research seem particularly relevant.

To what extent does spatial pattern affect the ability of systems to recover from disturbance? We know that northern hardwoods may take sixty to eighty years to replace biomass and nutrients lost in harvesting (Likens and others 1978). How would this recovery time change if distances to seed sources were increased or if erosion set in?

To what extent is spatial pattern critical to the sustainability of plant and animal communities? For example, pollinators and nectar feeders fly, which permits them to cover large areas and explicitly integrate across spatial heterogeneity.

They require something to be blooming somewhere throughout the season. If the spatial scale of the heterogeneity is increased to exceed their ability to integrate, the result could be important changes in the plant community.

We need to identify ecological systems that are particularly sensitive to spatial disturbances. The proverbial erosion effects of tire tracks in the Arctic tundra are well known, but arid lands may be equally sensitive. Even the casual observer can see how small alterations in natural land forms result in major changes in the vegetation of arid lands.

The potential sensitivity of arid lands also alerts us to the need to identify critical thresholds in landscape pattern. Percolation theory indicates that small changes in land cover can critically alter connectivity between landscapes. But we also know from tragic experience in the American plains and the African Sahel that other critical thresholds exist. Beyond these thresholds, cascading effects or positive feedbacks cause bifurcations that move the system into new modes of operation (Schlesinger and others 1990).

To address sustainability at large scales, we need to integrate socioeconomic theory with ecology. Landscapes change because of human decisions. To predict such change requires an understanding of the economic forces that determine land tenure and land use (Jones and O'Neill 1993a, 1993b, and forthcoming). To reverse current trends requires that ecological consequences be translated into feedbacks, into the real cost of supplying environmental subsidies. The development of this interdisciplinary theory is critical, yet almost no support is available for this research.

Conclusions

The analysis presented in this chapter seems to justify three conclusions. First, an emphasis on landscape ecology is required since most threats to a sustainable biosphere involve changes in land use at large scales. Second, the combination of remote sensing, geographic information systems, and landscape theory permits us to define a significant number of new metrics that are both practical and interpretable. Third, continued progress involves difficult new areas of research. New research, particularly interdisciplinary socioeconomic-ecological studies, requires new sources of funding that currently do not exist.

Note

1. A billion is 1,000 million.

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