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Dealing with Scale in Landscape Analysis: An Overview

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I. SCALE AND SCALING

Scale is an essential concept in both natural and social sciences, and has been defined in several different ways (Gibson et al. [4], van Gardingen [19], Peterson and Parker [16], Marceau [12], Withers and Meentemeyer [21], Jenerette and Wu [6]). In landscape ecology, scale refers primarily to grain (or resolution) and extent in space or/and time. Scale may be absolute (measured in spatial or time units) or relative (denoted as a ratio). Scale may be the observer's measuring stick or viewing window size, a spatial or temporal characteristic of an ecological pattern or process, or a fundamental framework in which diverse ecological phenomena can be more effectively studied and understood individually and collectively. Scaling, on the other hand, is usually defined as the process of extrapolating or translating information from one scale to another, including scaling up and scaling down (Caldwell et al. [3], King [8], Wu [24]). Scale and scaling have become buzzwords in ecology in recent years as the research emphasis of the field has shifted from local to increasingly broader scales. This research emphasis shift is inevitable for at least two reasons. First, it has become evident that most if not all environmental and resource management problems can only be dealt with effectively at broad scales. The second and more profound reason is that ecologists are now acutely aware that, in order to unravel how nature works, we must understand broad-scale patterns and processes and relate them to those at fine scales with which we are most familiar. In both cases, transferring information between scales is indispensable.

II. LANDSCAPE AND LANDSCAPE ECOLOGY

Landscapes are spatially heterogeneous areas and often manifest themselves as mosaics of patches with varying size, shape, composition, and history. They may be as large as thousands of square kilometers or as small as tens of square meters if landscapes are defined according to organisms or ecological processes under consideration. However, human-scale landscapes that span over tens or hundreds of square kilometers are more familiar and convenient to us, and often are relevant geographic domains for dealing with many ecological and environmental issues. But, many have argued that fixing the spatial dimension of landscape at a particular size is arbitrary, and may impede rather than facilitate the development of landscape ecology as a science (see Allen and Hoestra [2], Wiens and Moss [20]). Although landscape ecologists still can not agree on the spatial dimension of the very object they study, they do converge on the most essential feature of a landscape: spatial heterogeneity. They also tend to agree that spatial heterogeneity exhibits different patterns at different scales, and that organisms and ecological processes with distinctive characteristic scales respond to spatial heterogeneity at different scales. This means that the same landscape is heterogeneous to certain organisms or ecological processes, but not to others because of their distinctive abilities to perceive and filter spatial information.

Landscape ecology is simply the study of relationship between spatial pattern and ecological processes over a range of spatial scales (Pickett and Cadenasso [17]). Because of the scale multiplicity in spatial pattern and ecological processes, scale holds the key to understanding the pattern-process interactions and, indeed, becomes one of the corner-stone concepts in landscape ecology. The existence of scale multiplicity in patterns and processes in landscapes has naturally resulted in the hierarchical perspective in landscape ecology (Urban et al. [18], O'Neill et al. [14], Wu and Levin [22]). Hierarchy theory provides a conceptual framework for investigating and explaining the multiple-scale patterns and processes, and has contributed substantially to our understanding of ecological scale (O'Neill [15]). Because a landscape usually is composed of smaller "landscapes nested in larger landscapes" (Allen and Hoestra [2]), or a hierarchical patch dynamic mosaic (Wu and Loucks [23]), scale and hierarchy are inevitably related in landscape ecological studies.

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III. SPATIAL HETEROGENEITY AND THE PROBLEM OF SCALE

As spatial heterogeneity becomes a major theme in a wide range of ecological studies (Kolasa and Pickett [9], Li and Reynolds [11]), the concepts of scale, scaling, and hierarchy become increasingly important in ecology in general. A literature survey reveals that the number of papers that contain words, "scaling", "hierarchy", "hierarchies", "hierarchical", or "hierarchy theory", has increased exponentially in four of the major ecology journals since 1930s (Table 1 and Figure 1). This confirms, and is indicative of, the rapidly rising awareness of the importance of scale and hierarchy by ecologists. Several recent reviews on scale and scaling seem to suggest that a science of scale is emerging from studies in many different disciplines encompassing both natural and social sciences (Gibson et al. [4], Peterson and Parker [16], Marceau [12], Withers and Meentemeyer [21], Wu [24]).

In dealing with scale in ecological research and applications, three related but distinctive tasks stand out. First, we need to appreciate and understand how changing the scale of observation affects research results and their interpretation. Much work has been done in this area either in the name of "the modifiable areal unit problem" (MAUP), or "scale effects" where scale can be grain or extent in space or time (see Jelinski and Wu [5], Marceau [12] for reviews). However, it is not always clear whether the effect of changing scale is an artifact due to improper use of analysis methods, an indication of the scale multiplicity of ecological systems, or neither of the two. Second, if ecological systems are multiple-scaled or hierarchically structured, identifying characteristic scales and hierarchical levels becomes extremely important for understanding and predicting ecological phenomena. Although many studies exist, the issue of characteristic scales and hierarchical levels is not without controversy. Third, theories, models, and procedures for extrapolating information across scales need to be developed for understanding and managing heterogeneous landscapes. Although simple "scaling laws" do exist in ecology, extrapolating information over a wide range of scales may often require a hierarchical approach (Wu [24]).

IV. OVERVIEW OF THE SPECIAL ISSUE

The goal of this special issue, The Problem of Scale in Spatial Analysis of Landscapes, is to shed new light on the three aspects of dealing with scale in landscape analysis. It includes seven papers that address the issues of scale, scaling, and hierarchy. Wu et al. distinguish between two major approaches to detecting scale multiplicity and identifying hierarchical levels in heterogeneous landscapes: the direct approach that uses multiscale statistical methods and the indirect approach that uses single-scale methods often with hierarchically resampled data. In particular, they compare scale variance and semivariance methods with landscape metrics methods in multiscale analysis, and find that scale variance seems more effective than other methods in detecting scale breaks. However, most existing methods used in multiscale analysis today may become less effective in detecting scale breaks when the shapes of patches vary greatly and are elongated with different orientations. Wu et al.

Table 1. The number of articles that contain the words, "scaling", "hierarchy", "hierarchies", "hierarchical", or "hierarchy theory" in 4 major ecology journals: 2 from North America (Ecology and Ecological Monographs published by Ecological Society of America) and 2 from Europe (Journal of Ecology and Journal of Animal Ecology published by British Ecological Society) in the last 7 decades. Note that the number of years in the 1990's actually included was seven instead of ten (1990-1996) due to the data availability of the online database (JSTOR).

Words searched for: scaling, hierarchy, hierarchies, hierarchical, hierarchy theory					
Years	1931-1996	1920-1996	1932-1996	1913-1996	
Decade Year	*Ecological Monographs*	*Ecology*	*Journal of Animal*	*Journal of Ecology*	Total
1930's	0	4	2	2	8
1940's	2	5	1	2	10
1950's	7	36	1	7	51
1960's	7	34	15	23	79
1970's	26	83	21	46	176
1980's	34	203	53	56	346
1990's	30	230	74	83	417
Total	106	595	167	219	1087

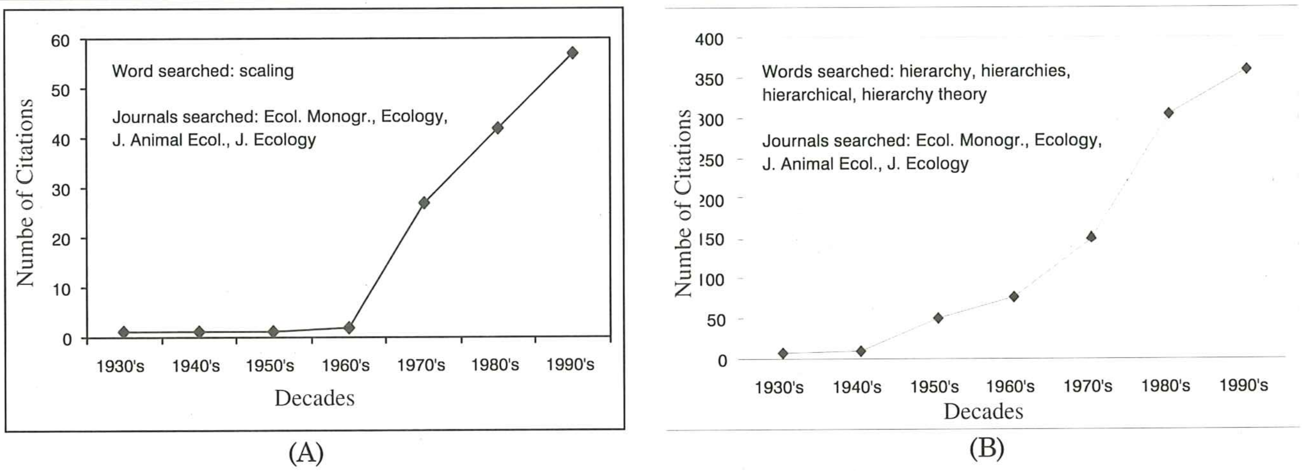

Figure 1. Number of articles that contain the word, "scaling" (A), and words, "hierarchy", "hierarchies", "hierarchical", or "hierarchy theory" (B) in four major ecology journals (Ecology, Ecological Monographs, Journal of Ecology, and Journal of Animal Ecology between 1930 and 1996. See Table 1 for more details.

indicate that the scale effects and scale detection in ecology are closely related to MAUP, which has long been studied in geography and social sciences and, thus, that the results of MAUP are immediately relevant to the problem of ecological scale and scaling.

Dong provides an excellent review of a powerful multiscale analysis method, lacunarity analysis. He discusses the relationship between lacunarity and fractal geometry, various methods to compute lacunarity, including a new method he has developed recently, and an ArcView Extension for Lacunarity Analysis. Lacunarity has been used in landscape analysis since early 1990s, and seems effective in depicting multiscale textural patterns of landscapes. While Dong's new algorithm for estimating lacunarity for gray-scale images is innovative, his AV GIS Extension will hopefully facilitate the application of lacunarity analysis in landscape studies. In the third paper, Francis and Klopatek investigate how changing the grain size of classified NDVI maps (arbitrarily discretized into three categories: low, medium and high) affects several landscape indices. They show that all metrics, except mean patch shape index, vary smoothly and monotonically with grain size. Thus, they suggest that scaling up the spatial pattern may be readily done. Due to the rather limited range of grain sizes used in this analysis (5 to 30 meters on a side, only 6 data points for each index), some of the trends found here are in contrast with those shown by Wu et al. (in this issue) in which the range of grain sizes is 16.7 times larger in linear dimension and 278 times larger in area.

Among the hypotheses for explaining species richness, the role of habitat heterogeneity still needs to be tested empirically. Unlike area or energy, habitat heterogeneity is difficult to quantify. Moreover, it depends highly on spatial scale. Using empirical data collected along a sizable transect that goes across a heterogeneous landscape, Xu and Qi are able to relate species richness of understory plants to the spatial pattern of a number of ecosystem and microclimate variables used to characterize habitat variations. The results lead to two findings. First, not all variables, when their heterogeneity is used, are positively related to species richness. In fact, some variables such as slope and aspect are negatively correlated with species richness, while the heterogeneity of elevation is only weakly correlated with species richness. Second, at some particular scale, the correlation between the spatial heterogeneity of some variables is very strong. For example, at the 2000m scale, the spatial heterogeneity of microclimate variables explains 98% of the total variation in plant species richness. In contrast with Xu and Qi's study, Fairbanks and McGwire's analysis of plant species diversity covers a much larger region, the entire state of California. Accordingly, the spatial resolution in the analysis is coarser. Nevertheless, both studies show that the community variation is well correlated with species diversity. Fairbanks and McGwire's results also confirm their previous studies at a finer spatial resolution. These results suggest that the relationships between plant species richness and landscape heterogeneity discussed here seem to hold across a wide range of spatial scales.

Bradshaw and Fortin discuss the interactions among scale of spatial pattern, image analysis and scale of process, and the implications of these interactions for designing monitoring plans for large geographic areas that include terrestrial systems and aquatic networks. They argue that spatial pattern alone often fails to capture or infer the underlying ecological processes, and that interactions between pattern and process ought to be considered explicitly in monitoring landscapes with remote sensing data. Bradshaw and Fortin use the term "spatio-temporal coherence" to reflect the degree to which spatial patterns and ecological processes are related, and assert that the challenge for monitoring landscapes using remote sensing data is to identify and quantify the spatio-temporal coherence. They further point out that the ability to detect change in pattern decreases as spatio-temporal coherence increases, which has important implications for monitoring landscape dynamics. In the last paper of this special issue, Chen applies the concepts of scale and hierarchy developed in landscape ecology to the study of non-point source pollution. She argues that landscape heterogeneity must be explicitly considered and its hierarchical structure may serve as a basis for linking data and knowledge across scales. She concludes that a multiple-scale, hierarchical approach is essential for monitoring and modeling non-point source pollution problems.

Kauffman ([7]), a leader in the rapidly evolving science of complexity, stated that 18th century science was characterized by developing sciences of organized simplicity (small-number systems) with predominantly the Newtonian approach; 19th century science focused on disorganized complexity (large-number systems) for which the statistical mechanics approach is particularly successful; and 20th and 21st century science confronts organized complexity (middle-number systems). Ecosystems and landscapes are prototypical middle-number systems that exhibit organized complexity, and hierarchy theory has been used to shed light on it (Allen and Starr [1], O'Neill et al. [13], Wu [24]). In general, theories and methods that can effectively deal with organized complexity are lacking, but emerging. We believe that issues of heterogeneity, pattern, process, scale, scaling, and hierarchy are essential in developing a general understanding or theory of complex landscapes. While recent developments in complexity theory (e.g., complex adaptive systems, self-organized criticality) may help us understand how order and complexity evolve and are maintained in ecosystems and landscapes (Levin [10]), a theory of scaling must be developed to understand and predict spatial heterogeneity in landscapes. We are not there yet, but with exciting progress being made expeditiously in landscape ecology and nonlinear sciences we are hopeful that this day will come soon.

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