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CHAPTER ABSTRACTS

PART I: CONCEPTS AND METHODS

1. CONCEPTS OF SCALE AND SCALING
Jianguo Wu and Harbin Li

Scale and scaling are now among the most fundamental concepts in ecology as well as other sciences. In general, scale is the temporal or spatial dimension of a phenomenon, whereas scaling refers to the translation of information between or across spatial and temporal scales or organizational levels. The concept of scale is indispensable for studying heterogeneity and pattern-process relationships, and scaling is essential for both prediction and understanding. In this chapter, we review and synthesize the diverse ideas and concepts of scale and scaling used in various disciplines, ranging from physical to social sciences. Then we attempt to propose a three-tiered conceptual framework of scale in terms of its dimensions, kinds, and components. This framework should provide a clear picture of how various concepts of scale differ from or relate to each other. Furthermore, our understanding of scaling can be improved with more precise and appropriate use of scale-related terms.

2. PERSPECTIVES AND METHODS OF SCALING
Jianguo Wu and Harbin Li

Scaling refers to the translation of information between or across spatial and temporal scales or organizational levels. We distinguish two general scaling approaches: similarity-based and dynamic model-based methods, and discuss the pros and cons of specific scaling methods within each approach. In particular, dimensional analysis, similarity analysis, biological allometry, and spatial allometry are discussed as the main scaling methods of the similarity-based approach. For the dynamic model-based scaling approach, we examine several upscaling and downscaling methods. Upscaling methods include extrapolation by lumping, extrapolation by effective parameters, direct extrapolation, extrapolation by expected value, explicit integration, spatially interactive modeling, and extrapolation along a scaling ladder. Downscaling methods include both statistical techniques and process model-based schemes. The topic of scaling is enormously diverse, and this review is by no means inclusive. Nevertheless, we hope that it provides a comprehensive and balanced overview of the perspectives and methods of scaling in a broad context of ecology.

3. UNCERTAINTY ANALYSIS IN ECOLOGICAL STUDIES: AN OVERVIEW
Harbin Li and Jianguo Wu

Uncertainty in scaling is inevitable because of system complexity due to spatial heterogeneity and nonlinear relationships, lack of reliable data of the system, and problems in scaling techniques. Thus, uncertainty analysis must be regarded as an essential part of scaling process because it provides critical information about the accuracy of scaling results and the adequacy of the models and algorithms used. The main purposes of uncertainty analysis are to quantify uncertainty arising from various sources, assess the effects of uncertainty on scaling results, and identify critical factors in models. Important techniques for analysis of uncertainty include probability theory, Taylor series expansion, Monte Carlo simulation, generalized likelihood uncertainty estimation, Bayesian statistics, and sequential partitioning. Given the increasing role of large-scale modeling and scaling in today's scientific research and environmental decision-making, understanding, quantifying, reporting, and ultimately reducing uncertainties in large-scale assessment are of great interest to both scientists and policy makers. In this chapter, we will review different aspects of uncertainty analysis, including sources of uncertainty in scaling, evaluation of scaling algorithms, error propagation from parameters and input data to scaling results, and presentation of prediction accuracy and error partitioning.

4. MULTILEVEL STATISTICAL MODELS AND ECOLOGICAL SCALING
Richard A. Berk and Jan De Leeuw

Hierarchy theory suggests that certain parts of a multiscaled system can be studied in isolation insofar as these parts are distinguished from the rest by "near-decomposability". In this chapter, we focus on a particular kind of nested systems in which higher levels are composed of the components of the level below. We discuss multilevel statistical models that can be used to describe how variables characterizing higher levels affect processes operating at lower levels. Our goal is to summarize some recent extensions of multilevel models to more complicated and realistic situations common in ecological research. We discussed tools for the construction of multilevel linear models with ecological data and extensions to multilevel generalized linear models.

5. DOWNSCALING ABUNDANCE FROM THE DISTRIBUTION OF SPECIES: OCCUPANCY THEORY AND APPLICATIONS
Fangliang He and William Reed

The distribution of a species in landscapes is often documented by an atlas, a black and white map with black representing the presence and white the absence of the species. We aimed to develop methods to scale down the number of organisms (abundance) from such maps and as such to link the distribution and abundance of species. We approached the problem by dividing the map into a lattice and conceiving of the lattice cells as boxes into which balls are placed. We wanted to know how many balls were placed given u empty boxes out of M total boxes being observed. We first derived estimates using the classical occupancy theory assuming that organisms were randomly and independently placed into boxes. While simulations showed that these models worked very well for random and independent placement, abundances were substantially underestimated for real data. To overcome this problem, we next derived an abundance model for aggregated species based on contagious occupancy processes. The model greatly improved the estimation although for those very abundant species a certain degree of underestimation still persisted. The accuracy of the abundance estimates greatly depended on map resolution and models performed progressively poorer with the decrease in resolution. We also addressed the issue of species detectability using occupancy models and quantified the uncertainty in the detectability.

6. SCALING TERRESTRIAL BIOGEOCHEMICAL PROCESSES: CONTRASTING INTACT AND MODEL EXPERIMENTAL SYSTEMS
Mark A. Braford and James F. Reynolds

An interdisciplinary approach to studying systems dynamics on a planetary scale has emerged, known as Earth System Science. Central to this research is the need to document change, diagnose underlying causes, and develop plausible projections of how natural variability and human actions may affect global biogeochemical cycles. With regards to the latter, once we have the requisite quantitative understanding of process rates, as well as a detailed understanding of key regulatory mechanisms, the goal is to extrapolate findings obtained at one temporal and spatial scale to another. In this chapter, we discuss the issues that must be considered prior to designing an experiment that can inform about process rates, regulatory factors and treatment impacts at temporal and spatial scales greater than at which the experiment is conducted. We compare and contrast two general types of systems: intact and model ecosystem experiments. We demonstrate that: (i) Intact ecosystem experiments can provide process rates, mechanistic understanding and absolute/relative treatment effects suitable for direct extrapolation, but rarely do; (ii) Model ecosystem experiments can provide the sign (positive or negative) of treatment effects and insights into their mechanistic basis but data obtained on process rates and absolute/relative treatment effects are not suitable for extrapolation. As others have done, we conclude there is a need for much greater 'scale awareness' in experimental ecology; this will only be achieved once there is a greater appreciation of nonlinearity, variability and validity by those who seek to predict the behaviors of complex, ecological systems.

7. A FRAMEWORK AND METHODS FOR SIMPLIFYING COMPLEX LANDSCAPES TO REDUCE UNCERTAINTY IN PREDICTIONS
Debra P.C. Peters, Jin Yao, Laura F. Huenneke, Robert P. Gibbens, Kris M. Havstad, Jeffrey E. Herrick, Albert Rango, and William H. Schlesinger

Extrapolation of information from sites to landscapes or regions is especially problematic in spatially and temporally heterogeneous ecosystems. Although linear extrapolations are the easiest and most cost-effective, other approaches are necessary when spatial location and contagious or neighborhood processes are important. Because landscapes and regions consist of a mosaic of sites differing in spatial heterogeneity and degree of connectivity, we expect that a combination of scaling approaches is needed to characterize these areas. Nonspatial extrapolations may be most appropriate for areas that are relatively homogeneous and can be described by a relatively small number of units that repeat across a landscape or region. Spatially implicit or explicit approaches are expected to be necessary for those parts in which functionally similar, repeating units do not exist because of the importance of multiple interacting internal factors (spatially implicit) or connectivity with neighboring sites (spatially explicit). Our goal was to develop a conceptual framework to simplifying complex landscapes in order to minimize uncertainty in predictions. We illustrate our framework for arid and semiarid landscapes where determining spatial variation in carbon dynamics, and, in particular, aboveground net primary production (ANPP), is a timely and important problem.

8. BUILDING UP WITH A TOP-DOWN APPROACH: THE ROLE OF REMOTE SENSING IN DECIPHERING FUNCTIONAL AND STRUCTURAL DIVERSITY
Carol A. Wessman and C. Ann Bateson

Terrestrial ecosystems are characterized by vast functional and structural diversity. Our understanding of the functioning of the earth system and its response to environmental change depends on our grasp of how key processes are coupled across spatial and temporal scales. The structure of landscapes and regions (i.e. the configuration and properties of cover types at these scales) are of great importance and interest to this effort for two reasons. First, structure superimposes constraints on the functioning of ecological systems at broad to finer scales. Second, the structure itself is an expression of the functional properties that emerge from interactions among biological, physical and geochemical processes. Remote sensing can provide the synoptic view of biophysical and biochemical structure across a range of scales, but must be used wisely, keeping in mind sensor-specific measurements, the physical process involved in transmission of solar radiation, and the functional relationship between measured reflectance and biophysical parameters. With appropriate use, remote sensing data can delimit cover types and, to some degree, measure the physical properties that both drive and express processes of interest. Coupled with ecosystem models, remote sensing offers the necessary constraints for model simulations of real-world spatial and temporal heterogeneity.

PART II: Case Studies

9. CARBON FLUXES ACROSS REGIONS: OBSERVATIONAL CONSTRAINTS AT MULTIPLE SCALES
B.E. Law, D. Turner, J. Campbell, M. Lefsky, M. Guzy, O. Sun, S. Van Tuyl, and W.B. Cohen

Estimating terrestrial carbon storage and fluxes at multiple spatial and temporal scales is one of the major challenges in carbon cycle science, where the goal is to understand the role of terrestrial vegetation in the global carbon cycle. Primary objectives are to quantify the geographical and temporal distributions of major fluxes and storage of carbon, and understand the underlying mechanisms and feedbacks between terrestrial vegetation and the atmosphere. Advances in satellite remote sensing and computer-based modeling of forest ecosystems now make it feasible to simulate the carbon cycle over large domains. The resulting spatially-distributed estimates of variables like net ecosystem production reflect the influence of land use, climatic gradients, and soil properties on plant and microbial processes. This chapter illustrates a scaling strategy that is based on a spatially nested hierarchy of observations and model simulations of terrestrial processes for estimating carbon pools and fluxes in a region.

10. LANDSCAPE AND REGIONAL SCALE STUDIES OF NITROGEN GAS FLUXES

Peter M. Groffman, Rodney T. Venterea, Louis V. Verchot, and Christopher S. Potter

This chapter presents a case study of scaling one particular biogeochemical process--soil:atmosphere fluxes of nitrogen (N) gases. These fluxes present great conceptual and practical scaling challenges because they are mediated by microorganisms at the scale of microns and seconds but have relevance at relatively large spatial (meters to kilometers and larger) and temporal (years, decades) scales. The case study is based on a US Environmental Protection Agency funded research project investigating the "effects of N deposition on gaseous N loss from temperate forest ecosystems." This project takes advantage of an N deposition gradient in the northeastern US that runs from West Virginia (high deposition) north and east to Maine (low deposition). In this paper we address three scaling challenges, 1) the need to account for landscape scale variability in regional scale studies, 2) the use of models as tools to account for the episodic nature of gas fluxes and 3) validation of landscape and regional scale flux estimates. We first discuss "motivations for scaling," introduce the topics of N gas fluxes and deposition, briefly describe our regional project and then show how we have addressed the three scaling challenges listed above.

11. MULTISCALE RELATIONSHIPS OF LANDSCAPE CHARACTERISTICS AND NITROGEN CONCENTRATIONS IN STREAMS

K. Bruce Jones, Anne C. Neale, Timothy G. Wade, Chad L. Cross, James D. Wickham, Maliha S. Nash, Curtis M. Edmonds, Kurt H. Riitters, Elizabeth R. Smith, and Rick D. Van Remortel

In this chapter, we analyze relationships between total stream nitrogen and explanatory variables representing three different scales - regional atmospheric nitrogen deposition, watershed level land surface characteristics, and land cover composition within the riparian zone - using a statistical approach that was used to design the NASA space shuttle. We also discuss potential sources of error in the application of the statistical approach. Finally, we discuss how changes in scaling functions might be used as an indicator of overall watershed condition.

12. UNCERTAINTY IN SCALING NUTRIENT EXPORT COEFFICIENTS

James D. Wickham, K. Bruce Jones, Timothy G. Wade, and Kurt H. Riitters

Nutrient export coefficients are used as environmental management tools. They are most often estimated for individual watersheds. Watersheds are inherently scalable, but the effects of changes in scale on nutrient export coefficients have not been studied. We examined the effect of scale on nutrient export coefficients through changes in subwatershed resolution. The Deer Creek watershed (Maryland) was subdivided into two to 20 subwatersheds to examine changes in nutrient export variance. The relationship between scale and variance included evaluation of two sources of uncertainty: 1) the rate of in-stream nutrient decay (loss), and 2) the degree to which subwatersheds can be assumed to have similar (dependent) or dissimilar (independent) nutrient export behavior. Strong, inverse relationships between variance and scale were found when individual subwatersheds were assumed to have independent nutrient export behavior, but the relationship between scale and variance was lacking when subwatersheds were assumed to have dependent (i.e., similar) nutrient export. The rate of in-stream decay had little effect on the relationship between scale and variance. However, both in-stream decay and the degree of similarity in subwatershed nutrient export showed the importance of these ecological services in attaining environmental management goals. Model results for the combination of high in-stream decay and independence met published nutrient management goals more frequently than other modeling combinations (low in-stream decay and independence, high in-stream decay and dependence, low in-stream decay and dependence).

13. CAUSES AND CONSEQUENCES OF LAND USE CHANGE IN THE NORTH CAROLINA PIEDMONT: THE SCOPE OF UNCERTAINTY
D.L. Urban, R.I. McDonald, E.S. Minor, and E.A. Treml

We are engaged in a long-term study of the causes and consequences of changes in land use and land cover in the Triangle region of the North Carolina Piedmont, a region framed by the cities of Durham, Chapel Hill, and Raleigh. The project integrates studies of forest dynamics, conservation value (forest songbird communities), and ecosystem processes (watershed hydrology and biogeochemistry). As part of this modeling effort, we are committed to attending the uncertainties due to errors in imagery and ground data, model selection, parameter estimation, and process error. Because the research program comprises a set of interacting models and data products, our task is beyond the scope of the conventional framework for uncertainty analysis and error propagation but yields to a relaxation of the conventional analysis. We illustrate our approach with spatially mapped errors in land cover classification, extrapolation and forecasts of modeled forest dynamics, and bird metapopulation response to available forest habitat patches. We discuss the methods and implications of incorporating these sources of uncertainty in models used for integrated assessments at regional scales.

14. ASSESSING THE INFLUENCE OF SPATIAL SCALE ON THE RELATIONSHIP BETWEEN AVIAN NESTING SUCCESS AND FOREST FRAGMENTATION
Penn Lloyd, Thomas E. Martin, Roland L. Redmond, Melissa M. Hart, Ute Langner, and Ronald D. Bassar

Many ecological processes are scale-dependent, to the extent that a process at one scale may be influenced by factors at other scales. The nesting success of most North American land birds is influenced primarily by two ecological processes: 1) nest predation; and 2) for some species, brood parasitism by the Brown-headed Cowbird (*Molothurus ater*). These two processes are strongly influenced by edge effects at the local habitat scale, and evidence is mounting that their expression at the local scale is constrained by factors acting at landscape and perhaps biogeographic scales. Using data on Ovenbird (*Seiurus aurocapillus*) nesting success collected from 15 sites scattered across the eastern United States we assess: 1) the relationships between forest fragmentation and nest parasitism and predation; and 2) how these relationships vary with the scale at which habitat fragmentation is assessed. We found strong evidence that factors associated with predator/parasite population regulation at landscape scales constrain the processes of nest predation and parasitism acting at the habitat patch scale. We highlight the importance of considering the effects of forest fragmentation on patch-specific demography within a top-down spatial hierarchy that includes biogeographic effects, landscape-level area effects, and patch-level edge effects.

15. SCALING ISSUES IN MAPPING RIPARIAN ZONES WITH REMOTE SENSING DATA: QUANTIFYING ERRORS AND SOURCES OF UNCERTAINTY
Thomas P. Hollenhorst, George E. Host and Lucinda B. Johnson

The fine-scale variation of land cover in riparian zones poses a challenge for the mapping and analysis of riparian systems, particularly in agricultural landscapes where riparian zones are often narrower than the resolution of standard land cover data sets. We conducted a comparative analysis of the Landsat-based National Land Cover Database (NLCD) with a high-resolution aerial photograph classification to 1) quantify errors and sources of uncertainty in the use of NLCD data for mapping riparian conditions, 2) assess scaling effects related to data grain and extent, 3) compare scaling effects in stream vs. wetland riparian ecosystems, and in densely agricultural vs. more diverse landscapes. We found that landscape context matters; NLCD interpretations of land cover near streams greatly overestimate rowcrop agriculture, particularly in heavily agricultural landscapes. Differences between the aerial photo and NLCD data converge as buffer distances from the wetland and stream increase, but the residual differences at distances of 500 m are still significant and may lead to uncertainty in model predictions. While NLCD and other satellite-derived land cover products remain important tools for researchers and modelers, they must be used with caution when addressing fine-scale landscape structures.

16. SCALE ISSUES IN LAKE/WATERSHED INTERACTION: ASSESSING SHORELINE DEVELOPMENT IMPACTS ON WATER CLARITY
Carol A. Johnston and Boris A. Shmagin

Land use restrictions limit human activities within the shoreland zone adjacent to lakes in several states, with the assumption that perturbations proximal to the lake have the greatest effect on water quality. This case study examined lake, shoreland, and watershed properties to assess the relationship between development and the condition of lakes in Minnesota's Northern Lakes and Forest Ecoregion. The analysis of scaling effects was not an *a priori* goal of this research, but scaling issues emerged as unanticipated findings of the research. Independent variables measured at one scale often seemed to indicate processes occurring at a different scale. For example, lake depth is a lake-scale measurement, but can be an indicator of regional ground-water inputs. The proportion of mining land use in the shoreland zone also appeared to be an indicator of regional ground-water inputs, because it was associated with deep mine pit lakes that had filled with clear ground water. Average watershed slope is a watershed-scale measurement, but in northeastern Minnesota it appeared to indicate a larger underlying geomorphic region associated with very clear lakes. Discovery of these relationships required critical examination of the results with a knowledge of lake-scale limnological processes and regional-scale hydrology and geology.

17. SCALING AND UNCERTAINTY IN REGION-WIDE WATER QUALITY DECISION-MAKING
Orie L. Loucks, Harry J. Stone, and Bruce M. Kahn

In this paper we consider scaling as it relates to policy-development processes and decision-making, linking the work to ecological process scaling where possible. Unlike ecological systems, however, state, federal and local regulatory decision-making is bounded by historical precedents and legal jurisdiction issues associated with the responsibilities of each level of government. We do not focus initially on any one scale as being more important than others, but on scaling as understanding and analysis of the flow of information, influence, and control across scale. Thus we consider scaling of ecological systems, such as watersheds, along with scaling among levels of governmental institutions and public policy systems. Our hypothesis is that hierarchical flows of information across scale determine policy and decision outcomes by modifying institutional power structures at local to national scales. In this model, scaling influences institutional responses at either or both the next lower and the next higher level. Two case studies are summarized, from which we learn to expect uncertainty in both ecological system scaling and from problems in policy system scaling. We also see a pattern of adaptive change in the institutions managing resources, change that is brought about in large part by information flows across scales. The Big Darby case study demonstrates the principle that a hierarchy in ecological scale, seen in watershed systems, is associated with a hierarchy in decision-making and concomitant power. Perhaps most important, this review shows that understanding who benefits and who loses among federal, state and local stakeholders after certain decisions are made is critical for appreciating the outcomes, often referred to as the public interest.

PART III: Synthesis

18. SCALING WITH KNOWN UNCERTAINTY: A SYNTHESIS
Jianguo Wu, Harbin Li, K. Bruce Jones, and Orie L. Loucks

The previous chapters have demonstrated an immerse diversity of scaling issues present in different areas of ecology, covering species distribution, population dynamics, ecosystem processes, and environmental assessment. Scale issues occur in every facet of ecological research, including study design, data collection, experimentation, statistical analysis, and modeling. The scales of observations and outcomes in the case studies range from plots, local ecosystems, landscapes, to regions. Readers will surely ask then, what new synthesis can be achieved from these and other recent contributions to the literature on scale? We see several overarching themes evident in the theory, methods, and case studies presented here, not necessarily in every chapter, but from the body of work as a whole. The following themes are illustrative: novel ideas for integrating diverse scaling perspectives, distinctions among sources of uncertainty, advances in the quantification of scaling error, improved applications of scaling principles, improved recognition of the phenomenon of scale effects (especially for cross-scale material exchange of chemicals, gases, etc.), and advances in the use of scale-related understandings for public policy and decision-making.

Taken together these themes can be understood and organized by thinking through three closely related scale issues: identifying characteristic scales, understanding scale effects, and developing methods for scaling and quantifying sources of error in relation to uncertainties. In this last chapter of the book, we attempt to build from the richness of the methods and case studies toward an integration of the entire volume. To do this we briefly recapitulate scale and scaling concepts, summarize how different kinds of scale issues are dealt with in the chapters, and present a synthesis in the form of a pluralistic scaling paradigm. In the end, we conclude with some general guidelines for scaling.