CHAPTER 18

SCALING WITH KNOWN UNCERTAINTY:

A Synthesis

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18.1 INTRODUCTION

Scale is a fundamental concept in ecology and all sciences (Levin 1992, Wu and Loucks 1995, Barenblatt 1996), which has received increasing attention in recent years. 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, 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

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chapters, and present a synthesis in the form of a pluralistic scaling paradigm. In the end, we conclude with some general guidelines for scaling.

18.2 WHAT HAVE WE LEARNT ABOUT SCALE AND SCALING?

In the past two decades, scale and scaling have become a central issue in biological and earth sciences. While many concepts exist, a comprehensive conceptual framework of scale and scaling is still lacking. To address this gap we first need to answer the question, what do authors really mean by "scale" and "scaling?"

Diversity of concepts is not necessarily a problem in development of a new area of science or discipline, but divergence of concepts without addressing a common set of key questions can be a profound problem (Wu and Hobbs 2002). The issues may be manageable when the same terms have been used with only small differences in connotations across disciplines, but major problems arise when the terms are used without clear definitions. To achieve a comprehensive understanding of scale issues, therefore, the full range of concepts relating to scale and scaling in ecology need to be compared and contrasted in a coherent framework. This has not always been accomplished in the chapters of this book, but it is one of the main objectives of the book.

Chapter 1 introduced the definitions of scale and scaling used in disciplines ranging from physical to social sciences, and proposed a three-tiered conceptual framework: dimensions, kinds, and components of scale. Space, time, and levels of organization are the three common dimensions in discussion of scale issues, evident in many of the proceeding chapters. Although there are general scaling rules common to the three dimensions, the behavior of one phenomenon across scales may differ significantly when examined in each of these dimensions. Time and space emerge as the most fundamental dimensions for scaling. Scaling across hierarchical or integrative levels of organization, which inevitably involves change in time and space, is also important in many studies. As hierarchy theory suggests, response patterns at higher levels of organization tend to be massive and slow, while phenomena at lower levels tend to be fine-grained and fast. Thus, scaling in the three dimensions can be related to one another through space-time correspondence principles along with hierarchy theory. As shown in the case study chapters, observational, experimental, modeling and policy scales can all be distinguished from the intrinsic scale of a phenomenon within each dimension. Each different kind of scale has its own meaning, as determined by a variety of factors, and these do not necessarily correspond to the intrinsic scale of phenomena. In the practice of scaling, or to develop quantitative relationships across scales, the components by which scale is defined (e.g., extent, grain, and coverage) also have to be specified.

Ecological scaling as the study of organism-based allometry has existed for several decades, but the recent burst of interest in spatial scaling coincided with the rapid development of landscape ecology in the past two decades. While the term, scale, has acquired a score of connotations in different sciences, the early definition of scaling used in physics and biological allometry has proven to be too narrow for development of a science of scaling in ecology. Our search of papers on scaling

published in Nature and Science (using the ISI Web of Knowledge^{SM}) has shown that nearly all of them deal with power-law scaling one way or another. However, a review of the ecological literature and of the chapters in this book indicates that scaling is more than the search for power laws or systematic size relationships. These sources show that ecological scaling includes, but is more than, organism-centered allometric studies. Scaling is generally defined as the translation of information across spatial, temporal, and organizational scales in this book.

This general definition of scaling neither prescribes its goal as the search for power-law relationships, nor as documentation of narrowly-defined scale-invariant phenomena. This synthesis chapter, therefore, adopts the above broad definition of scaling, with emphasis on the translation of information across space. Why is this broad definition necessary? As the previous chapters have shown, ecological patterns and processes can be related in a number of different ways across scales, and pluralistic theories and methods will be needed to discover them. Power laws are elegant and compelling when they are found to exist, but most scaling issues in practice cannot be equated to a search for such simplistic relationships (see also the next section). Accordingly, a range of scaling methods have been developed in the case studies to deal appropriately with the broad range of scaling problems encountered.

18.3 DEALING WITH SCALE ISSUES

Current literature in ecology, and in this book, requires that three types of scale issues be distinguished: characteristic scales, scale effects, and scaling and associated uncertainty. The chapters of this book have dealt with these issues through a variety of objectives and from different perspectives, as illustrated by the summary in Table 18.1. In this section, we provide a systematic overview of how these three types of scale issues have played out, using material from the chapters as well as from recent literature on scale and scaling.

18.3.1 Characteristic Scales

Characteristic scales are "intrinsic scales" on which phenomena of interest operate, and thus are central to description and understanding of the phenomena (Wu and Li, Chapter 1). Characteristic scales are intrinsic because they are inherent to the system to be observed and do not change at the pleasure of the observer. However, because they are usually determined through observation and analysis, characteristic scales have the possibility of being distorted or misrepresented, which leads to the problem of scale mismatch between the intrinsic and observed scale. In general, fine-grained sampling schemes tend to generate data that blur coarse-scale patterns (i.e., high noise/signal ratio), whereas coarse-grained sampling schemes will surely miss fine-scale patterns. Thus, in any study it is critically important to choose a scale that is commensurate with the characteristic scale of the phenomenon of interest based on relevant empirical knowledge or through an exploratory scale analysis.

Table 18.1. *Major objectives, system properties, scale domains, and scaling issues covered in each chapter of the book.*

Chapter	*Main Objectives*	*System Properties*	*Scale Domain*	*Scaling Issues*
1	• to review the concepts of scale and scaling and propose a three-tiered conceptual framework	• generic	• all scales	• concepts and definitions • characteristic scales • scale effects • scaling
2	• to review perspectives and methods of scaling in different disciplines	• generic	• all scales	• scaling theory and principles • upscaling methods • downscaling methods • problems and prospects
3	• to review major methods in uncertainty analysis as applied in ecology and earth sciences	• generic	• all scales	• concepts of uncertainty • sources of uncertainty • methods for estimating upscaling errors
4	• to develop new multilevel statistical models to link ecological variables at different scales	• generic	• local ecosystem to region	• hierarchical scaling • cross-scale relationships linking multiple organizational levels • characterizing uncertainty at different levels
5	• to develop new statistical methods to link distribution and abundance estimates of tree species	• distribution and abundance of species	• local community to landscape	• downscaling • estimating species abundance based on presence/absence data • uncertainty estimation using variance in specie detectability
6	• to compare and contrast intact and model experimental systems for upscaling biogeochemical processes	• biogeochemical processes in ecosystems	• controlled environment • ecosystem or landscape	• upscaling with experiments in space and time • internal validity vs. external validity • upscaling uncertainties with experiments

Table 18.1 (contd.)

Chapter	*Main Objectives*	*System Properties*	• *Scale Domain*	*Scaling Issues*
7	• to discuss an upscaling framework for estimating aboveground net primary production and associated uncertainties	• carbon dynamics • aboveground net primary production	• landscape or region	• upscaling as spatial extrapolation • spatial modeling • reducing scaling uncertainty by spatially decomposing heterogeneous landscapes
8	• to examine the methods and problems of upscaling with remote sensing	• land surface characteristics • remote sensing • biophysical variables	• landscape, region, or beyond	• upscaling with remote sensing • uncertainties due to heterogeneity and nonlinearity • aggregation error • scale effects
9	• to demonstrate a spatially explicit upscaling approach using field observations, remote sensing tools, and a biogeochemistry model	• carbon pools • fluxes • net ecosystem production	• landscape or region	• characteristic scales • upscaling using a spatially nested hierarchy • estimating uncertainty at different spatial scales
10	• to explore challenges and solutions in upscaling nitrogen gas fluxes in landscapes	• nitrogen gas fluxes in ecosystems • landscape-scale variability	• watershed or landscape	• characteristic scales • spatial upscaling with "representative fluxes" and ecosystem modeling • temporal scaling of nitrogen fluxes • sources of uncertainties
11	• to relate stream nitrogen concentrations to regional atmospheric nitrogen deposition, watershed-level land surface characteristics, and within-riparian-zone land cover composition	• total stream nitrogen • biophysical factors at local, watershed, and regional scales	• landscape or region	• characteristic scales • linking biophysical variables at different scales • scaling functions • sources of uncertainty • estimating uncertainty using variance measures

Table 18.1 (contd.)

Chapter	*Main Objectives*	*System Properties*	*• Scale Domain*	*Scaling Issues*
12	• to examine scaling relations of nutrient export to watershed resolution	• nitrogen and phosphorous export from watersheds	• watershed or landscape	• scale effects • scaling relations • quantifying scaling errors
13	• to explore uncertainty issues in integrated, regional-scale assessments using coupled models (meta-models)	• land use change • bird population dynamics	• landscape or region	• upscaling through coupling models at different scales • sources of uncertainties • quantifying uncertainties
14	• to assess scale dependence of relationships between avian nesting success and forest fragmentation	• fragmented forests • bird population dynamics	• landscape or region	• characteristic scales • scale effects • cross-scale relationships • scale-related uncertainties
15	• to quantify scale effects and uncertainties in mapping riparian zones	• agricultural landscapes • riparian systems	• landscape or region	• scale effects • scaling relations • errors in mapping and classification
16	• to explore scaling issues in assessing relationship between lake water quality and lakeshore development	• lake and watershed interactions • water clarity	• watershed or region	• characteristic scales • scale effects • between-scale influences
17	• to examine scaling issues in decision-making processes on water quality through a hierarchy of institutions	• water quality • resource planning and policy • decision-making hierarchies	• watershed or region	• characteristic scales • hierarchical scaling in policy-development and decision-making • relationships between ecological and geopolitical scaling • sources of uncertainty
18	• to provide a synthesis of the book	• generic	• all scales	• characteristic scales • scale effects and scaling in general

Different scales of observation or policy-making may lead to disparate outcomes (see, for example, Wessman and Bateson, Chapter 8, Groffman et al., Chapter 10, Loucks et al., Chapter 17). Indeed, scale mismatching may have been one of the most common problems in ecological studies. Such problems may be a consequence of a flawed study design in which mismatches between different kinds of scale (intrinsic, observational, experimental, analytic, modeling, and policy scale) are encountered. This situation is also an example of scale effects, which will be further discussed. Therefore, to describe and understand a given phenomenon, there may be no single correct scale (Levin 1992, Wu and Levin 1994), but there are certainly scales that are more revealing than others.

The idea of characteristic scale appears to be at odds, however, with the often misinterpreted prevalence of scale-invariant phenomena in nature, inferred frequently from theories such as fractal geometry and self-organized criticality (e.g., Bak 1996). Recent studies based on these theories have claimed that ecological systems are characterized by self-organized criticality and self-similarity, and exhibit scale invariant patterns over several to many orders of magnitude (e.g., Bak 1996, Jørgensen et al. 1998, Sole et al. 1999, Brown et al. 2004). However, others have pointed out that some of these analyses were problematic because of misinterpreting ecological data or overreaching from the results (e.g., Raup 1997, Kirchner and Weil 1998, Dodds et al. 2001, Plotnick and Sepkoski 2001, Cyr and Walker 2004). Studies of both biophysical and socioeconomic systems have shown much evidence that complex systems often exhibit both scale-dependent behaviors and characteristic scales (Clark 1985, Courtois 1985, Urban et al. 1987, Delcourt and Delcourt 1988, Holling 1992). Such findings are consistent with the prediction from hierarchy theory that patterns and processes in complex systems tend to have distinctive characteristic scales, through both internal self-organization and multiple-scale external constraints (O'Neill et al. 1986, Schweitzer 1997, Wu 1999). Several chapters of this book also provide evidence to support the presence of distinctive characteristic scales, illustrated in the context of carbon cycling (Law et al., Chapter 9), nitrogen fluxes (Groffman et al., Chapter 10), avian population dynamics (Lloyd et al., Chapter 14), lake-watershed interactions (Johnston and Shmagin, Chapter 16), and policy-making processes (Loucks et al., Chapter 17).

In reality, neither all patterns and processes always have a clearly identifiable hierarchical structure, nor do they all exhibit scale-invariant behavior. These two perspectives should be viewed as complementary, rather than opposing to each other. For example, as discussed by Wu and Li (Chapter 2), extrapolation along a scaling ladder (or the hierarchical patch dynamics scaling approach) integrates both perspectives. Dealing with scale issues requires as much appreciation of scale-dependent phenomena as seeking scale-invariant instances. For either one, the kinds of phenomena and the ranges of scale (or scale domains) in which scale-dependence or scale-invariance occurs must be specified if the higher-level, comprehensive integration is to be achieved. The existence of characteristic scales suggests that scale analysis should be a necessary first step in dealing with complex phenomena (Levin 1992, Wu and Loucks 1995). Numerous landscape metrics and spatial statistical methods can be used for this purpose (Turner et al. 2001). Jones et al. (Chapter 11) provides an example of using classification and regression trees

(CART) to analyze relationships between total stream nitrogen and its controlling variables at local riparian, watershed, and regional scale. While multiple-scale dynamic models are commonly used for this purpose (Wu and Li, Chapter 2), statistical methods such as multilevel statistical models (Berk and Leeuw, Chapter 4) may also be effective in identifying and linking characteristic scales.

18.3.2 Scale Effects

Scale effects occur whenever changes in the scale of observation, analysis, modeling, or experimentation lead to changes in the results of a study. The idea of characteristic scales suggests that scale effects are bound to occur whenever the scale of observation involves a mismatch with the intrinsic scale of a phenomenon. Such effects, although generally expected, may not be specifically predictable. In contrast, theories of scale-invariance and self-similarity tend to imply that scale effects either do not occur or can be readily predicted mathematically. Empirical studies have shown that scale effects may result in inaccurate classifications or distorted maps (see Wessman and Bateson, Chapter 8 and Hollenhorst et al., Chapter 15), and altered or erroneous statistical and modeling results (see Jones et al., Chapter 11, Wickham et al., Chapter 12, Lloyd et al., Chapter 14, Johnston and Shmagin, Chapter 16). Bradford and Reynolds (Chapter 6) show that, in experimental studies, scale effects may be more common than ecologists tend to admit when microcosms or artificial systems are used to mimic natural systems. In this case, a crucial issue at stake is the tradeoff between the internal and external validity of experiments (Naeem 2001). Thus, scale effects do seem often to impede our ability to accurately interpret the results of a study, be it observational or experimental, and add to the uncertainty of scaling operations. In general, an increase in grain size may lead to lower variability in system variables due to averaging or smoothing effects, while an increase in extent may lead to higher variability due to the inclusion of more diverse conditions.

The studies in this book and elsewhere show that scale effects are pervasive in natural and social systems, and commonly found in basic research studies as well as in policy-making and political processes (Loucks et al., Chapter 17). It is interesting to note the problem of gerrymandering, dating from more than a hundred years ago, as an example of scale effects as well as the interaction between observational science and social and political processes. Elbridge Gerry (1744-1814), the governor of Massachusetts from 1810 to 1812, signed a bill into law that redistricted the state allegedly to benefit his Republican Party in elections. As a result of the redistricting, one of the congressional districts was shaped like a salamander, and the term gerrymander was derived from the two words: Gerry and salamander (http://webster.com/). The purposeful manipulation of the local boundaries of electoral districts (i.e., changing grain size and configuration) altered the outcome of an election process at a larger scale. Scale effects have long been studied in human geography as part of what has been known generally as "the modifiable area unit problem" or MAUP (Openshaw 1984). Although MAUP studies clearly are relevant to understanding scale effects and space-scale interactions in general, the subject has generally been ignored in ecological literature until recently (Jelinski and Wu 1996).

In parallel, plant community ecologists have long studied the effects of changes in sample size and position on vegetation pattern results from field surveys. The diversity of studies on scale effects in the previous chapters demonstrates that, today, most ecologists are aware of these effects. However, no discipline outside landscape ecology, which focuses on the relationships among pattern, process, and scale (Turner et al. 2001, Wu and Hobbs 2002), has placed more emphasis on understanding scale effects.

Of course, scale effects may also be artifacts if the scales of study are entirely arbitrary, in which case the actual patterns and processes become distorted. When the scales of study are determined based on understanding of the phenomena of concern, however, observed scale effects can be used to improve understanding of scaling relationships and the accuracy of scaled outcomes (Jelinski and Wu 1996, Wu 2004). Hence, future studies of scale effects will have to move beyond merely reporting their occurrence to focus work on the development of more sophisticated scaling relations and scale-dependent understanding (Wu 2004).

18.3.3 Approaches to Scaling

As the previous chapters have shown, scaling has become an increasingly important element of ecological research. While ecologists are among those who are most aware of scale issues, most scaling theories and methods have originated in physics, meteorology, and hydrology, and some of these methods have remained underutilized in ecology. Chapters 1 and 2 have reviewed the full range of scaling methods, breaking them into two complementary general approaches according to their conceptual foundations: the similarity-based scaling approach, widely used in geophysical and biological sciences, is rooted in the idea of similitude or self-similarity, whereas the dynamic model-based approach includes scaling methods that emphasize processes and mechanisms. Similarity-based scaling methods may start with first principles and proceed deductively with mathematical analysis (the analytical approach), or seek scaling relations inductively with statistical regressions (the empirical approach).

For similarity-based scaling, methods available from current literature and the earlier chapters include dimensional analysis, similarity analysis, biological allometry, and spatial allometry, all of which draw on the principles of similarity (geometric, physical, and functional) and self-similarity (fractal scaling). Dimensional and similarity analysis are fundamental to modeling and scaling in general, but we have not yet seen how effective these methods are for complex ecological and socioeconomic processes that are not explained well by physical laws alone. Biological allometry, where the techniques of dimensional and similarity analysis are invoked often, has dominated the literature in "ecological scaling" for many years. However, organism-based allometric scaling may have little relevance for spatial scaling problems, unless space can be incorporated into the scaling relation through, for example, population density or home range. In contrast, spatial allometry relates ecological variables directly to spatial scale, facilitating cross-scale predictions when the domains of applicability can be determined. While this book is

not focused on the similarity-based methods, a review of them, as used in biology and geophysical sciences, has been provided by Wu and Li in Chapter 2.

Dynamic model-based scaling includes explicit upscaling and downscaling methods. Wu and Li (Chapter 2) review several upscaling methods used in ecology and geophysical sciences, including extrapolation by lumping, extrapolation by effective parameters, direct extrapolation, extrapolation by expected value, explicit integration, spatially interactive modeling, and hierarchical scaling. A major difference among these methods lies in how spatial heterogeneity is treated in the model-based scaling procedure. Extrapolation by lumping essentially ignores spatial heterogeneity, and is more likely to produce results with high uncertainty. Extrapolation by effective parameters treats spatial heterogeneity in an aggregated way, and has had success in hydrology and meteorology. It may be equally useful in scaling up population and ecosystem processes in situations where the procedures for deriving effective parameters are applicable. Both direct extrapolation and extrapolation by expected value treat spatial heterogeneity in explicit ways, and are widely used methods in ecology and earth sciences. Explicit integration, although probably the most elegant and accurate, is not generally practical. When horizontal flows, time delays, and feedbacks become significant and when spatial heterogeneity can no longer be decomposed discretely or characterized statistically, spatially interactive modeling may be the only sensible alternative.

The discussion by Peters et al. (Chapter 7) treats several upscaling methods in terms of their degrees of spatial explicitness (also see Peters et al. 2004). In their view upscaling methods are of three kinds: non-spatial, spatially implicit, and spatially explicit. The non-spatial method refers mainly to extrapolation by lumping; the spatially implicit method to direct extrapolation, and the spatially explicit method to spatially interactive modeling. These authors also illustrate how and when the different scaling methods should be used through an example of the extrapolation of net primary production in a desert landscape. We should note that the definition of "spatially implicit" in Chapter 7 (and also Peters et al. 2004) is different from that commonly used in ecology and earth sciences. Spatial explicit models usually refer to those that consider spatial interactions of processes of interest explicitly, or represent the spatial locations of model variables or parameters explicitly. Thus, extrapolation by lumping and extrapolation by effective parameters both are spatially implicit methods. Extrapolation by expected value incorporates spatial heterogeneity in terms of probability density functions and thus is quasi-spatial; direct extrapolation, explicit integration, and spatially interactive modeling are all spatially explicit methods. With rapidly increasing computational capabilities and available remote sensing data, direct extrapolation and similar methods are becoming the most widely used approach in landscape and regional case studies.

Although most of the chapters in this book deal with upscaling, Wu and Li (Chapter 2) reviewed the two major downscaling approaches: empirically-based statistical downscaling and downward nested modeling. In contrast with upscaling, downscaling seeks to derive detailed patterns within a spatial domain by disaggregating coarse-grained information. A number of sophisticated statistical and modeling techniques have been developed for downscaling the outputs of General Circulation Models (GCMs) from regions to local landscapes or ecosystems and for

estimating fine-scale patterns of hydrological and soil properties from coarse-grained information (see Chapter 2 and references therein). While many downscaling studies have been carried out in the context of global climate, hydrological, and soil sciences, He and Reed (Chapter 5) present a new downscaling method for a time-honored ecological problem–linking species distribution to abundance. Their statistical models, based on the combinatorial theory of occupancy, allow for estimation of the number of organisms (abundance) from species presence-absence maps (distribution). Not surprisingly, the accuracy of these models was found to decrease with decreasing map resolution, a manifestation of scale effects and a source of uncertainty. This method is similar to the statistical downscaling methods reviewed by Wu and Li (Chapter 2) in that they all assume some statistical distribution of the variable to be downscaled and then seek model parameters that satisfy the assumption. However, He and Reed's method (Chapter 5) is suited for discrete variables, whereas most other downscaling methods deal with continuous variables associated with hydrological, soil, and climatic processes.

Which of these scaling methods should be chosen for specific research problems in ecology? In practice, it is frequently the case that several different scaling methods are used together in a single study. This has been true of complex scaling projects that either cover a wide range of scales or consider a diversity of processes (Reynolds and Wu 1999, Wu 1999, Law et al., Chapter 9). Also, models that are spatially more realistic tend to have higher explanatory potential, but not necessarily higher predictive accuracy. For a particular scaling problem, therefore, one cannot expect a single best method or approach; some methods may be more effective and accurate for certain goals than others. Therefore, the choice of scaling methods should be resolved in relation to the purpose of the study, the acceptable level of uncertainty, and data availability. Multiple methods are usually preferred for purposes of comparison and confirmation.

18.3.4 Approaches to Uncertainty

No matter what scaling methods are used, uncertainty in scaling is inevitable due to spatial heterogeneity, nonlinear relationships, lack of reliable data, and problems in scaling techniques. All of these are illustrated by Peters et al. (Chapter 7) and Urban et al. (Chapter 13). However, uncertainty analysis, or accuracy assessment, has not consistently been a part of ecological scaling. In Chapter 3, Li and Wu have provided an overview of uncertainty analysis, focusing on the sources of uncertainty, evaluation of scaling algorithms, error propagation, and presentation of prediction accuracy. Uncertainty analysis should be regarded as an essential part of the scaling process because it provides critical information about confidence in the results and the adequacy of the models and algorithms used. The main purposes of uncertainty analysis, therefore, are to quantify the various sources, assess the effects of uncertainty on scaling results, and identify critical factors in models (see He and Reed, Chapter 5, Peters et al., Chapter 7, Law et al., Chapter 9, Urban et al., Chapter 13). The methods used for uncertainty analysis include probability theory, Taylor series expansion, Monte Carlo simulation, generalized likelihood uncertainty estimation, Bayesian statistics, and sequential partitioning.

Several of the earlier chapters provide examples of how to deal with scaling uncertainty. In particular, Peters et al. (Chapter 7) advocate a general approach to reducing scaling uncertainty by dividing a complex landscape into a number of regions for which different scaling methods are selected. The idea behind this approach is a spatial extension of the decomposability principle of hierarchy theory, and consistent with the hierarchical patch dynamics paradigm (Wu and Loucks 1995, Wu 1999). While Law et al. (Chapter 9), Groffman et al. (Chapter 10), Jones et al. (Chapter 11), Wickham et al. (Chapter 12), Lloyd et al. (Chapter 14), and Hollenhorst et al. (Chapter 15) estimate uncertainty using conventional measures such as standard deviations and variances, Urban et al. (Chapter 13) has explored new methods for estimating error propagation and communicating scaling uncertainty to scientists as well as landscape managers and planners. Given the increasing role of large-scale modeling and scaling in ecological research and environmental decision-making (e.g., Johnston and Shmagin, Chapter 16, Loucks et al., Chapter 17), the obligation to understand, report, and reduce uncertainties in scaling are becoming increasingly important.

18.4 TOWARDS A PLURALISTIC SCALING PARADIGM

Inevitably, one must ask now whether some overarching pattern is evident in the material just summarized. The reviews in Chapters 1 and 2 by Wu and Li show that scaling has often been associated with power laws, fractals, and self-organized criticality. Such scaling laws would be elegant and powerful for ecosystems and landscapes if they could be validated through empirical evidence. The recent resurgence of interest in biological allometry is epitomized by the development of a "metabolic theory of ecology" (Brown et al. 2004), which attempts to use organismal allometry with a temperature correction to predict "ecological processes at all levels of organization from individuals to the biosphere." Such grand theory based on first principles in physics, chemistry, and biology, would be eminently useful in ecological scaling, but skepticism and sharp criticisms are rooted in the dearth of empirical support, mathematical limitations, diminishing rigor at organizational levels beyond whole organisms, and an inability to deal with heterogeneous structures and transient dynamics (Dodds et al. 2001, Bokma 2004, Cyr and Walker 2004, Kozlowski and Konarzewski 2004). Can a pluralistic approach be an alternative?

Not all ecosystems and landscapes, or their properties, exhibit fractal characteristics, and "self-organized criticality is not likely to be a universal feature" (Levin 1999). In ecological systems, scale invariance may be common, but scale-dependence is ubiquitous. The previous chapters illustrate the complexity of scaling problems in ecology, and explain why holistic approaches have had limited scientific success, despite often appearing to be of high ecological relevance. At the same time, extreme reductionist approaches, although mechanistically appealing, often fail to resolve ecological problems that hinge on emergent properties, self-organization, and other nonlinear interactions. Ecologists have long called for an integration between the two kinds of approaches, and such an integration could be accomplished in the context of a pluralistic approach (McIntosh 1987, Wu and

Loucks 1995). A pluralistic scaling paradigm would be able to deal with the diverse problems of transferring information across the various kinds of scale. Such a paradigm is implied in the previous chapters as well as in other recent publications.

Pluralism does not mean an anarchic development of views and approaches free of an underlying common framework. As a scaling paradigm, pluralism accepts the organized diversity of scaling problems seen in the previous paragraphs, and discourages exaggeration of a monistic theory or methodology. It allows promoting of alternative but complementary perspectives arising out of interdisciplinary sources. A pluralistic scaling paradigm should start with the clearly defined concepts of scale and scaling that we have sought to provide here. It also reconciles their different connotations within and among disciplines.

The definitional hierarchy outlined in Chapter 1 can serve as a point of departure. Because human influences have become pervasive in all ecological systems, scaling over large areas requires considering explicitly how biophysical and socioeconomic processes interact at different but hierarchically inked scales. Thus, the pluralistic scaling paradigm is inherently interdisciplinary, integrating natural and social sciences. In it the two general scaling methodologies, the similarity-based and dynamic model-based approaches, can be brought together through a complementary, rather than an adversarial, conceptual framework. Hierarchy theory may provide such a scaling framework for both the natural and the social sciences (Wagenet 1998, Marceau 1999, Wu 1999, Haila 2002).

Because all environments have a hierarchical structure (MacArthur 1972), and because "space is inherently hierarchical" (Meentemeyer 1989), a hierarchical frame work for pluralistic scaling is not only intuitive but also captures the essential scale-dependent complexity of biophysical and socioeconomic systems. As a general strategy, the "scaling ladder approach" (sensu Wu 1999) provides general guidelines for decomposing heterogeneous landscapes or regions into nested spatial hierarchies, along which information can be transferred. The scaling ladder approach is based on the hierarchical patch dynamics paradigm (Wu and Loucks 1995) that integrates hierarchy theory with the patch dynamics perspective. The approach has proven useful in scaling landscape patterns and processes (Hay et al. 2001, 2002, Poole 2002, Wu and David 2002, Burnett and Blaschke 2003, Hall et al. 2004, Poole et al. 2004).

While scale-invariance may exist over broad geographic regions in some circumstances, most ecological patterns and processes show scaling thresholds at which abrupt changes in scaling relationships occur, corresponding to shifts in underlying mechanisms. In the hierarchical context of the scaling ladder approach, both similarity-based and dynamic model-based scaling methods are useful for transferring information between adjacent hierarchical levels (or scaling thresholds). To transfer information across a broad range of scales along the scaling ladder (e.g., from single leaves, canopies, ecosystems, landscapes, to regions or the entire biosphere), there may be more scientific justification and technical feasibility through use of a hierarchy of scale-specific models rather than single monolithic models with several hierarchical levels built in (Wu 1999). Such multiple-step procedures require novel model-linking techniques, including nested modeling and meta-modeling (e.g., Reynolds et al. 1993, Wu and David 2002, Urban et al., Chapter 13),

and combine both bottom-up and top-down conceptualizations. Because both ecological and socioeconomic systems are complex adaptive systems (Levin 1999), their structure and function can change in response to changing environments. Such responses need to be accommodated through pluralistic scaling. Accordingly, the structure of scaling ladders–patch hierarchies used for scaling particular ecological patterns and processes–may also change when the time horizon involved is much longer than the characteristic spatial and temporal scales of the phenomenon of interest.

18.5 CONCLUSIONS

Throughout this volume we have tried to view scaling consistently as the process of translating information across space, time, and organizational levels. Scaling is ubiquitous and of paramount importance in ecology. Although ecologists are acutely aware of such issues as characteristic scale and scale effects, the commonly used scaling methods have tended to be inadequate for dealing quantitatively with the spatial heterogeneity and nonlinearity embedded in ecological systems. While the availability of accurate multiple-scale data sets are, and will always be, crucial to successful scaling, we argue that a key impediment to be overcome now derives from the limited scaling methodologies currently in wide use in ecology. The field can benefit significantly from, and contribute to, the development of a coherent science of scaling by embracing a number of theories and methods from the physical and geophysical sciences, and moving forward with an ecologically comprehensive, pluralistic scaling paradigm.

We would fall short of a reader's expectations for a book on scaling if no guidelines for further development of scaling were offered. However, it is still difficult to provide a general "recipe" for scaling considering the idiosyncrasies of many specific scaling problems and the diversity of scaling methods available. Still, the following general guidelines, although by no means inclusive, should be useful for the practice of spatial scaling.

18.5.1 Some general principles for scaling

- The most effective scaling strategies are those that integrate bottom-up and top-down approaches through combining field observations, experimentation, with mathematical modeling. In developing models for scaling, bottom-up approaches supply mechanistic details, whereas top-down approaches provide constraints and boundary conditions.
- The relationships between pattern and process, be they physical, biological, or social, are multifaceted and scale-dependent. Only when pattern and process operate at similar time scales within the same geographic region, can they possibly have interactive relationships. If spatial patterns change much more slowly than the processes that influence them, then the relationship between pattern and process can be reduced to the one-directional effect of pattern on process. This general principle can be used as

a guide for simplifying ecological complexity during study design, and for coupling biophysical and socioeconomic patterns, processes and outcomes from scaling.

- The feasibility and accuracy of translating information across scales depend greatly on properly identifying scaling thresholds. Thus, scale analysis using landscape metrics and spatial statistics should be a first step in scaling. Key processes or variables with similar scales of variation should then be grouped, and examined for potential interactions within each group and for hierarchical linkages between different groups.
- Ecological systems can be considered spatially nested hierarchies *a priori*, or based on cross-scale analyses, which provide the context necessary for scale invariance to be properly interpreted. Nested hierarchies also facilitate mechanistically transferring information across multiple domains of scales.

18.5.2 Selecting appropriate methods for scaling

- Spatial heterogeneity is the most pervasive and critical factor to influence the process of scaling. Accordingly, quantifying spatial heterogeneity at multiple scales, whenever feasible, should be a priority in the early stage of a scaling study. This analysis may provide critical information for selecting appropriate scaling methods and reducing overall scaling uncertainty.
- Scaling methods have to be selected with sensitivity to particular study goals because they differ in efficiency and accuracy. Each is constrained by a different set of assumptions, data requirements, capabilities, and acceptable levels of uncertainty.
- Similarity-based methods, often relying on relatively simple statistics such as regression and correlation, can be quite useful for prediction and for suggesting possible underlying explanations for observed patterns. However, only dynamic modeling methods, based on processes and mechanisms, have the potential to achieve reliable predictions for evolving systems in changing environments.
- Most existing scaling methods operate only by not crossing scaling thresholds or organizational levels. Scaling across multiple levels of organization often requires a hierarchical approach. In particular, most models are scale-specific and should be used only within the domain of scales for which they are designed. Applying models outside their intended scale domains is expected to result in high uncertainties.

18.5.3 Scaling with known uncertainty

- Errors are bound to occur in scaling, and uncertainty analysis must be considered as an integral part of scaling because it provides critical information on the adequacy of models or algorithms used in the scaling process. Thus, it is not adequate simply to ask how to scale; rather, one needs to ask how to scale with known uncertainty.

- Scaling uncertainty comes from the model structure, parameters, driving variables, and scaling algorithms. Errors from these different sources may propagate to produce nonlinear effects on the accuracy of scaling results. Some uncertainties can be quantified and reduced (e.g., measurement and sampling errors); others can be quantified but are hard to reduce (e.g., natural variability in data); and still others may not even be quantifiable (e.g., model uncertainty). Wherever possible, one should identify and reduce the critical sources of errors.
- Scaling results should be presented along with uncertainty measures such as probability distributions, variance, coefficient of variation (CV), confidence levels, and root mean square error (RMSE). Predictions without accuracy information are of little value, and may even be misleading no matter how impressive the numbers appear to be.

The importance of scaling can hardly be overemphasized. Every time an average of some property is derived across space, time, or organizational levels, scaling is at work. The accumulation of our experience and knowledge is essentially a product of scaling. As ecologists, we must be more conscious about scaling and associated uncertainties. To better understand and manage the diversity and complexity of ecological systems, we need to make more efforts to develop a coherent science of ecological scaling. We certainly hope that this book will be able to help, in some ways, to achieve this goal.

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REFERENCES

Bak, P. 1996. How Nature Works: The Science of Self-Organized Criticality. Copernicus, New York.

Barenblatt, G. I. 1996. Scaling, Self-Similarity, and Intermediate Asymptotics. Cambridge University Press, Cambridge.

Bokma, F. 2004. Evidence against universal metabolic allometry. Functional Ecology 18:184-187.

Brown, J. H., J. F. Gillooly, A. P. Allen, V. M. Savage, and G. B. West. 2004. Toward a metabolic theory of ecology. Ecology 85:1771-1789.

Burnett, C., and T. Blaschke. 2003. A multi-scale segmentation/object relationship modeling methodology for landscape analysis. Ecological Modelling 168:233-249.

Clark, W. C. 1985. Scales of climate impacts. Climatic Change 7:5-27.

Courtois, P. J. 1985. On time and space decomposition of complex structures. Communications of the ACM 28:590-603.

Cyr, H., and S. C. Walker. 2004. An illusion of mechanistic understanding. Ecology 85:1802-1804.

Delcourt, H. R., and P. A. Delcourt. 1988. Quaternary landscape ecology: relevant scales in space and time. Landscape Ecology 2:23-44.

Dodds, P. S., D. H. Rothman, and J. S. Weitz. 2001. Re-examination of the "3/4-law" of metabolism. Journal of Theoretical Biology 209:9-27.

Haila, Y. 2002. Scaling environmental issues: problems and paradoxes. Landscape and Urban Planning 61:59-69.

Hall, O., G. J. Hay, A. Bouchard, and D. J. Marceau. 2004. Detecting dominant landscape objects through multiple scales: an integration of object-specific methods and watershed segmentation. Landscape Ecology 19:59-76.

Hay, G. J., P. Dube, A. Bouchard, and D. J. Marceau. 2002. A scale-space primer for exploring and quantifying complex landscapes. Ecological Modelling 153:27-49.

Hay, G., D. J. Marceau, P. Dubé, and A. Bouchard. 2001. A multiscale framework for landscape analysis: object-specific analysis and upscaling. Landscape Ecology 16:471-490.

Holling, C. S. 1992. Cross-scale morphology, geometry, and dynamics of ecosystems. Ecological Monographs 62:447-502.

Jelinski, D. E., and J. Wu. 1996. The modifiable areal unit problem and implications for landscape ecology. Landscape Ecology 11:129-140.

Jørgensen, S. E., H. Mejer, and S. N. Nielsne. 1998. Ecosystem as self-organizing critical systems. Ecological Modelling 111:261-268.

Kirchner, J. W., and A. Weil. 1998. No fractals in fossil extinction statistics. Nature 395:337-338.

Kozlowski, J., and M. Konarzewski. 2004. Is West, Brown and Enquist's model of allometric scaling mathematically correct and biologically relevant? Functional Ecology 18:283-289.

Levin, S. A. 1992. The problem of pattern and scale in ecology. Ecology 73:1943-1967.

Levin, S. A. 1999. Fragile Dominions: Complexity and the Commons. Perseus Books, Reading.

MacArthur, R. H. 1972. Geographical Ecology: Patterns in the Distribution of Species. Princeton University Press, Princeton.

Marceau, D. J. 1999. The scale issue in social and natural sciences. Canadian Journal of Remote Sensing 25:347-356.

McIntosh, R. P. 1987. Pluralism in Ecology. Annual Review of Ecology and Systematics 18:321-341.

Meentemeyer, V. 1989. Geographical perspectives of space, time, and scale. Landscape Ecology 3: 163-173.

Naeem, S. 2001. Experimental validity and ecological scale as criteria for evaluating research programs. Pages 223-250 *in* R. H. Gardner, W. M. Kemp, V. S. Kennedy, and J. E. Petersen, editors. Scaling Relations in Experimental Ecology. Columbia University Press, New York.

O'Neill, R. V., D. L. DeAngelis, J. B. Waide, and T. F. H. Allen. 1986. A Hierarchical Concept of Ecosystems. Princeton University Press, Princeton.

Openshaw, S. 1984. The Modifiable Areal Unit Problem. Geo Books, Norwich.

Peters, D. P. C., J. E. Herrick, D. L. Urban, R. H. Gardner, and D. D. Breshears. 2004. Strategies for ecological extrapolation. Oikos 106:627-636.

Plotnick, R. E., and J. J. Sepkoski. 2001. A multiplicative multifractal model for originations and extinctions. Paleobiology 27:126-139.

Poole, G. C. 2002. Fluvial landscape ecology: addressing uniqueness within the river discontinuum. Freshwater Biology 47:641-660.

Poole, G. C., J. A. Stanford, S. W. Running, C. A. Frissell, W. W. Woessner, and B. K. Ellis. 2004. A patch hierarchy approach to modeling surface and subsurface hydrology in complex flood-plain environments. Earth Surface Processes and Landforms 29:1259-1274.

Raup, D. M. 1997. A breakthrough book? Complexity 2:30-32.

Reynolds, J. F., and J. Wu. 1999. Do landscape structural and functional units exist? Pages 273-296 *in* J. D. Tenhunen and P. Kabat, editors. Integrating Hydrology, Ecosystem Dynamics, and Biogeochemistry in Complex Landscapes. Wiley, Chichester.

Reynolds, J. F., D. W. Hilbert, and P. R. Kemp. 1993. Scaling ecophysiology from the plant to the ecosystem: a conceptual framework. Pages 127-140 *in* J. R. Ehleringer and C. B. Field, editors. Scaling Physiological Processes: Leaf to Globe. Academic Press, San Diego.

Schweitzer, F., editor. 1997. Self-Organization of Complex Structures: From Individual to Collective Dynamics. Gordon and Breach Science Publishers, Amsterdam.

Sole, R. V., S. C. Manrubia, and P. Bak. 1999. Criticality and scaling in evolutionary ecology. Trends in Ecology and Evolution 14:156.

Turner, M. G., R. H. Gardner, and R. V. O'Neill. 2001. Landscape Ecology in Theory and Practice: Pattern and Process. Springer-Verlag, New York.

Urban, D. L., R. V. O'Neill, and H. H. Shugart. 1987. Landscape ecology. Bioscience 37:119-127.

Wagenet, R. J. 1998. Scale issues in agroecological research chains. Nutrient Cycling in Agroecosystems 50:23-34.

Wu, J. 1999. Hierarchy and scaling: extrapolating information along a scaling ladder. Canadian Journal of Remote Sensing 25:367-380.

Wu, J. 2004. Effects of changing scale on landscape pattern analysis: scaling relations. Landscape Ecology 19:125-138.

Wu, J., and J. L. David. 2002. A spatially explicit hierarchical approach to modeling complex ecological systems: theory and applications. Ecological Modelling 153:7-26.

Wu, J., and R. Hobbs. 2002. Key issues and research priorities in landscape ecology: an idiosyncratic synthesis. Landscape Ecology 17:355-365.

Wu, J., and S. A. Levin. 1994. A spatial patch dynamic modeling approach to pattern and process in an annual grassland. Ecological Monographs 64(4):447-464.

Wu, J., and O. L. Loucks. 1995. From balance-of-nature to hierarchical patch dynamics: a paradigm shift in ecology. Quarterly Review of Biology 70:439-466.