INTRODUCTION

Scale, Multiscaling, Remote Sensing, and GIS

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THE IMPORTANCE OF SCALE

Of all words that have some degree of specialized scientific meaning, *scale* is one of the most ambiguous and overworked. Webster (Guralnik, 1974) devotes over half a column to the meaning of the noun, more even than the amount devoted to other similarly overworked terms like *space* and *system.* "Scale" is used to refer both to the magnitude of a study (e.g., its geographic extent) and also to the degree of detail (e.g., its level of geographic resolution). It is used in the context of space (geographic scale), time (temporal scale), and many other dimensions of research. At the same time, scale is undoubtedly one of the most fundamental aspects of any research. The world in which we live is intriguing at least in part because of its ability to reveal more detail almost *ad infinitum*; the closer we look at the world, the more detail we see. The inventions of the microscope and telescope helped to convince us of this, as did the advent of space exploration and satellite remote sensing in the 1960s.

Although the concept of scale can be applied more broadly, this book is primarily about geographic scale. Scale is an old topic, but surprisingly little has been written about it as a generic issue. There are extensive literatures on scale effects in particular disciplines (e.g., Rosswall et al., 1988; Schneider, 1994; Woodcock and Strahler, 1987; Robinson, 1950; Foody and Curran, 1994; Ehleringer and Field, 1993; Wessman, 1992). But recently the emergence and widespread use of geographic information technologies, including remote sensing and geographic information systems (GIS), has prompted interest in scale as a generic issue, and in the development and implementation of techniques for dealing explicitly with scale. Traditionally, the primary vehicle for storing, disseminating, and analyzing geographic data was the paper map. Paper maps portray the Earth's surface, and phenomena distributed on

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it, in a static, flat format with a constant or near-constant ratio between distance as measured between pairs of points on the map and distance as measured between the same pairs of points on the Earth's surface (the ratio known to cartographers as "scale"). But GIS in particular has opened the possibility for multiscale representations, and for databases that contain digital versions of the contents of many maps at different scales. Statistical and other techniques for dealing explicitly with scale are now widely available as functions implemented in GIS — and such implementations arouse interest in the possibility of approaching scale as a generic issue — a "science of scale."

Recently, the generic issues of geographic information, which include concepts of accuracy and error modeling, technical issues of data structures, and legal issues of liability, among many others, have been identified as key components of a geographic information science, defined as the systematic study of generic issues of geographic information. First suggested about five years ago (Goodchild, 1992), the term has gained some currency, and recently a University Consortium for Geographic Information Science (UCGIS; http://www.ucgis.org) was formed in the U.S.

Geographic scale is important because it defines the limits to our observations of the Earth. All Earth observation must have a *small* linear dimension, defined as the limiting spatial resolution, the size of the smallest observable object, the pixel size, the grain of the photographic emulsion, or some similarly defined parameter. Observation must also have a *large* linear dimension, defining the geographic extent of the study, project, or data collection effort. There are many ways of defining both parameters, and this is one of the factors contributing to the richness of the scale issue. The ratio of large to small is also an interesting parameter, since it often determines data volume, and is thus constrained by storage and processing capacities, particularly in the case of images of pixel arrays. A change of the small dimension implies a change in resolution, or metaphorically a movement of the observing eye toward or away from the surface.

Geographic scale is also important because it is often a parameter in the physical and social processes that shape geographic phenomena. A process whose outcome at a point depends only on the values of variables at that point merely inherits the patterns of spatial variability of its independent variables. But processes that depend on the values of variables at other points, and thus influences acting across space, reflect the ways in which influence responds to distance. For example, a new arrival in a city judges a neighborhood by averaging its qualities over a certain area, in a process that is thus similar to the ways plants integrate the properties of their physical environment as determinants of success. The distance–decay functions that characterize such processes have parameters expressed in linear geographic measure, and are mathematically similar to the functions one might use to filter or smooth geographic distributions, or to account for the blurring that occurs when the Earth is viewed from a distance. Thus from a mathematical perspective, models of the effects of scale on observation are similar to those of the effects of scale on processes, and are useful across the full range of human and physical processes.

Figure 1 (Delcourt et al., 1983) summarizes the view of scale prevalent in many environmental sciences, particularly ecology, where each major process operating on the landscape is believed to occur over a limited range of characteristic scales.

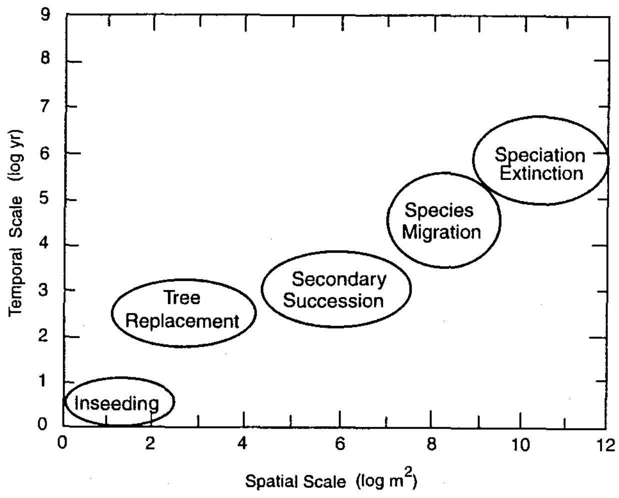

Figure 1 Forest demographic processes as functions of spatial and temporal scales. (Modified from Delcourt et al., 1983.)

A major proposition of hierarchy theory in ecology is that spatial and temporal scales tend to covary, as shown in the diagram — processes which operate over long temporal scales also operate over large spatial scales (long distances), in part because space and time are linked through transport mechanisms. But on the human side, transport mechanisms now include the ability to pass information across the entire surface of the planet in seconds, so one might speculate that the same covariation would be missing in modern social processes. Can't modern communication mechanisms sway large populations as quickly as small ones?

PERCEPTIONS OF SCALE

One of the problems in addressing the issue of scale is that its meaning varies so much between disciplines and communities, and its usage within any one discipline is largely tacit. To a landscape ecologist, scale might connote "grain," a measure of the sizes of the patches in a landscape fragmented into discrete habitats. To a cartographer, scale is defined simply as the ratio between distance on the map and distance on the ground — the usage is often qualified as "metric scale." The development of photographic reproduction and photocopying made it possible to change the ratio easily, and the move to digital representation of map contents complicated the issue further, since there is no distance to measure in a database. Today, the meaning of "scale" in a mapping context is largely a legacy of the earlier technology of paper maps. It helps to define content, since the scale of a paper map was often used as a surrogate for the types of features likely to be shown — a topographic map at a scale of 1:24,000 shows streets but not individual buildings. It also helps to define positional accuracy, since the National Map Accuracy Standards prescribe the positional accuracy of features as a function of map scale. Paradoxically, scale is still sometimes used as the effective surrogate for positional accuracy and content for many digital databases that never existed as paper products at any point in their history (the U.S. Geological Survey Digital Orthophoto Quads, for example, are said to have a "scale" of 1:12,000, as a way of stating that their positional accuracy is consistent with paper map products at that scale).

This issue is complicated further by the use of "scale" as a basic dimension of generalization. The world as mapped at 1:24,000 is more rugged, complex, and detailed than the world as mapped at 1:250,000. A larger scale map may show more instances of the same feature, or entirely different classes of features, and more detail in the features that are common to both scales. From a cartographic perspective, both representations are correct — the difference lies in the different specifications of feature types applied at each level. The case is often made that generalization adds information rather than reducing it, because some kinds of geographic information can only become apparent if the world is viewed from a distance. But to a scientist, the representation of topography at 1:24,000 is clearly more accurate than that at 1:250,000 — the effect of generalization is to introduce uncertainty into the representation of a real phenomenon that could only be mapped perfectly at a much larger scale. Even at 1:1, the representation would still only approximate reality because of measurement errors and the generalizations introduced by any representation of a real phenomenon, Lewis Carroll's story about the autocrat who demanded nothing less than a 1:1 map of his kingdom notwithstanding (Muehrcke and Muehrcke, 1974).

To most scientists, the term "scale" is likely to imply some aspect of the small linear dimension discussed above. For remote sensing data, a simple measure is available in the pixel size, although the size of the pixel's footprint on the Earth's surface can be only roughly constant because of orbital and optical effects, and the issue is complicated further by factors related to the instantaneous field of view (IFOV) of the sensing system which ultimately controls the minimum resolvable unit or resolution of the sensor. For other data types it may be more difficult to identify a single linear measure to characterize the observations. In climatology, for example, there is no obvious measure for the "scale" of an observation network, although there are many candidates, such as the mean distance to nearest neighbor, or the square root of the inverse of station density. For the data types variously known as "polygon coverages" or "area class maps," and characterized by the assignment of a single class to every point on the mapped surface (e.g., vegetation, soil, land cover, or surficial geology maps), there are many candidates and nothing approaching a consensus. The "minimum mapping unit" defines the smallest polygon the cartographer is willing to map (smaller polygons are forcibly merged with a neighbor), and its square root would be a linear measure, but it is often much coarser than the scale implied by the detail of the map's boundaries.

In summary, while the small linear dimension of spatial data "scale" is well-defined for some types of digital data, it is not at all well-defined for other types. We are entering an era where unprecedented data resources will be available through technologies like the Internet and the World Wide Web, and funding agencies are increasingly concerned that scientific Earth data collected at great expense be used effectively — yet we lack effective ways to describe one of the most basic dimensions of data in terms that are precisely meaningful to others.

To a decision-maker, the generalization associated with scale can be a way of obscuring information that is vital to a correct decision, particularly when information must be integrated from a number of sciences and sources. This can be particularly critical in studies that must combine data from the physical sciences in order to make decisions on a geographic basis defined by political units: trying to determine the impact of a flood modeled by a hydrologist on a human system defined in terms of settlements and counties, for example. Scale is also a determinant of cost in most situations, since detailed data is inevitably more expensive to collect, process, store, and analyze. Scale is often largely outside the control of the scientist, being determined during data collection activities that may have been designed for entirely different or generic purposes. The user of Landsat Thematic Mapper data, for example, is very unlikely to have had any say in the choice of 30-m resolution for its sensor, and users of hydrographic data may have had little to do with the choice of mapping scales or the positioning of measurement locations.

As science becomes more complex, data-dependent, and multidisciplinary, it is more and more important that we develop the tools and techniques needed to operate at multiple scales, to work with data whose scales are not necessarily ideal, and to produce results that can be aggregated or disaggregated in ways that suit the decision-making process. Long gone are the days when the scientist controlled the entire process of collection, interpretation, compilation, management, analysis, and modeling of the data needed to understand some particular branch of Earth science, or could afford to study the branch in isolation from other fields or from policy making. Contemporary science is constantly struggling with compromises, and the data available for particular projects rarely fit perfectly the scales at which the processes being studied operate, or the scales at which decisions are needed. Another constraint on scale comes from the limitations of computing resources, and forces global climate modelers, for example, to simulate climate at scales that are far too coarse to capture regional or local variations in topography, land cover, or other factors that are known to influence climate.

PROBLEMS OF SCALE

A full "science of scale" would seek answers to a host of interrelated questions, in the interests of providing a formal structure for the management and manipulation of scale. It would address:

- *Invariants of scale*: what measures of scale are invariant properties of the geographic detail in data that survive routine manipulations, such as the conversion from analog to digital form, or transformation of coordinates? What properties of physical and human systems are invariant with respect to scale?
- *The ability to change scale*: what kinds of transformations of scale are available, to aggregate or disaggregate data in ways that are logical, rigorous, and well-

grounded in theory? Can we develop a generic set of methods for disaggregating coarse data, and aggregating fine data, in ways that are compatible with our understanding of Earth system processes?

- *Measures of the impact of scale*: is it possible to implement methods that assess the impact of scale change, through measures of information loss or gain, for example? How is the observation of processes affected by changes of scale, and how can we measure the degree to which processes are manifested at different scales?
- *Scale as a parameter in process models*: how is scale represented in the parametrization of process models, and how are models affected by the use of data at inappropriate scales?
- *Implementation of multiscale approaches*: what is the potential for integrated tools to support multiscale databases, and associated modeling and analysis? Can tools provide a compatible framework for multiscale data? What are the problems that must be overcome in integrating data from different scales?

Partial answers to many of these questions already exist, but they are scattered throughout the disciplines, with little cohesion or integration. The integrated tools that do exist, GIS and image processing systems, for example, offer only limited capabilities for multiscale approaches. The commonly used raster-based GIS packages, such as GRASS, often require that the various layers in a GIS database all use exactly the same raster, with the same pixel size and study area. All aspects of a project must share the same large and small linear dimensions. But is it truly necessary to force all data to a single scale, with associated information degradation, or can we be more imaginative in constructing databases and analytic engines?

The chapters in this book range from case studies to systematic reviews of techniques, but all in one form or another address these and related questions about scale. This is at least in concept a "how to" book that provides both practical and theoretical approaches to the problems of relating, manipulating, and making sense of data obtained at different scales. Of course, there are no simple answers to the problems of scale, and there is no simple set of techniques waiting to be defined and implemented. It seems to us, however, that the problems of scale have reached a new plateau with the widespread development of geographic information technologies, and that these technologies hold at least part of the key to their solution, through the development of multiscale databases and integrated techniques for their manipulation.

The next section of this introduction takes the reader on a quick tour of the contents of the book, and explain how we have ordered the chapters to give a sense of a steady progression from encounters with the basic issues of scale to comprehensive theoretical approaches to their solution.

A TOUR OF THE CONTENTS

To begin, we have grouped four chapters that each provide an overview of the basic issues, and an illustration of how they have been approached in specific projects. Taken together, they illustrate both what people are prepared to agree on, in definitions of terms and the use of techniques, and also the degree of divergence that exists. One might think that the widespread adoption of GIS and related technology would have produced a convergence of terminology, but in practice the various developers and vendors of GIS have each chosen somewhat different solutions to the development of databases and GIS functionality. The lack of a consensus on terminology remained one of the field's most striking features and weaknesses.

Ling Bian (Chapter 1) begins with an analysis of the terminology of scale, identifying four common and distinct interpretations, and concluding that cartographic scale is both the best defined and the most studied. She discusses the use of aggregation to change scale, through the widely discussed practice of "scaling up." A case study of a multiscale database for Glacier National Park is used to illustrate many of these issues, and to introduce the types of data commonly encountered in environmental modeling, and for which scale is often well outside the researcher's control. Concepts of spatial autocorrelation are introduced as a basis for understanding the effects of scale, but fractals provide a more comprehensive framework for prediction of scale effects. Both of these themes are taken up at much greater length in later chapters.

Stephen Walsh and his co-authors (Chapter 2) follow with a more complex analysis based in the same geographic area and aimed at showing how GIS and remote sensing can be used to explore hypotheses about scale in the specific context of vegetation observed through NDVI (normalized difference vegetation index) measurements and its links to environment. The scale of environmental processes is often unknown, and must be inferred from geographically distributed phenomena, as measured by remote sensing — in other words, we must deduce parameters of process from form. A relatively simple way to do this is to explore how the relationship between two variables, which are known to be linked in a process sense, varies with scale, since one would expect that the relationship would be strongest at the scales at which the process operates. The authors illustrate this process using a multiscale database of Glacier National Park vegetation and related physical variables. They introduce a number of measures of pattern that can be computed from imagery and other spatial data sets, and show how their values can be expected to vary with scale.

We chose the third chapter in this set, by Changyong Cao and Nina Lam (Chapter 3), to help illustrate the generic nature of scale issues — that they apply both to social and environmental processes, and that much can be learned by attempting to bridge the human–physical divide. Social and economic data is often reported by arbitrarily shaped geographic divisions such as counties or census tracts that can vary enormously in size and shape, unlike the pixels used in remote sensing, but more like the divisions of space used to map soils or land cover. Although counties owe their origins to the dominance of agricultural areas by central market towns, with size determined by the willingness of farmers to travel long distances to market, the westward expansion of the U.S. and political fragmentation in the East have caused a variation in area between the largest and smallest U.S. county of many orders of magnitude; and in California, the variation in population between the largest and smallest counties is now over four orders of magnitude. If one analyzes data at the county scale, one is clearly not controlling scale in any well-defined way.

Cao and Lam review the social science literature on scale, and point to areas in which thinking on scale issues in social science might usefully inform other areas of science as well.

In Chapter 4, which completes this first set, Lee De Cola argues that scale is such a pervasive issue in analysis of spatial data as to require raising it to the level of a basic dimension, along with space, time, and theme. Although studies of a particular process may justifiably limit themselves to a single scale appropriate to the process, almost all uses of spatial data necessarily involve multiple processes, and thus multiscale approaches should be the norm. De Cola emphasizes the importance of multiscale visualization as a component of exploration and analysis of spatial data.

We grouped the next set of seven chapters to form a progression from environmental analysis to environmental modeling, and from local to global scales. Environmental science is served by remotely sensed data at a wide range of spatial resolutions, from the 1-m sensors likely to begin producing data in 1997 to the 1-km resolution of the Advanced Very High Resolution Radiometer (AVHRR) and even coarser resolutions of many meteorological sensors. The purposes to which sensors are put also vary widely, from largely descriptive mapping and monitoring to mathematically-based modeling in which the sensor acts essentially as a measuring instrument.

Ralph Dubayah, Eric Wood, and Daniel Lavallée (Chapter 5) begin the set with a study of soil moisture. They take us more deeply into fractals by describing how the scaling properties of fractals facilitate change of scale, by providing a mathematical framework for multiscale analysis; by exploiting scaling properties, it is possible for a process to be observed or modeled at one scale, and its statistical properties inferred at another. They illustrate these ideas with a case study of soil moisture modeling based on the ESTAR passive microwave instrument.

In Chapter 6, Mark Friedl introduces a truly multiscale simulation model of vegetation. The First ISLSCP Field Experiment (FIFE) was designed to explore the use of satellite remote sensing in understanding land surface climate, and explicitly addressed the need to combine data sources at widely different scales. To disaggregate data, Friedl uses a statistical simulation of spatial variation characterized by known spatial autocorrelation structures. In addition, correlation between spatial variables can be used to disaggregate one spatial variable if it is known to be correlated with another variable that is available at higher resolution. Friedl experiments with these methods over the Konza Prairie in Kansas, and shows how the results can be used to simulate relatively coarse resolution satellite data, and to study the propagation of errors in environmental models.

Janet Franklin and Curtis Woodcock help to move the focus from local to regional scale in Chapter 7, and provide a detailed discussion of the issues of scale in vegetation mapping. The hierarchies established by taxonomies and ecological processes are both expressed spatially, but in ways that are too complex to be expressed in simple spatial concepts of resolution or scale. An important question is whether the spatial expression of hierarchies results in nesting — do subdivisions nest within larger units? They illustrate these issues with data from a mountainous area in Southern California, and conclude that a multiscale approach has clear advantages

once it is recognized that every level in the hierarchy contains useful information for ecosystem management.

Chapter 8, by Jeff Luvall, addresses the issues of scaling up and down in the context of latent heat flux. He compares fine spatial resolution data collected from aircraft sensors to point measurements obtained on the ground, and finds that they are consistent except where modified by topographic effects. Such research allows for the estimation of fluxes at regional scales, and thus for their use in improving regional–scale estimates from global models. He also introduces a technique for relating thermal responses of different land cover characteristics at different scales.

In Chapter 9, Steven McNulty, James Vose, and Wayne Swank move to the regional scale of the southeastern U.S., in an application of an ecosystem process model (PnET-IIS) to predict forest hydrology and productivity at a range of scales from the forest stand to the region. Predictions were better at the coarser scales, deviating significantly from directly measured data at the smallest scales. They show how GIS can be used to support such multiscale analyses, and to make explicit tests of the influence of scale on model results.

Habin Li and James Reynolds (Chapter 10) describe a spatially explicit model of vegetation dynamics applied to rangeland. In spatially explicit models the scale of the process is determined by model parameters, in this case by the cell size used for the cellular automaton model, and by the rules that link changes in a cell's contents to the contents of its neighbors. They discuss how such models can be calibrated and validated, and address directly the need to relate process to spatial pattern, or form. They advocate the use of cellular automata at multiple scales to model the combined effects of the hierarchies of scale-dependent processes that affect ecological patterns.

In the final chapter in this group (Chapter 11), Ruth DeFries, John Townshend, and Sietse Los move the context to the global scale. Global climate models require information about the land surface, but are unable to accommodate land surface data at scales appropriate to the surface's inherent variability because to do so would be far beyond current storage and processing capacities — and such data would also be prohibitively expensive to collect. They discuss various solutions to this problem, and efforts under way to provide more suitable data sources. Experiments with African data are used to evaluate the effects of input data scale on the SiB model, but more studies are needed to determine if the results are specific to this region, and to resolve alternative explanations of the results.

Each of the first 11 chapters uses a case study to illustrate more general principles, and the approaches vary widely from simple, largely inductive analysis to more complex approaches grounded in a variety of theoretical frameworks. In the next group of two chapters, we have placed studies whose approach is more distinctly methodological, to provide a transition to the final group of four chapters that are strongly focused on specific methodologies. Studies of scale effects have access to a growing arsenal of techniques and theoretical structures, and among them we have already encountered fractals and various kinds of scale-based decomposition of variation. In the first of these two chapters (Chapter 12), Ferenc Csillag provides an overview of quadtrees, one of the more powerful ideas to emerge from the development of GIS and spatial databases over the past three decades, and ties it to techniques for hierarchical decomposition of variance, and to spatial statistics. The wavelet decomposition has recently attracted attention in image processing, and Csillag shows how it and similar ideas can be applied to the study of scale effects in geographic data. He argues that such structures provide a consistent, logical approach to multiscale modeling that is well grounded in theory and compatible with many ideas of physical process.

The second chapter in the pair, by Donald Myers (Chapter 13), makes an interesting contrast by looking at multiscale analysis from a statistical perspective, and introduces a general and powerful notation and analytic framework. For any set of spatial subdivisions, total variation can be partitioned into within- and between-division variation, allowing the behavior of standard statistics to be analyzed and general constraints established. Concepts of spatial dependence and correlation are critical in establishing these behaviors.

The final group of three chapters focuses on fractals, a theoretical framework that offers a rich series of models for the behavior of geographic data across scales, and prediction of scale effects. Dale Quattrochi and his co-authors (Chapter 14) begin the set with a description of ICAMS, a GIS for multiscale analysis of remote sensing data that integrates more generic, popular GIS software into a set of specialized functions. Many of the basic algorithms for fractal analysis and estimation of fractal dimension are included, and one very significant advantage of ICAMS's integrated approach is the ability to compare different methods of fractal analysis within a single framework.

Chapter 15, by Zong-Guo Xia and Keith Clarke, provides an extensive and detailed review of the literature on empirical analysis of data within the framework of fractals, and with an emphasis on analysis of terrain. Many methods are available, and the often unexplained variation in their results is a constant problem. The authors provide results that will be of value to researchers using fractal methods in many other contexts.

The last chapter, by Sean Pecknold and his co-authors (Chapter 16), takes the reader deep into the rapidly expanding literature of multifractals, a theoretical framework which attempts to account for systematic deviations between observed phenomena and the simple fractal model. Multifractal models provide a very general framework, by generalizing the notion of scale invariance, or the persistence of certain systematic properties as scale changes. Multifractals are substantially more challenging to the reader than simple fractals, which is one reason for our decision to place this chapter last; but in addition, we agree with the authors that multifractals hold great promise for systematic treatment of scale issues in multiscale, integrated GIS, although to date these techniques remain largely inaccessible to the average researcher.

FINAL COMMENT

We hope this introduction has given some pointers to how to navigate this book. We encourage readers to pick and choose, and to find their own paths through the chapters. The epilog which appears at the end of the volume gives us an opportunity as editors to reflect on the project as a whole, and to speculate on the directions that may emerge in the future as the disciplines concerned with the distribution of phenomena on the surface of the Earth learn to take advantage of the opportunities offered by new data sources and new computing technologies to master the problems raised by the scale dimension.

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