



# Does scale exist? An epistemological scale continuum for complex human–environment systems

Steven M. Manson

*University of Minnesota, Department of Geography, 414 Social Sciences, 267 – 19th Avenue South, Minneapolis, MN 55455, USA*

Received 21 February 2006; received in revised form 1 September 2006

## Abstract

Scale pervades interdisciplinary research on human–environment systems that exhibit hallmarks of complexity such as path dependence, nonlinearity, and surprise. Although scale concepts are woven through the data, methodology, and theory of human–environment research, the question remains: does scale exist? More broadly, can a single definition of scale suffice for human–environment systems? The meaning and use of scale is contested across the social, natural, and information sciences. Given that the study of human–environment systems spans many of these disciplines, specific research problems inherit a broad range of conflicting scale concepts. This paper proposes an epistemological scale continuum that arrays scale perspectives from the realist contention that there are natural scales independent of observers through to the constructionist view that scale is subjective and socially mediated. As seen in biocomplexity and human–environment research more broadly, this scale continuum establishes that scale is not a single measure or object of study, nor is any single definition of scale sufficient for human–environment systems. Viewpoints and tensions among scale epistemologies also suggest several general principles for using scale effectively in human–environment research.

© 2006 Published by Elsevier Ltd.

**Keywords:** Constructionism; Global environmental change; Realism; Scale

## 1. Does scale exist?

Scale is important to understanding complex human–environment systems, yet the very notion of scale is contested to the point where we can ask: does scale exist? An epistemological scale continuum is a useful rubric for reconciling scale concepts and expanding the explanatory power of scale. This continuum ranges from the realist contention that there are natural scales independent of observers to the constructionist argument that social forces actively manipulate scale and its underlying material basis. Understanding scale as an epistemological entity is important because it affects scientific research as such and the human–environment systems it studies. Close examination of the scale continuum, using examples from biocomplexity and other kinds of human–environment research, suggests

several guiding principles in approaching scale. This exploration also demonstrates the drawbacks of assuming that scale perspectives naturally map onto specific disciplines or the systems they study as a function of the degree to which they are ‘environmental’ versus ‘human’.

Biocomplexity exemplifies the study of complex human–environment systems and is a useful locus for an exploration of scale. Biocomplexity is a term for both the subject and study of “properties emerging from the interplay of behavioral, biological, chemical, physical, and social interactions that affect, sustain, or are modified by living organisms, including humans” (Michener et al., 2001, p. 1018). While biocomplexity is often nominally centered on natural systems, very few complex natural systems are immune from human influence, and few human systems exist without a significant environmental basis. This hybridity defines human–environment systems. The range of epistemological perspectives on scale bears on these systems and the social dimensions of the research itself. The interdisciplinary

*E-mail address:* manson@umn.edu

nature of human–environment issues has encouraged researchers of all stripes to explore the meaning of scale across subfields and disciplines (e.g., Levin, 1992; Marceau and Hay, 1999; Cash and Moser, 2000; Gibson et al., 2000; Marston, 2000; Wu and Qi, 2000; Herod and Wright, 2002a; Sheppard and McMaster, 2004).

We regularly engage in activities that invoke scale concepts. Scale identification lies in determining the scale at which a process such as land change or water pollution is best understood (Gibson et al., 2000). Scale optimization involves choosing the most efficient scales for human activity, such as assessing the level of government – local to global – best suited for carbon taxes (Jordan and Fortin, 2002). Scale generalization involves applying the lessons learned at one scale to another, as when attempting to apply knowledge of deforestation from specific locales to larger regions (Geist and Lambin, 2002). Scale causality involves discovering how phenomena at different spatial or temporal orders of magnitude are interrelated (Wilbanks and Kates, 1999).

Despite a good deal of research and policy using scale concepts, does scale exist as a single measure, discrete object of study, or evident characteristic of reality? Most research perspectives in human–environment research share the ontological premise that there is a real world, but they can differ dramatically in their epistemological trappings. This continuum suggests that cross-disciplinary research on scale should balance the desire to choose among competing conceptions of scale with the creative reassessment of its epistemological basis (after Jones, 1998). This exploration also questions the extent to which we can assume that one scale perspective is better than another for systems as a function of the extent to which they are natural or human.

The epistemological scale continuum runs from realism to constructionism (Fig. 1). One pole is anchored by the realist ontological premise that there is a single shared reality and the related epistemological claim that reality is readily accessible to objective observers. At the other pole is the constructionist ontological claim that while there may be a reality, in epistemological terms, knowledge about this reality is socially mediated and manipulated. This epistemological continuum frames scale in a manner that reflects larger debates in human–environment research (Woodgate and Redclift, 1998; Demeritt, 2001; Schneider, 2001; Jones, 2002). For the sake of exposition, we can identify three general groups of perspectives: realist, hierarchical, and constructionist. Each offers advantages and challenges for biocomplexity research in addition to emphasizing in aggregate that scale is an epistemological construct.

It is important to distinguish the positions of realism and constructionism from their more extreme relations. In particular, few scientists who identify themselves as realist or ‘positivist’ are practicing the extreme of logical positivism, which is premised on verification; most instead recognize the primacy of falsification in theory building (Popper, 1959). Similarly, few constructionists believe they exist in a

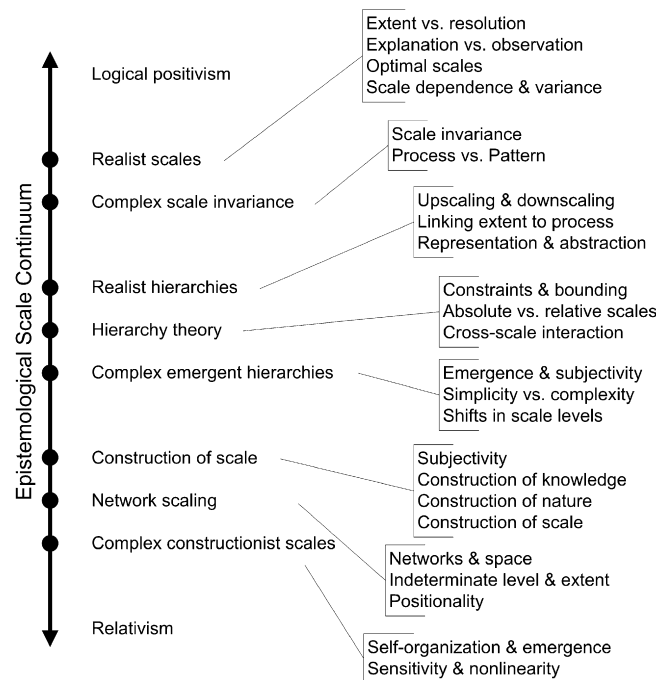


Fig. 1. Epistemological scale continuum.

relativist dreamland detached from reality. They instead make well-researched claims that knowledge, and the material reality on which it is based, is subject to social processes (cf. Feyerabend, 1993).

The epistemological ramifications of scale are interwoven with the corollaries of complexity science. Complexity theory offers a defacto ‘complex scale’ that is coincident with the scale continuum because it is epistemologically neutral with respect to the tension between constructionism and realism (Manson and O’Sullivan, 2006). It is beyond the scope of this piece to examine complexity in depth, but for the discussion that follows, it is useful to consider complexity research as comprised of three major currents of thought (Manson, 2001):

- algorithmic complexity is concerned with the perceived complexity of system structure, largely from the perspective of mathematic and information theory,
- deterministic complexity contends that seemingly complex systems can be understood through nonlinear analysis, chaos theory, and catastrophe theory,
- aggregate complexity focuses on how individual elements working in concert through local interactions can create complex systems.

All three streams of complexity, and much human–environment research, rely on matching real phenomena with archetypal ‘complex’ processes and patterns. Processes like self-organization, path dependence, and emergence are organizing principles for understanding the scalar nature of complex systems ranging from rivers to the international economy (Manson, 2001; Urry, 2003). Similarly, hallmark patterns of complexity such as power-law distributions are

used to explain (sometimes incorrectly) the complex nature of many systems (Malanson, 1999).

This paper examines the implications of the epistemological scale continuum for the data, methods, and theories of biocomplexity and human–environment research. This examination offers several overarching principles for approaching scale. First, there is no single canonical theory of scale and it is useful to understand how the range of epistemological viewpoints affect the definition and use of scale concepts in research, no matter how inapplicable some of these positions may seem. Second, scale perspectives towards the center of the continuum – particularly hierarchies and complex emergent hierarchies – are applicable to a broad array of research questions in human–environment systems when their attendant caveats are addressed. Third, it is prudent to adopt an constructionist epistemological posture to understand the role of society in constructing and manipulating knowledge, reality, and scale in complex human–environment systems. Fourth, the combination of complexity and scale – complex scale – lends critical insight into problems faced by individual scale perspectives while providing points of contact among these differing views.

## 2. Realist perspectives on scales

### 2.1. Realist scale

Realist scale relies on the premise that observers can objectively access reality. This assumption supports a sophisticated view of scale for all aspects of research – including measurement, modeling, and explanation. This realist approach has several corollaries for scale: a realist foundation for scale terminology; an inverse relationship between extent and resolution; twinned scales of explanation and observation; issues surrounding identifying the optimal scale for research; and challenges related to scale dependence and variance.

Realism suffuses scale terminology with words such as resolution, extent, and scale level that serve as the starting point in any discussion of scale (Turner, 1989). Resolution, or grain, is the smallest unit of observation and is dependent on the phenomenon of interest. It may be described in a number of ways, such as grid cells in satellite imagery or individuals in a population, but a general rule of thumb is that it is the unit of measurement below which heterogeneity is not found or not of interest. Extent is the scope of scale, such as the areal coverage of a remotely sensed image.

Complicating the definition of scale is the fact that everyday experience equates the term small-scale with the local, such as individual people or neighborhoods, and the term large-scale with the global, such as the climate system. The seemingly obvious nature of these terms owes much to, and somewhat suffers from, the fact that resolution and extent are often inversely related. Automatically assuming this relationship is increasingly difficult in some circumstances and points to the weakness of a purely intuitive understanding of scale in complex systems. In data collec-

tion, the cost per unit of extent typically rises with resolution, as seen with remote sensing or ground based measurements. Analog data such those found in paper maps typically have inversely related resolution and extent due to limitations of the physical medium and the human ability to process visual information. We continue to attenuate technical limits to these inverse relationships for data processing, as when using computers to store and access high resolution remotely sensed imagery spanning the globe. Nonetheless, we still face challenges in gathering these data in the first place and balancing resolution and extent when conveying data to humans. Beyond these data-centric considerations, equating small-scale with local or large-scale with global can mask features in complex systems marked by sensitivity and cross-scale interactions, as examined below.

Realism also gives us the fundamental scales of observation and explanation. Scale of *observation* is suggested by the importance of data to research, visual metaphors applied to scale, and the role the observer in defining scale (Lam and Quattrochi, 1992). The scale of *explanation* is that considered the best at which to understand a system or process. It is coincident with the term *operational* scale used to describe the resolution of global climate models (Wessman, 1992) or spatial partitioning in data models (Jenerette and Wu, 2000). Observational and explanatory scales are linked but usefully distinguished from one another. The microscope revolutionized biology by introducing a new scale of observation that led to a new scale of explanation exemplified by microbiology. A gendered scale of explanation leads to an observational scale that examines intrahousehold differentiation and can therefore give different conclusions about household decision making than when examining households as atomistic units of analysis (Schroeder and Suryanata, 1996). The distinction between explanatory and observational scales is useful because they can differ in human–environment research. Land change models often employ a household explanatory scale but are calibrated at observational scales defined by census tracts or pixels in satellite imagery (Bell and Irwin, 2002).

Determining observational or explanatory scales relies on scale dependence, or where scalar resolution and extent can influence system processes to the point where different scales require different analytical tools (Walsh et al., 1997). We assume scalar dependence by positing that processes such as land change have natural explanatory scales that may be discovered by varying the resolution of the observational scale and choosing that which gives the best apparent fit (Geist and Lambin, 2002; Verburg et al., 2002). Similarly, vulnerability to climate change is meaningless outside of the context of scale levels defined by individuals, households, institutions, or nations (Liverman, 1990). Stommel diagrams of time versus space convey scale dependence by partitioning phenomena such as forests (Fig. 2) into discrete regions (after Malanson, 1999, p. 749). Scale dependence is solidly realist because scale levels do

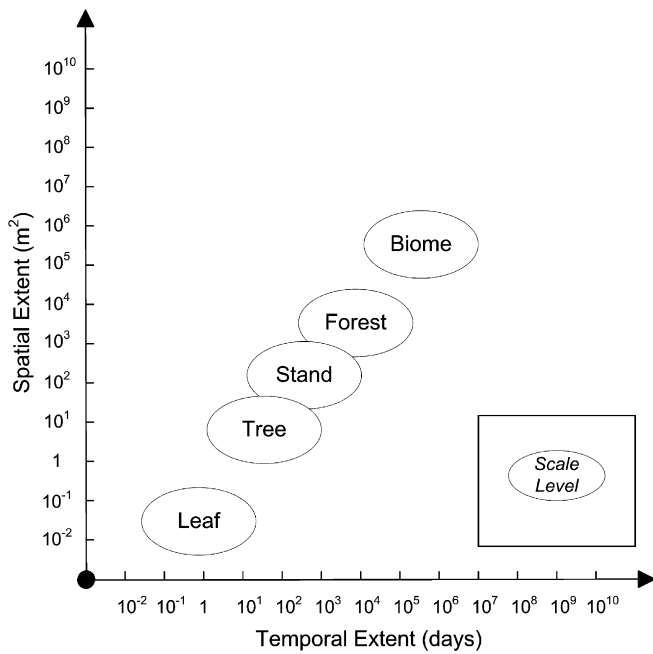


Fig. 2. Scale dependence for forests.

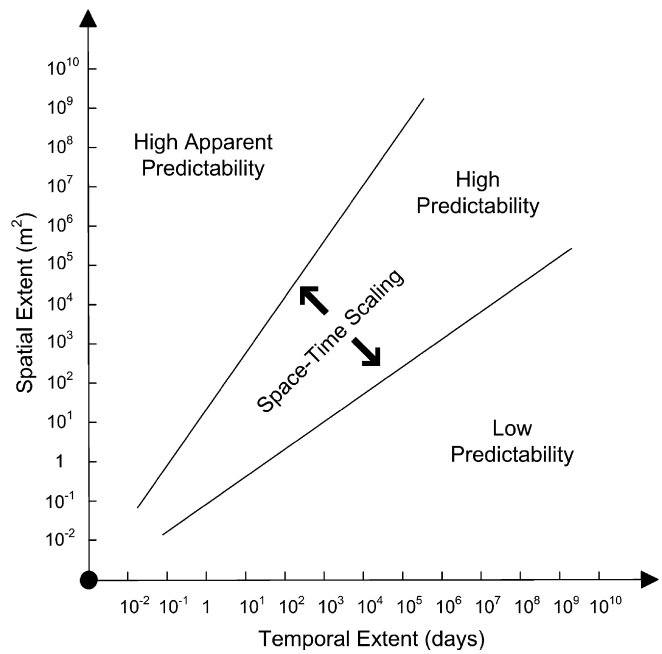


Fig. 3. Space-time scaling and predictability.

not vary according to observers and are instead given by reality.

Scale dependence is highly related to scale variance, where the functioning of a system varies over scales to the point where scales of observation divorced by an order of magnitude in resolution or extent can be treated as essentially independent (Walsh et al., 1997; Phillips, 1999). Here the word variance is not meant in the statistical sense, but instead a situation where two phenomena do not appear to influence one another. The spatial distribution of krill, for example, is dependent on gross water movement at large scales and how these animals move through the water at small scales (Levin, 1992). In other words, small-scale movements of individual krill have no effect on the patterning of krill at large scales. The large scale in turn is a background for small-scale patterns of individual krill. Scale variance allows us to treat a single phenomenon as essentially two or more unrelated phenomena, which frees researchers from having to choose a single optimal scale.

Scale variance also suggests “space-time scaling” (Wiens, 1989, p. 1949), which allows us to predict the behavior of systems within a range of matched spatial and temporal scales (Fig. 3). Under space-time scaling, phenomena studied over long temporal scales at small spatial scales have low predictability because they are complicated and have a strong random element. Conversely, systems examined over large spatial scales and short periods have high apparent predictability simply by virtue of experiencing little change over the time in question. While these relationships between scale and predictability work well with realist scales, they are weaker according to perspectives further along the epistemological scale continuum.

## 2.2. Complex scale invariance

Complementing scale variance and scale dependence is the complex scale concept of scale invariance, where a single process or phenomenon behaves identically across scales. Identifying scale invariant phenomena involves applying some measure – frequency, power, fractal – across a series of observational scales in order to trace regularities in patterns across scales. Scale invariance combined with complexity is farther along the epistemological scale continuum because it requires an observer to draw connections, actual and imagined, between process and pattern across scales and thereby invites observer bias.

If an invariance measure quantifies patterns over scales, it is tempting to assume that the processes giving rise to these patterns may be operating across scales as well. If so, understanding processes at one scale is equivalent to understanding them at others. Measures such as fractal dimension or rank-size are invoked as means of parameterizing scale invariance in systems ranging from urban agglomerations to landscape ecologies assumed to be characterized by deterministic and aggregate complexity, (e.g., Mandelbrot, 1982; White and Engelen, 1993; Marquet, 2000). While the root causes of scale invariance in a complex system are varied, one key source is self-organization and bottom-up emergence of structure in complex systems (Lee, 2004; Crawford, 2005).

Establishing scale invariance requires a good deal of evidence and robust explanations. As multiple processes can lead to identical patterns and many different patterns can result from a single process, it is not enough to match archetypal patterns across multiple scales in a system and assume that the generating processes are invariant. Complex

319 processes such as dissipative systems and self-organized crit-  
 320 icality are powerful templates for linking processes across  
 321 scales (Prigogine and Allen, 1982; Bak, 1996). Such explana-  
 322 tions run the risk of incorrectly conflating pattern with pro-  
 323 cess, however, and creating findings that may just be  
 324 artifacts of an incomplete analysis. As Malanson notes,  
 325 under complexity “simple rules can be derived that produce  
 326 complex patterns but that have no discernable relations to  
 327 biological or physical processes. For example, self-organiza-  
 328 tion has been ascribed to phenomena that exhibit scaling  
 329 features with little attention to the processes of organiza-  
 330 tion” (1999, p. 751).

### 331 2.3. Summary: realist perspectives

332 Realist perspectives on scale, relying as they do on the  
 333 epistemological premise that we can objectively observe  
 334 reality, provide a firm foundation for human–environment  
 335 research. Realist epistemology provides much of our scale  
 336 terminology and the foundation for the inverse relationship  
 337 between extent and resolution. Realism is also the starting  
 338 point for identifying relationships between scales of expla-  
 339 nation and observation, particularly with respect to identi-  
 340 fying the best scales for collecting data or building theory.  
 341 Realist perspectives illustrate the need for, and the chal-  
 342 lenges faced, in defining scale dependence, variance, and  
 343 invariance. For the latter, complex scale offers several  
 344 advantages and cautionary notes.

## 345 3. Hierarchical perspectives on scale

### 346 3.1. Realist hierarchies

347 Challenges faced in using realist scales relate to the  
 348 potential for phenomena to interact across scales and  
 349 thereby disrupt clear distinctions among scale levels. Many  
 350 systems are linked across scales in a manner that belies  
 351 dependence or variance and yet more complicated than  
 352 suggested by scale invariance. One means of identifying and  
 353 understanding cross-scale interaction is the concept of hier-  
 354 archies, which for the purposes of this discussion, map well  
 355 onto realism (Simon, 1961). Realist hierarchies have several  
 356 ramifications for biocomplexity research with respect to:  
 357 upscaling and downscaling; linking spatial extent to pro-  
 358 cess; and representation and abstraction.

359 Hierarchies are inclusive, having ranked and aggregative  
 360 subdivisions, or exclusive, merely having ranked subdivi-  
 361 sions (Gibson et al., 2000). Under realism, seemingly evi-  
 362 dent divisions in nature such as the cell–organism–  
 363 community ecological construct define hierarchies. Areal  
 364 extents of socioeconomic or political units, like the hierar-  
 365 chy of city–county–state–nation, commonly define inclu-  
 366 sive hierarchies in human systems.

367 Hierarchies highlight the importance of identifying rela-  
 368 tionships between levels, particularly the mechanisms by  
 369 which lower levels are connected to higher ones through  
 370 upscaling, and the reverse, downscaling (Wessman, 1992).

Scaling physical processes of importance to biocomplexity 371  
 has met with success, even if this work may deal with less 372  
 with complex systems and more with just very complicated 373  
 ones. This is seen in up-scaling the effects of precipitation 374  
 on individual plant respiration to atmospheric carbon diox- 375  
 ide (Cernusca et al., 1998) or downscaling global climate 376  
 models to regions (Walker, 1994). Other systems, particu- 377  
 larly coupled human–environment systems, have suffi- 378  
 ciently complex cross-scale relationships that, while scale 379  
 variance or scale dependence still apply, it may be necessary 380  
 to pursue a purposely multiscale approach. Calls for 381  
 regional level global change research stem in part from the 382  
 desire to take advantage of the tension between global and 383  
 local research foci (Easterling, 1997). Land change model- 384  
 ing, for example, is often conducted at the regional scale in 385  
 order to accommodate higher and lower levels without 386  
 being confined to them (Verburg et al., 2002). 387

When using hierarchies, we face a long recognized prob- 388  
 lem in that fixed scalar levels do not map onto all important 389  
 processes (Haggett, 1965). Using watersheds to define reso- 390  
 lution, for instance, can help a study capture a variety of 391  
 biophysical processes but may make it difficult to consider 392  
 other phenomena that do not share these boundaries, such 393  
 as political institutions or air movements (even when these 394  
 watersheds serve as an indirect way of crossing otherwise 395  
 arbitrary boundaries). Similarly, hierarchical phenomena 396  
 may have lateral movements of matter or energy across the 397  
 branches of the hierarchy (Dowlatabadi and Morgan, 398  
 1993). A sufficiently small study site may not face issues 399  
 raised by scales levels not mapping well onto real phenom- 400  
 ena or intralevel lateral interactions, but human–environ- 401  
 ment systems are often complex and large. 402

Use of hierarchies faces additional challenges arising 403  
 from issues of aggregation (McMaster and Shea, 1992). 404  
 Hierarchies rely on the assumption that a higher level 405  
 encapsulates myriad processes at lower levels, which 406  
 requires the observer to choose a system of aggregation. 407  
 Observations at a fine resolution, such as satellite pixels, are 408  
 often aggregated into larger spatial extents whereby charac- 409  
 teristics of finer grained units are assumed to be subsumed 410  
 by coarser units even when this is not necessarily the case 411  
 (Kimble, 1951). Realist scale hierarchies can also suffer 412  
 from the ecological fallacy and the modifiable areal unit 413  
 problem, requiring use of any number of remedies for these 414  
 statistical effects of scale (Tate and Atkinson, 2001). 415

### 3.2. Hierarchy theory 416

Hierarchy theory offers some answers to issues raised by 417  
 realist hierarchies, such as the challenges of aggregation or 418  
 intralevel interaction. A good deal of research has been 419  
 done on linking hierarchy theory and scale (Allen and 420  
 Starr, 1982; O’Neill et al., 1986; Gibson et al., 2000; Easter- 421  
 ling and Kok, 2002), so here we dwell on just a few aspects 422  
 of this theory with respect to the epistemological nature of 423  
 scale. Of particular interest are: the commentary on subject- 424  
 ivity; the importance of constraints and bounding in scale 425

426 levels; the distinction between absolute and relative scales;  
427 and ways to understand cross-scale interaction in complex  
428 human–environment systems.

429 Important to defining a given scale level in hierarchy  
430 theory is the concept of constraints – each level is charac-  
431 terized by the behavior of its components and bounded by  
432 constraints at other levels. Hierarchy theory identifies eco-  
433 logical structures that are composed vertically across scales  
434 and horizontally through holons at a single scale (Allen and  
435 Starr, 1982; O'Neill et al., 1986). Holons are organized col-  
436 lections of interacting components (e.g., cells in an organ)  
437 that are in turn typically part of some larger entity (e.g.,  
438 organs in a body). Processes in a given level are bounded by  
439 a higher level, in which processes move too slowly to be  
440 anything but a backdrop, and a lower level in which pro-  
441 cesses move too quickly to influence those in the current  
442 level.

443 The concept of boundedness in defining hierarchy high-  
444 lights the role of the observer in identifying scale levels and  
445 contextualizes the realist basis of scale. Hierarchy theory  
446 encourages us to examine phenomena in terms of their  
447 functional and organizational aspects in order to define  
448 their spatial and temporal scales. Instead of assuming that a  
449 small spatial observational scale is useful for examining  
450 minnows and a larger one for sharks, for example, it may be  
451 better to consider minnows via a large explanatory scale of  
452 community and the shark at the small scale of individuals  
453 (O'Neill et al., 1986). Hierarchy theory does not necessarily  
454 imply subjectivity – multiple informed observers should be  
455 able to identify similar hierarchies – but it does question a  
456 priori scale definitions and points to the importance of the  
457 observer in defining scale.

458 Hierarchy theory contributes to the distinction between  
459 absolute scale and relative scale. Absolute scale buttresses  
460 concepts of scale variance, scale dependence, and scale  
461 invariance by assuming that levels are independent. Rela-  
462 tive scales are interdependent by virtue of measures com-  
463 mon to different levels, expressed as state variables. Varying  
464 the scales of observation and explanation along a state vari-  
465 able allows an observer to focus on a single level while rec-  
466 ognizing that other levels exist and are potentially  
467 important. Identifying scale levels therefore requires know-  
468 ingly moving across levels rather than dogmatically staying  
469 in one (O'Neill et al., 1986). Research on agriculture and  
470 land use, for example, can leverage the role of absolute and  
471 relative scale via multilevel models (Polsky and Easterling,  
472 2001; Verburg et al., 2002).

473 Hierarchy theory adds another entry point to the analy-  
474 sis of adaptation, cross-scale interaction, and boundedness  
475 in complex human–environment systems (Holling, 1995).  
476 Interaction across scales occurs at the interface of hierar-  
477 chical levels through state variables, which provide a useful  
478 counterpoint to scale dependence (Fig. 4). Hierarchy theory  
479 allows for nested hierarchies. In ecological settings, for  
480 instance, organisms of different size can range across spatial  
481 scale levels and yet use the same resources without conflict  
482 due to boundedness and different spatiotemporal tempos of

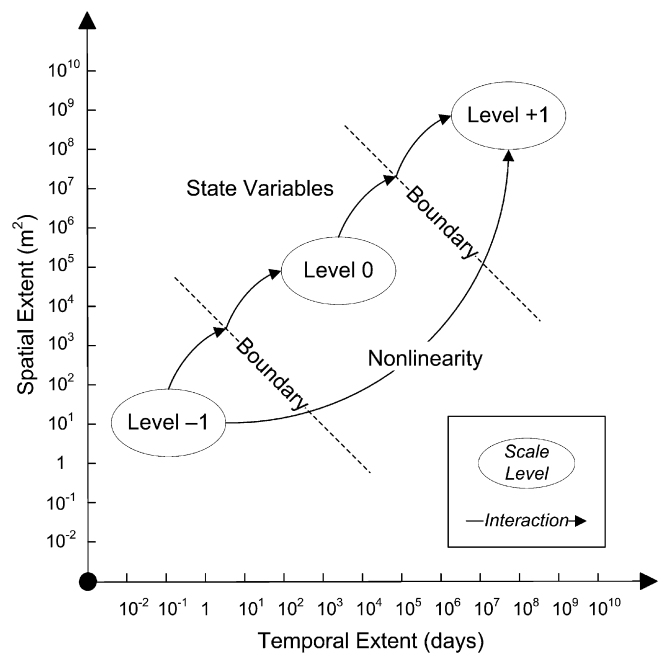


Fig. 4. Relative hierarchical scales, boundaries, and state variables.

resource use (Pimm, 1984). At the same time, rigidity, over  
484 consumption of resources, or attempts at independence by  
485 holons imperil the larger whole while simultaneously  
486 threatening the subunit with being cut off from the whole  
487 (Giampietro, 1994).

### 3.3. Complex emergent hierarchies

488 Hierarchy theory contributes to, and in some senses is a  
489 subset of, the complex scale concept of complex emergent  
490 hierarchies. The term emergent refers to the synergistic  
491 qualities of a system that do not result from superposition  
492 (i.e., additive effects of system components) but instead  
493 from interactions among components. Emergence results  
494 from archetypal complex processes such as self-organiza-  
495 tion or self-organized criticality. Examples of emergent sys-  
496 tems include institutions that result from the interactions  
497 among individuals (Ostrom, 2005) or the relationships  
498 among economic, agricultural, and climate processes (East-  
499 erling and Kok, 2002). Issues raised by the existence of  
500 complex emergent hierarchies are relevant to biocomplexity  
501 in several ways: the role of emergence in subjectivity; recon-  
502 ciling simplicity and complexity in scale; and the potential  
503 for sudden shifts in complex systems to change apparent  
504 scale levels.

506 Emergent hierarchies lie towards the constructionist  
507 pole of the scale continuum because identifying emergent  
508 phenomena can be subjective. An emergent phenomenon is  
509 one that exhibits a structure that may not be explained by  
510 lower level dynamics and typically persists for a longer  
511 period of time than the average lifetimes of entities upon  
512 which it is built (Crutchfield, 1994). The related notion of  
513 supervenience relies on the less restrictive assumption that

changes in macrostates (higher scale levels) are linked to changes in microstates (lower scale levels) of a system (after Sawyer, 2002). With either emergence or supervenience, the fact that larger-scale phenomena cannot be easily predicted from smaller-scale phenomena leads to the danger that an observer must sift through data without a priori expectations as to what constitutes emergence, which increases the role of subjectivity (after Holland, 1992).

A broader challenge to biocomplexity research and emergent hierarchical scaling is the task of reconciling the simplicity of complexity theories with complex reality. Emergence is key to aggregate complexity, with its focus on local interactions, but is also important to deterministic complexity when straightforward mechanisms at small scales can lead to seemingly complex outcomes at larger scales. Adapting complexity concepts to fit empirical data while adequately addressing existing research and theories remains a significant challenge because many complex models – agent-based models, neural networks, cellular automata – can become very complicated and therefore at odds with the basic precept that complexity arises from simplicity (Torrens and O’Sullivan, 2001). There is also a growing amount of complexity research that is too simplistic because it makes wholly unrealistic assumptions about real systems. This critique applies in particular to human societies when messy issues like culture or individual decision making are ignored (Stewart, 2001).

The final challenge posed by complex emergent hierarchies is that they, and therefore their scale levels, may not be stable. Complex economies, for example, exhibit “multiple equilibria, nonpredictability, lock-in, inefficiency, historical path dependence, and asymmetry” (Arthur, 1999, p. 108). Any of these mechanisms can serve to change the extent or resolution at which an economic system must be studied. Ecological landscapes can likewise be treated as complex systems driven by interactions at multiple scales among humans and natural actors such as animals or plants (Bousquet and Le Page, 2004). The capacity for sudden change not only highlights the potential for subjectivity, following from hierarchy theory, but also requires us to reassess constantly how scale levels shift in space, time, or organization.

### 3.4. Summary: hierarchical perspectives

Hierarchical perspectives on scale highlight that the observer is critical to defining scale and, in the case of complex emergent hierarchies, demonstrate the potential for subjectivity in interpreting the effects of scale. Hierarchical scales can be reconciled with realist concepts of scale variance, scale invariance, and scale dependence. At the same time, hierarchical scales challenge the extent to a single external reality defines scalar hierarchies even when this reality is shared by multiple observers. The concept of relative scale essentially mandates the coexistence of multiple observational and explanatory scales that are heavily conditioned, but not determined, by a shared reality. Similarly,

the concepts of complex emergence and rapid shifts in complex systems highlight the role of the observer in subjectively defining scale via complex emergent hierarchies. Not only will scale levels shift over time but also their definitions can shift as multiple observers vary in their identification of what distinguishes one emergent scale from another.

## 4. Constructionist perspectives on scale

### 4.1. Construction of scale

The construction of scale argument goes beyond stating the importance of the observer in defining scale by positing that scale is actively created, not only in terms of its definition but also, over time, the underlying scales of reality. Construction of scale comprises several complementary theses on the role of society in constructing and manipulating knowledge, space, nature, and scale. From this manipulation stems several effects on scale in human–environment research: an expanded role for subjectivity; construction of knowledge about real phenomena; how nature is perceived and controlled; and most importantly, how purposeful scale construction has material impacts.

The construction of knowledge thesis holds that many apparent aspects of reality are in fact subjective mental models, so much so that the degree of correspondence between the model and an external reality may be impossible to ascertain. Just as scale has been a central concern of geography in general, the social construction of scale thesis is a central concern of human geography (this research cannot be done justice here, see Marston, 2000; Sheppard and McMaster, 2004). When taken to an extreme, constructionism becomes relativism based on the ontological premise that there is no reality as such and the epistemological principle that all mental models are equal. Unfortunately, this extreme variant has come to exemplify all of constructionism for some human–environment researchers.

Social construction of knowledge happily acknowledges for the most part that there is a reality but contends that knowledge of reality is crafted by through societal practices not usually identified with the realist vision of science, such as intentional manipulation of language and power. Constructionists “propose that attention needs to be turned away from trying to ascertain ‘objective conditions’ through more data and better science, towards understanding the plurality of constructions, how various assertions are made, how these are related to various interests of stakeholder groups and how outcomes are affected by power relations” (Jones, 2002, p. 248).

Following from social construction of knowledge are related theses on the construction of space, production of nature, and social reproduction. These views go beyond noting that knowledge is constructed to examining how this knowledge leads to material impacts. Their roots are fixed in the longstanding differences between the definitions of absolute space, characterized by extent and resolution, and relative space, which deals with spatial relationships

between objects (Harvey, 1969). Relative space emphasizes the role of context in spatial relationships by treating spatial distance less as an immutable Cartesian construct and more as a medium or result of socioeconomic processes (Sheppard, 1995). The construction of space and social reproduction theses holds that economic, social, and political processes manipulate relative space and social reproduction within the context of capital flows, development, and information access (Lefebvre, 1974; Smith, 1984; Marston, 2000). The related production of nature argument sees humans, through socioeconomic systems, commodifying nature to the point where nature does not exist outside the context of human activities (Castree, 1995; Escobar, 1996). Importantly, according to the production of nature argument, science is appropriated by subsections of society in order to manipulate how nature is perceived and thereby controlled. This is seen in agricultural irrigation in Latin America, for example, where both village-based and valley-wide control of water are manipulated through cultural imagery (Zimmerer, 2000).

If space and nature are constructed, then so too is scale. It therefore must be treated as an overtly epistemological device that not only frames knowledge but also possesses the power to construct and change material reality (Delaney and Leitner, 1997; Jones, 1998; Swyngedouw, 2000). Scale is intentionally manipulated for political and economic gain (Herod, 1991; Staeheli, 1994; Cox, 1998; Brenner, 2001). Small scales, instead of serving as simply a place where large-scale forces play out, are sites where meaning, representation, and difference across scales are explored (Pratt, 1991). In this view, scale “is not predetermined, but produced in the act of creating and contesting social identity” (Ruddick, 1996, p. 139).

Importantly, scale has a discursive identity in that the language used to formulate scale issues is granted the power to structure reality (Kelly, 1999). At this point, it is prudent to ask, “How can language be granted the power to do anything?” This question speaks to the literal sense of language – they are just words after all – instead of how language frames debate, knowledge, and thinking about the world. The terminology used to describe phenomena actively guides public attitudes and policy by defining scales of investigation and action, and thereby feeds back onto the reality it describes. The UCS (2004a,b) highlight a number of cases, for example, where the executive branch of the United States routinely changed the wording of reports created by federal scientists on human–environment topics including climate change, endangered species, biodiversity, forest management, and water quality. These changes in language were often scale related (e.g., defining animal population or areas in which policies should be applied) and were designed to have a material impact by guiding debate, policy, and funding priorities. Arguments over who should reduce carbon emissions that contribute to climate change often have a scalar element in order to emphasize the culpability of certain locales – such as developing countries – and not others (Agarwal and

Narain, 1991). The discourse of scale is not limited to governments. Multinational companies position themselves as local players to receive benefits from the state while simultaneously evoking global-scale competition to finesse local environmental regulations (Jonas, 1994; Miller, 1997). In sum, there is ample evidence that many actors – ranging from businesses to activists to governments – routinely use language to define scales in ways that influence real human–environment systems. In these cases, scale is constructed and manipulated in order to have material impacts.

#### 4.2. Networks

The scale construction thesis is extended by what may be termed network scaling, where the importance of space, and thereby scale, is driven by social, economic, and political flows in networks. The increased importance of networks bears on several aspects of scale in human–environment research: the issue of how networks map onto space; the potential for networks to unmake scale level and extent; and the role of positionality.

Scale may be defined by networks that may only incidentally map onto a given spatial extent (Murdoch, 1997; Urry, 2003). Information and transportation technologies are important to creating systems in which flows of capital, information, material, and energy ignore actual spaces and places (Castells, 1996). In this way, a given object (say a tree or person) can be simultaneously local, regional, or global in terms of its linkages to other phenomena. Networks challenge the concept of fixed or objective scale levels because the extent or resolution of any given level depends on how multiple actors and viewpoints dynamically define the network. The simplest definition would hold that extent maps onto the furthest reach of the network, but this belies heterogeneity in the importance of nodes and connections among them. These in turn may vary among observers and those creating the network, leading to multiple definitions of scale for something as seemingly straightforward as interactions between a single household and other actors with which it has relationships, which range from individuals within the household to other households and organizations around the world (Fig. 5). In this case, the household may be the unit of analysis but it does not fall easily into a single scale.

One possible implication of networks is that they are multiscale to the point where scale as a concept loses relevance and the very notion of easy distinctions between scale levels and extent is extinguished (Leitner et al., 2002). Taken to an extreme, network scale runs the risk of being constituted by an almost infinite multiplicity of shifting conditions, leaving little room for hierarchies or realist conceptions of stable resolution or extent. An emphasis on flows and temporary emergence of order gives rise to ‘flat ontologies’ that entirely displace hierarchical scale or network scale with a nonscalar structure of flows (cf. Graham, 1992; Marston et al., 2005).



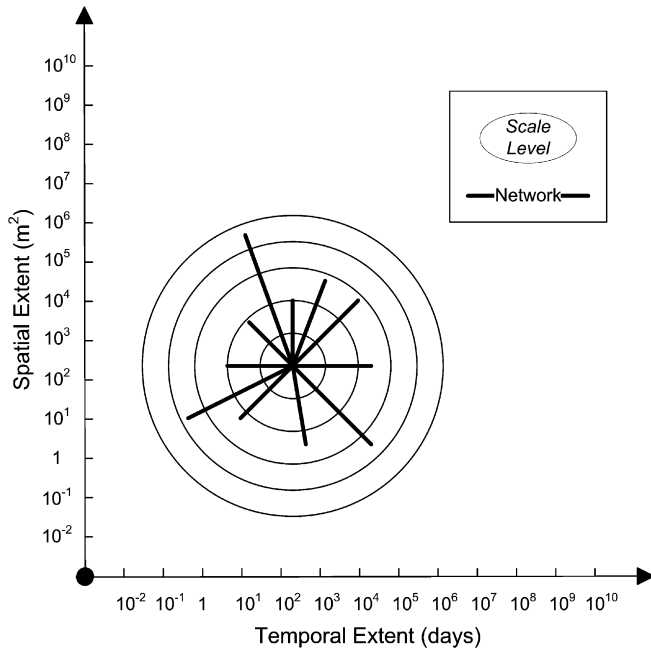


Fig. 5. Network scales for a single household.

735 While a network does not necessarily conform to geo-  
 736 graphic extent or resolution, scale is still very conditioned  
 737 by place or “positionality” with respect to the “shifting,  
 738 asymmetric, and path-dependent ways in the futures of  
 739 places depend on their interdependencies with other places”  
 740 (Sheppard, 2002, p. 308). While capital is often seen as mov-  
 741 ing freely in a manner that reconfigures space and scale, the  
 742 situated and material nature of reality applies friction to  
 743 this movement, serving to constrain and mold it (e.g., when  
 744 instantiated in buildings or slowed by bureaucratic rules).  
 745 Positionality complements research that treats scale as  
 746 being defined by tensions between actors at different scales,  
 747 such as global versus local (Herod and Wright, 2002b).

#### 748 4.3. Complex constructionist scales

749 Complex scale has several points of contact with con-  
 750 structionist and network scales. There is a good deal of cor-  
 751 respondence between self-organization, emergence, and the  
 752 manner in which social construction and networks channel  
 753 knowledge, discourse, and power (Cilliers, 1998). The evo-  
 754 lution of knowledge in the complex ecology of human  
 755 thought are akin to complex emergence; “knowledge, rep-  
 756 resentation, information, cognitions of any kind, are materi-  
 757 al consequences of this same [complex] ecology” (Smith  
 758 and Jenks, 2005, p. 142). Emergence and complex emergent  
 759 hierarchies in particular are powerful templates for the  
 760 manner in which self-organization or self-organized criti-  
 761 cality create protean structures and hierarchies in both of  
 762 knowledge and material systems (Thrift, 1999; Nowotny,  
 763 2005). Emergent hierarchies and their attendant scale levels  
 764 manifest the instabilities, emergence, supervenience, shift-  
 765 ing equilibria, unpredictability, and path dependence on  
 766 which many features of network and constructionist scales

are predicated. As noted above, human–environment phe-  
 767 nomena as different as economies and ecologies are (or at  
 768 least act like) complex systems driven by interactions  
 769 among constituent entities that dynamically define scale.  
 770 This capacity for sudden structural change points to the  
 771 role of subjectivity in analysis and the potential for actors  
 772 to manipulate spatial, temporal, and organizational levels.  
 773

Complex sensitivity and nonlinearity usefully comple-  
 774 ment constructionist scale because they upset the notion of  
 775 scalar hierarchies in which small scales are merely the con-  
 776 text for large-scale processes; instead, a local action may  
 777 directly affect those at a larger scale without moving  
 778 through intermediary scales. Scale jumping, for example, is  
 779 the process by which an actor influences events at another  
 780 scale without working through intermediary levels (Smith,  
 781 1993). Protestors demonstrating against environmental  
 782 damage caused by globalization, for instance, use interna-  
 783 tional coalitions to by-pass regional and national political  
 784 scales to leap onto the global stage (Glassman, 2002). In  
 785 protests around the globe, Greenpeace Canada has simi-  
 786 larly used the icon of the hungry polar bear, which faces  
 787 shorter hunting seasons as the polar ice melts earlier each  
 788 year (Slocum, 2004). The potential for a small change at  
 789 one level to lead to large changes in others has metaphori-  
 790 cal and actual relevance for human–environment systems  
 791 that increasingly rely on technological networks to almost  
 792 instantly trade information (McLennan, 2003). In the  
 793 extreme, scale in a network is mutually constituted, where  
 794 scale levels such as the global and local are simultaneously  
 795 defined by one another (McGuirk, 1997).  
 796

#### 4.4. Summary: constructionist perspectives

Theories on the construction of knowledge, space, and  
 798 nature provide a view on scale that differs markedly from  
 799 realist and hierarchical perspectives. The latter concentrate  
 800 to varying degrees on the role of the observer and only flirt  
 801 with the possibility of subjectivity. Under hierarchy theory,  
 802 for example, “material systems have immutable scalar  
 803 properties, but this does not mean that the material world  
 804 fixes the scale of observation. The material world stub-  
 805 bornly retains its scalar properties, but scale of observation,  
 806 like the criteria for foreground and background, comes  
 807 from observer decisions” (Ahl and Allen, 1996, p. 55). Con-  
 808 structionist scale goes beyond recognizing the potential for  
 809 observer bias by giving the observer, or multiple observers,  
 810 the capacity to change the material nature of reality by  
 811 manipulating scale. There is ample evidence that many  
 812 individuals and organizations define and redefine scales –  
 813 through language and actions – in ways that affect real  
 814 human–environment systems.  
 815

## 5. Lessons of the scale continuum

The existence of the realist–constructionist scale contin-  
 817 uum makes it difficult, perhaps impossible, to justify a sin-  
 818 gle a priori theoretical framework to understand scale for  
 819

human–environment research. Exploring the epistemological scale continuum does suggest several overarching lessons or guidelines as a way forward for research on complex human–environment systems. These guidelines relate to the inherent value of a range of views on scale, the utility of realist and hierarchical scales, the need for constructionist interventions in human–environment research, and role of complex scale in supporting and reconciling differing scale perspectives.

First, we can complement, and perhaps supplant, the search for a single widely accepted theory of scale with the imperative to understand how epistemological context affects scale. While there are distinct differences in scalar concepts between specific disciplines (e.g., ecology versus sociology) and subdisciplines (e.g., human versus physical geography), the epistemological indeterminacy of scale makes it risky to assume that a given scale perspective is automatically applicable to a given research question, especially if it relates to a complex human–environment system. In addition to focusing on how to choose the best scalar combination of observation and explanation for a given problem, researchers should actively consider the range of scale perspectives, no matter how seemingly inapplicable. Scale perspectives along the continuum are scientifically valid by virtue of being successfully used by significant numbers of researchers. Moreover, each school of thought offers distinct advantages and challenges in dealing with any given scale problems and, by extension, there are often multiple entry points into any given complex human–environment system.

Second, some parts of the continuum are seemingly more welcoming than others to biocomplexity research and human–environment research more generally. Scale perspectives towards the center of the scale continuum readily deal with a broad array of research questions in human–environment systems, although they present specific challenges. In many ways, these perspectives rely on the argument that “space is not really constructed: it lies out there in the real world, and lay out there before we social beings entered the world” (Blaut, 1999, p. 513). Scale perspectives ranging from realist scale to complex emergent hierarchies describe reality in a way that many researchers share.

Realist and hierarchical perspectives work best when they recognize the role of the observer in research because they can encapsulate some epistemological aspects of scale while not straying far beyond the empirical and nomothetic bounds of normal science. These perspectives rely on researchers to move beyond glib conflation of subjectivity with personal bias or instrumentation error and ask seemingly straightforward questions, such as “Why did the funder of this research focus on this scale as opposed to another defined by a different problem/region/group?” or “To what extent do existing data and research influence or limit the scale of this research?” While all researchers should ask these questions, they do not address many elements of constructionist scale.

Third, all research processes and research problems have social and political dimensions that should not be (but often are) ignored due to the primacy of realist and hierarchical scales in human–environment research. While constructionist and network conceptions of scale offer many advantages, in a larger sense they are particularly useful for their recognition that social processes intentionally manipulate space and scale. This utility can come at the cost, however, of complicating scale to the point where it may diminish the notion of causality sought in much human–environment research. In particular, the need to develop a unique, nuanced understanding of a given time and place to craft a constructionist argument is potentially at odds with the scientific imperative to generalize. Nonetheless, the mounting body of evidence on real, material impacts of constructed knowledge, space, nature, and scale point to the need to incorporate, or at least accommodate, constructionist scale.

Human–environment researchers should at least occasionally step back and take a constructionist view on their work. While this can be done by individuals, it is probably more useful and intellectually honest to have interdisciplinary research teams that include scientists comfortable with differing epistemological views (easier said than done; see Nicolson et al., 2002). “Interdisciplinary and interinstitutional” (Michener et al., 2001, p. 1021) teams are ingrained in the US National Science Foundation Biocomplexity program, for example, but in practice teams for most projects tend towards the realist end of the continuum. This is partially an unintentional ramification of the program’s focus on computer modeling and ecological issues, but it is also likely due to larger institutional and disciplinary biases towards realism in the study complex human–environment systems (Manson and O’Sullivan, 2006).

Fourth, complexity theory offers a complex scale that supports individual epistemological positions on scale while simultaneously bridging difference among these differing perspectives (for a related argument for geography, see O’Sullivan, 2004). Realist, hierarchical, and constructionist perspectives on scale all invoke variants complex scale, such as scale invariance, emergent hierarchies, scalar sensitivity, and nonlinearity. More importantly, fundamentally different epistemological perspectives share related complex scale concepts, providing points of communication between differing scale perspectives. Self-organization and emergence are critical to realist scale invariance, complex emergent hierarchies, and knowledge construction.

While there is much potential for complexity to fuel communication among differing epistemological positions, the primacy of the natural sciences and attendant realist perspectives in complexity science hampers this exchange of ideas (Richardson, 2005). A case in point is the rapidly growing body of research on complexity, networks, and scale in social systems that is largely published in the natural sciences with a realist perspective and little engagement with social science (e.g., Boguna et al., 2004; Csanyi and Szendroi, 2004). This important work on scale in networks

934 work could benefit social science in general and construc-  
935 tionist research on networks in particular, while itself gain-  
936 ing from greater engagement with these fields.

937 In sum, we must strike a balance between accepting seem-  
938 ingly apparent scales of observation and explanation and  
939 recognizing their purposeful construction for social, eco-  
940 nomic, and political ends. Realist scales provide an organiz-  
941 ing principle for a variety of systems. Realist hierarchies and  
942 hierarchy theory leave some room for observer objectivity  
943 but neither addresses many of the corollaries of social con-  
944 structionism, particularly when dealing with complex  
945 human–environment systems. In terms of raw subject mat-  
946 ter, movement along the continuum from realism to con-  
947 structionism seems more necessary as one goes from  
948 physical and biological systems through ecological and  
949 human–environment systems to the social and policy  
950 domains. Physical systems are not immune to social con-  
951 structionism, but the relative absence of explicit human deci-  
952 sion making and intentionality in the system of study makes  
953 them more amenable to realist perspectives on scale. In  
954 terms of scientific practice, however, social constructionism  
955 is very applicable to the messy human research enterprise (in  
956 and of itself) and its focus on a world in which few nomi-  
957 nally ‘natural’ systems remain untouched by human activity.

## 958 Acknowledgements

959 This work is supported in part by the National Aeronau-  
960 tics and Space Administration Earth System Science Fel-  
961 lowship program (ESS 99-0000-0008), NSF doctoral  
962 dissertation improvement grant (DDI 9907952), and the  
963 University of Minnesota’s College of Liberal Arts and the  
964 McKnight Land-Grant Professorship Program. This work  
965 is partially an outgrowth of the Southern Yucatán Peninsu-  
966 lar Region (SYPR) project, the principal sponsors of which  
967 have been NASA-LCLUC (Land Cover and Land Use  
968 Change) program (NAG5-6046, NAG5-11134, and  
969 NNG06GD98G), Center for Integrated Studies of the  
970 Human Dimensions of Global Environmental Change,  
971 Carnegie Mellon University (NSF SBR 95-21914), and  
972 NSF-Biocomplexity (BCS-0410016). The author gratefully  
973 acknowledges the assistance of the editor and anonymous  
974 reviewers. Responsibility for the opinions expressed herein  
975 is solely that of the author.

## 976 References

- 977 Agarwal, A., Narain, S., 1991. *Global Warming in an Unequal World: A*  
978 *Case of Environmental Colonialism*. Centre for Science and Environ-  
979 *ment*, New Delhi.
- 980 Ahl, V., Allen, T.F.H., 1996. *Hierarchy Theory: A Vision, Vocabulary, and*  
981 *Epistemology*. Columbia University Press, New York.
- 982 Allen, T.F.H., Starr, T.B., 1982. *Hierarchy: Perspectives for Ecological*  
983 *Complexity*. University of Chicago Press, Chicago, IL.
- 984 Arthur, W.B., 1999. Complexity and the economy. *Science* 284 (5411), 107–  
985 109.
- 986 Bak, P., 1996. *How Nature Works: The Science of Self-Organized Critical-*  
987 *ity*. Copernicus Books, New York.

- Bell, K.P., Irwin, E.G., 2002. Spatially explicit micro-level modelling of  
land use change at the rural–urban interface. *Agricultural Economics*  
27 (3), 217–232. 988
- Blaut, J.M., 1999. Maps and spaces. *Professional Geographer* 51 (4), 510–  
515. 989
- Boguna, M., Pastor-Satorras, R., Diaz-Guilera, A., Arenas, A., 2004. Mod-  
els of social networks based on social distance attachment. *Physical*  
*Review E (Statistical, Nonlinear, and Soft Matter Physics)* 70 (5),  
56122. 990
- Bousquet, F., Le Page, C., 2004. Multi-agent simulations and ecosystem  
management: a review. *Ecological Modelling* 176 (3–4), 313–332. 991
- Brenner, N., 2001. The limits to scale? Methodological reflections on scalar  
structuration. *Progress in Human Geography* 25 (4), 591–614. 992
- Cash, D.W., Moser, S.C., 2000. Linking global and local scales: designing  
dynamic assessment and management processes. *Global Environmen-*  
*tal Change—Human & Policy Dimensions* 10 (2), 109–120. 993
- Castells, M., 1996. *The Rise of the Network Society*. Blackwell, Oxford. 994
- Castree, N., 1995. The nature of produced nature. *Antipode* 27 (1), 12–48. 995
- Cernusca, A., Bahn, M., Chemini, C., Graber, W., Siegwolf, R., Tappeiner,  
U., Tenhunen, J., 1998. ECOMONT: a combined approach of field  
measurements and process-based modelling for assessing effects of  
land-use changes in mountain landscapes. *Ecological Modelling* 113,  
167–178. 996
- Cilliers, P., 1998. *Complexity and Postmodernism: Understanding Com-*  
*plex Systems*. Routledge, New York. 997
- Cox, K.R., 1998. Spaces of dependence, spaces of engagement and the poli-  
tics of scale, or: looking for local politics. *Political Geography* 17 (1),  
1–23. 998
- Crawford, T.W., 2005. Spatial fluctuations as signatures of self-organiza-  
tion: a complex systems approach to landscape dynamics in Rondônia,  
Brazil. *Environment and Planning B: Planning & Design* 32 (6), 857. 999
- Crutchfield, J.P., 1994. Is anything ever new? Considering emergence. In:  
Cowan, G.A., Pines, D., Meltzer, D.E. (Eds.), *Complexity: Metaphors,*  
*Models, and Reality*. Addison-Wesley, Reading, MA, pp. 515–531. 1000
- Csanyi, G., Szendroi, B., 2004. Structure of a large social network. *Physical*  
*Review E (Statistical, Nonlinear, and Soft Matter Physics)* 69 (3),  
36131. 1001
- Delaney, D., Leitner, H., 1997. The political construction of scale. *Political*  
*Geography* 16 (1), 93–97. 1002
- Demeritt, D., 2001. The construction of global warming and the politics of  
science. *Annals of the Association of American Geographers* 91 (2),  
307–337. 1003
- Dowlatabadi, H., Morgan, M.G., 1993. A model framework for integrated  
studies of the climate problem. *Energy Policy* March, 209–221. 1004
- Easterling, W.E., 1997. Why regional studies are needed in the develop-  
ment of full-scale integrated assessment modeling of global climate  
change processes. *Global Environmental Change* 7, 337–356. 1005
- Easterling, W.E., Kok, K., 2002. Emergent properties of scale in global  
environmental modeling – are there any? *Integrated Assessment* 3 (2–  
3), 233–246. 1006
- Escobar, A., 1996. The deconstruction of nature. In: Peet, R., Watts, M.  
(Eds.), *Liberation Ecologies: Environment, Development, and Social*  
*Movements*. Routledge, London, pp. 46–68. 1007
- Feyerabend, P., 1993. *Against Method*. Verso, London. 1008
- Geist, H., Lambin, E., 2002. Proximate causes and underlying driving  
forces of tropical deforestation. *Bioscience* 52 (2), 143–150. 1009
- Giampietro, M., 1994. Using hierarchy theory to explore the concept of  
sustainable development. *Futures* 26 (6), 616–625. 1010
- Gibson, C., Ostrom, E., Ahn, T.-K., 2000. The concept of scale and the  
human dimensions of global change: a survey. *Ecological Economics*  
32 (2), 217–239. 1011
- Glassman, J., 2002. From Seattle (and Ubon) to Bangkok: the scales of  
resistance to corporate globalization. *Environment and Planning D* 20  
(5), 513–533. 1012
- Graham, J., 1992. Anti-essentialism and overdetermination – a response to  
Dick Peet. *Antipode* 24 (2), 141–156. 1013
- Haggett, P., 1965. *Locational Analysis in Human Geography*. Edward  
Arnold, London. 1014

- 1056 Harvey, D., 1969. Explanation in Geography. Edward Arnold, London.
- 1057 Herod, A., 1991. The production of scale in United States labour relations. *Area* 23 (1), 82–88.
- 1058 Herod, A., Wright, M.W. (Eds.), 2002. *Geographies of Power. Placing Scale*. Blackwell, Malden, MA.
- 1060 Herod, A., Wright, M.W., 2002b. Theorizing scale. In: Herod, A., Wright, M.W. (Eds.), *Geographies of Power. Placing Scale*. Blackwell, Malden, MA, pp. 17–24.
- 1064 Holland, J., 1992. *Adaptation in Natural and Artificial Systems: An Introductory Analysis with Applications to Biology, Control, and Artificial Intelligence*. MIT Press, Cambridge, MA.
- 1065 Holling, C.S., 1995. Sustainability: the cross-scale dimension. In: Murasighe, M., Shearer, W. (Eds.), *Defining and Measuring Sustainability*. The World Bank, Washington, DC, pp. 65–75.
- 1069 Jenerette, G.D., Wu, J., 2000. On the definitions of scale. *Bulletin of the Ecological Society of America* 81 (1), 104–105.
- 1072 Jonas, A.E.G., 1994. The scale politics of spatiality. *Environment and Planning D* 12, 257–264.
- 1074 Jones, K.T., 1998. Scale as epistemology. *Political Geography* 17 (1), 25–28.
- 1075 Jones, S., 2002. Social constructionism and the environment: through the quagmire. *Global Environmental Change* 12, 247–251.
- 1077 Jordan, G.J., Fortin, M.-J., 2002. Scale and topology in the ecological economics sustainability paradigm. *Ecological Economics* 41 (2), 361–366.
- 1079 Kelly, P.F., 1999. The geographies and politics of globalization. *Progress in Human Geography* 23 (3), 379–400.
- 1081 Kimble, G.H.T., 1951. The inadequacy of the regional concept. In: Stamp, L.D., Woodridge, S.W. (Eds.), *London Essays in Geography*. Longman, London, pp. 151–174.
- 1084 Lam, N., Quattrochi, D.A., 1992. On the issues of scale, resolution, and fractal analysis in the mapping sciences. *Professional Geographer* 44, 88–98.
- 1087 Lee, C., 2004. Emergence and universal computation. *Metroeconomica* 55 (2–3), 219–238.
- 1088 Lefebvre, H., 1974. *The Production of Space*. Blackwell, Cambridge.
- 1090 Leitner, H., Pavlik, C., Sheppard, E., 2002. Networks, governance and the politics of scale: interurban networks and the European Union. In: Herod, A., Wright, M.W. (Eds.), *Geographies of Power. Placing Scale*. Blackwell, Malden, MA, pp. 274–303.
- 1094 Levin, S.A., 1992. The problem of pattern and scale in ecology: the Robert H. MacArthur Award Lecture. *Ecology* 73 (6), 943–1967.
- 1095 Liverman, D., 1990. Drought impacts in Mexico. *Annals of the Association of American Geographers* 80 (49–72).
- 1098 Malanson, G., 1999. Considering complexity. *Annals of the Association of American Geographers* 89 (4), 746–753.
- 1100 Mandelbrot, B.B., 1982. The many faces of scaling: fractals, geometry of nature, and economics. In: Schieve, W.C., Allen, P.M. (Eds.), *Self-Organization and Dissipative Structures: Applications in the Physical and Social Sciences*. University of Texas Press, Austin, TX, pp. 91–109.
- 1104 Manson, S.M., 2001. Simplifying complexity: a review of complexity theory. *Geoforum* 32 (3), 405–414.
- 1106 Manson, S.M., O'Sullivan, D., 2006. Complexity theory in the study of space and place. *Environment and Planning A* 38 (4), 677.
- 1108 Marceau, D.J., Hay, G.J., 1999. Remote sensing contributions to the scale issue. *Canadian Journal of Remote Sensing* 25 (4), 357–366.
- 1109 Marquet, P.A., 2000. Ecology: invariants, scaling laws, and ecological complexity. *Science* 289 (5484), 1487–1491.
- 1112 Marston, S.A., 2000. The social construction of scale. *Progress in Human Geography* 24 (2), 219–242.
- 1114 Marston, S.A., Jones III, J.P., Woodward, K., 2005. Human geography without scale. *Transactions of the Institute of British Geographers* 30 (4), 416–432.
- 1117 McGuirk, P.M., 1997. Multiscaled interpretations of urban change: the federal, the state and the local in the Western Area Strategy of Adelaide. *Environment and Planning D* 15, 481–498.
- 1120 McLennan, G., 2003. Sociology's complexity. *Systems Research and Behavioral Science* 37 (3), 547–565.
- 1122 McMaster, R.B., Shea, K.S., 1992. Generalization in Digital Cartography. Association of American Geographers, Washington, DC.
- Michener, W.K., Baerwald, T.J., Firth, P., Palmer, M.A., Rosenberger, J.L., Sandlin, E.A., Zimmerman, H., 2001. Defining and unraveling biocomplexity. *Bioscience* 51 (12), 1018–1023.
- 1126 Miller, B., 1997. Political action and the geography of defense investment: geographical scale and the representation of the Massachusetts Miracle. *Political Geography* 16 (2), 171–185.
- 1129 Murdoch, J., 1997. Towards a geography of heterogeneous associations. *Progress in Human Geography* 21, 321–337.
- 1130 Nicolson, C.R., Starfield, A.M., Kofinas, G.P., Kruse, J.A., 2002. Ten heuristics for interdisciplinary modeling projects. *Ecosystems* 5, 376–384.
- 1132 Nowotny, H., 2005. The increase of complexity and its reduction: emergent interfaces between the natural sciences, humanities and social sciences. *Theory Culture Society* 22 (5), 15.
- 1134 O'Neill, R.V., DeAngelis, D.L., Waide, J.B., Allen, T.F.H., 1986. *A Hierarchical Concept of Ecosystems*. Princeton University Press, Princeton, NJ.
- 1138 Ostrom, E., 2005. *Understanding Institutional Diversity*. Princeton University Press, Princeton, NJ.
- 1140 O'Sullivan, D., 2004. Complexity science and human geography. *Transactions of the Institute of British Geographers* 29 (3), 282–295.
- 1142 Phillips, J.D., 1999. *Earth Surface Systems: Complexity, Order, and Scale*. Blackwell, Malden, MA.
- 1144 Pimm, S.L., 1984. The complexity and stability of ecosystems. *Nature* 307, 321–326.
- 1146 Polsky, C., Easterling, W.E., 2001. Adaptation to climate variability and change in the US great plains: a multi-scale analysis of ricardian climate sensitivities. *Agriculture, Ecosystems & Environment* 85 (1–3), 133–144.
- 1148 Popper, K.R., 1959. *The Logic of Scientific Discovery*. Hutchinson, London.
- 1150 Pratt, A.C., 1991. Discourses of locality. *Environment and Planning A* 23, 257–266.
- 1154 Prigogine, I., Allen, P.M., 1982. The challenge of complexity. In: Schieve, W.C., Allen, P.M. (Eds.), *Self-Organization and Dissipative Structures: Applications in the Physical and Social Sciences*. University of Texas Press, Austin, TX, pp. 3–39.
- 1158 Richardson, K., 2005. The hegemony of the physical sciences: an exploration in complexity thinking. *Futures* 37, 612.
- 1160 Ruddick, S., 1996. Constructing difference in public places: race, class and gender as interlocking systems. *Urban Geography* 17 (2), 132–151.
- 1162 Sawyer, R.K., 2002. Nonreductive individualism, part I: supervenience and wild disjunction. *Philosophy of the Social Sciences* 32 (4), 537–559.
- 1164 Schneider, S., 2001. A constructive deconstruction of deconstructionists: a response to Demeritt. *Annals of the Association of American Geographers* 91 (2), 338–344.
- 1166 Schroeder, R.A., Suryanata, K., 1996. Gender and class power in agroforestry systems. In: Peet, R., Watts, M. (Eds.), *Liberation Ecologies: Environment, Development, Social Movements*. Routledge, London, pp. 188–204.
- 1170 Sheppard, E., 1995. GIS and society: towards a research agenda. *Cartography and GIS, Special Contents: GIS and Society* 22 (1GIS), 5–16.
- 1172 Sheppard, E., 2002. The spaces and times of globalization: place, scale, networks, and positionality. *Economic Geography* 78 (3), 307–330.
- 1174 Sheppard, E., McMaster, R., 2004. *Scale and Geographic Inquiry: Nature, Society and Method*. Blackwell, Oxford, UK.
- 1176 Simon, H.A., 1961. Aggregation of variables in dynamic systems. *Econometrica* 29, 111–138.
- 1178 Slocum, R., 2004. Polar bears and energy efficient light bulbs: strategies to bring climate change home. *Environment and Planning D: Society and Space* 22 (3), 413–443.
- 1182 Smith, N., 1984. *Uneven Development: Nature, Capital, and the Production of Space*. Blackwell, Oxford.
- 1184 Smith, N., 1993. Homeless/global: scaling places. In: Bird, J., Curtis, B., Putnam, T., Tickner, L. (Eds.), *Mapping the Futures: Local Cultures, Global Change*. Routledge, New York, pp. 88–119.
- 1187 Smith, J., Jenks, C., 2005. Complexity, ecology and the materiality of information. *Theory Culture Society* 22 (5), 141.
- 1188 Staeheli, L.A., 1994. Empowering political struggle: spaces and scales of resistance. *Political Geography* 13, 387–392.
- 1190
- 1191

- 1192 Stewart, P., 2001. Complexity theories, social theory, and the question of  
1193 social complexity. *Philosophy of the Social Sciences* 31 (3), 323–360.
- 1194 Swyngedouw, E., 2000. Authoritarian governance, power, and the politics  
1195 of rescaling. *Environment and Planning D: Society and Space* (18), 63–  
1196 76.
- 1197 Tate, N.J., Atkinson, P.M., 2001. *Modelling Scale in Geographical Infor-*  
1198 *mation Science*. John Wiley and Sons, Chichester, UK.
- 1199 Thrift, N., 1999. The place of complexity. *Theory, Culture and Society* 16  
1200 (3), 31–69.
- 1201 Torrens, P.M., O'Sullivan, D., 2001. Cellular automata and urban simula-  
1202 tion: where do we go from here? *Environment and Planning B* 28 (2),  
1203 163–168.
- 1204 Turner, M.G., 1989. Landscape ecology: the effect of pattern on process.  
1205 *Annual Review of Ecology and Systematics* 20, 171–197.
- 1206 UCS, 2004a. *Scientific Integrity in Policymaking: An Investigation into*  
1207 *the Bush Administration's Misuse of Science*. Union of Concerned Sci-  
1208 *entists*, Cambridge, MA.
- 1209 UCS, 2004b. *Scientific Integrity in Policymaking: Further Investigation*  
1210 *into the Bush Administration's Misuse of Science*. Union of Concerned  
1211 *Scientists*, Cambridge, MA.
- 1212 Urry, J., 2003. *Global Complexity*. Polity, Cambridge, UK.
- 1213 Verburg, P.H., Soepboer, W., Limpiada, R., Espaldon, M.V.O., Sharifa, M.,  
1214 Veldkamp, A., 2002. Land use change modelling at the regional scale:  
1215 the CLUE-S model. *Environmental Management* 30 (3), 391–405.
- Walker, B.H., 1994. Landscape to regional-scale responses of terrestrial  
1216 ecosystems to global change. *Ambio* 23 (1), 67–73. 1217
- Walsh, S., Moody, A., Allen, T.R., Brown, D.G., 1997. Scale dependence of  
1218 NDVI and its relationship to mountainous terrain. In: Quattrochi,  
1219 D.A., Goodchild, M.F. (Eds.), *Scale in Remote Sensing and GIS*. Lewis  
1220 Publishers, New York, pp. 27–55. 1221
- Wessman, C.A., 1992. Spatial scales and global change: bridging the gap  
1222 from plots to GCM grid cells. *Annual Review of Ecology and System-*  
1223 *atics* 23, 175–200. 1224
- White, R., Engelen, G., 1993. Cellular automata and fractal urban form: a  
1225 cellular modelling approach to the evolution of urban land-use patterns.  
1226 *Environment and Planning D: Society and Space* 25 (8), 1175–1199. 1227
- Wiens, J.A., 1989. Spatial scaling in ecology. *Functional Ecology* 3 (4),  
1228 385–397. 1229
- Wilbanks, T.J., Kates, R.W., 1999. Global change in local places: how scale  
1230 matters. *Climatic Change* 43 (3), 601–628. 1231
- Woodgate, G., Redclift, M., 1998. From a sociology of nature to environ-  
1232 mental sociology: beyond social construction. *Environmental Values* 7,  
1233 3–24. 1234
- Wu, J., Qi, Y., 2000. Dealing with scale in landscape analysis: an overview.  
1235 *Geographic Information Sciences* 6 (1), 1–5. 1236
- Zimmerer, K.S., 2000. Rescaling irrigation in Latin America: the cultural  
1237 images and political ecology of water resources. *Ecumene* 7 (2), 150–  
1238 175. 1239