

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
manson@umn.edu

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.

Keywords: constructionism, global environmental change, realism, scale

Citation: Manson, S. M. (2008). Does scale exist? An epistemological scale continuum for complex human-environment systems. *Geoforum* 39 (2): 776-788.

PREPRESS VERSION

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: 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 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 crossdisciplinary 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 (Figure 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 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 a 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 collection, 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 (

Figure 2) into discrete regions (after Malanson 1999: 749). Scale dependence is solidly realist because scale levels do 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: 1949), which allows us to predict the behavior of systems within a range of matched spatial and temporal scales (

Figure 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 processes such as dissipative systems and self-organized criticality are powerful templates for linking processes across scales (Prigogine and Allen 1982; Bak 1996). Such explanations run the risk of incorrectly conflating pattern with process, however, and creating findings that may just be artifacts of an incomplete analysis. As Malanson notes, under complexity “simple rules can be derived that produce complex patterns but that have no discernable relations to biological or physical processes. For example, self-organization has been ascribed to phenomena that exhibit scaling features with little attention to the processes of organization” (1999: 751).

2.3 Summary: realist perspectives

Realist perspectives on scale, relying as they do on the epistemological premise that we can objectively observe reality, provide a firm foundation for human-environment research. Realist epistemology provides much of our scale terminology and the foundation for the inverse relationship between extent and resolution. Realism is also the starting point for identifying relationships between scales of explanation and observation, particularly with respect to identifying the best scales for collecting data or building theory. Realist perspectives illustrate the need for, and the challenges faced, in defining scale dependence, variance, and invariance. For the latter, complex scale offers several advantages and cautionary notes.

3 Hierarchical perspectives on scale

3.1 Realist hierarchies

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

Hierarchies are inclusive, having ranked and aggregative subdivisions, or exclusive, merely having ranked subdivisions (Gibson et al. 2000). Under realism, seemingly evident divisions in nature such as the cell-organism-community ecological construct define hierarchies. Areal extents of socioeconomic or political units, like the hierarchy of city-county-state-nation, commonly define inclusive hierarchies in human systems.

Hierarchies highlight the importance of identifying relationships between levels, particularly the mechanisms by which lower levels are connected to higher ones through upscaling, and the reverse, downscaling (Wessman 1992). Scaling physical processes of importance to biocomplexity has met with success, even if this work may deal with less with complex systems and more with just very complicated ones. This is seen in up-scaling the effects of precipitation on individual plant respiration to atmospheric carbon dioxide (Cernusca et al. 1998) or downscaling global climate models to regions (Walker 1994). Other systems, particularly coupled human-environment systems, have sufficiently complex cross-scale relationships that, while scale variance or scale dependence still apply, it may be necessary to pursue a purposely multiscale approach. Calls for regional level global change research stem in

part from the desire to take advantage of the tension between global and local research foci (Easterling 1997). Land change modeling, for example, is often conducted at the regional scale in order to accommodate higher and lower levels without being confined to them (Verburg et al. 2002).

When using hierarchies, we face a long recognized problem in that fixed scalar levels do not map onto all important processes (Haggett 1965). Using watersheds to define resolution, for instance, can help a study capture a variety of biophysical processes but may make it difficult to consider other phenomena that do not share these boundaries, such as political institutions or air movements (even when these watersheds serve as an indirect way of crossing otherwise arbitrary boundaries). Similarly, hierarchical phenomena may have lateral movements of matter or energy across the branches of the hierarchy (Dowlatabadi and Morgan 1993). A sufficiently small study site may not face issues raised by scales levels not mapping well onto real phenomena or intralevel lateral interactions, but human-environment systems are often complex and large.

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

3.2 Hierarchy theory

Hierarchy theory offers some answers to issues raised by realist hierarchies, such as the challenges of aggregation or intralevel interaction. A good deal of research has been done on linking hierarchy theory and scale (Allen and Starr 1982; O'Neill et al. 1986; Gibson et al. 2000; Easterling and Kok 2002), so here we dwell on just a few aspects of this theory with respect to the epistemological nature of scale. Of particular interest are: the commentary on subjectivity; the importance of constraints and bounding in scale levels; the distinction between absolute and relative scales; and ways to understand cross-scale interaction in complex human-environment systems.

Important to defining a given scale level in hierarchy theory is the concept of constraints – each level is characterized by the behavior of its components and bounded by constraints at other levels. Hierarchy theory identifies ecological structures that are composed vertically across scales and horizontally through holons at a single scale (Allen and Starr 1982; O'Neill et al. 1986). Holons are organized collections of interacting components (e.g., cells in an organ) that are in turn typically part of some larger entity (e.g., organs in a body). Processes in a given level are bounded by a higher level, in which processes move too slowly to be anything but a backdrop, and a lower level in which processes move too quickly to influence those in the current level.

The concept of boundedness in defining hierarchy highlights the role of the observer in identifying scale levels and contextualizes the realist basis of scale. Hierarchy theory encourages us to examine phenomena in terms of their functional and organizational aspects in order to define their spatial and temporal scales. Instead of assuming that a small spatial observational scale is useful for examining minnows and a larger one for sharks, for example, it may be better

to consider minnows via a large explanatory scale of community and the shark at the small scale of individuals (O'Neill et al. 1986). Hierarchy theory does not necessarily imply subjectivity—multiple informed observers should be able to identify similar hierarchies—but it does question a priori scale definitions and points to the importance of the observer in defining scale.

Hierarchy theory contributes to the distinction between absolute scale and relative scale. Absolute scale buttresses concepts of scale variance, scale dependence, and scale invariance by assuming that levels are independent. Relative scales are interdependent by virtue of measures common to different levels, expressed as state variables. Varying the scales of observation and explanation along a state variable allows an observer to focus on a single level while recognizing that other levels exist and are potentially important. Identifying scale levels therefore requires knowingly moving across levels rather than dogmatically staying in one (O'Neill et al. 1986). Research on agriculture and land use, for example, can leverage the role of absolute and relative scale via multilevel models (Polsky and Easterling 2001; Verburg et al. 2002)

Hierarchy theory adds another entry point to the analysis of adaptation, cross-scale interaction, and boundedness in complex human-environment systems (Holling 1995). Interaction across scales occurs at the interface of hierarchical levels through state variables, which provide a useful counterpoint to scale dependence (

Figure 4). Hierarchy theory allows for nested hierarchies. In ecological settings, for instance, organisms of different size can range across spatial scale levels and yet use the same resources without conflict due to boundedness and different spatiotemporal tempos of resource use (Pimm 1984). At the same time, rigidity, over consumption of resources, or attempts at independence by holons imperil the larger whole while simultaneously threatening the subunit with being cut off from the whole (Giampietro 1994).

3.3 Complex emergent hierarchies

Hierarchy theory contributes to, and in some senses is a subset of, the complex scale concept of complex emergent hierarchies. The term emergent refers to the synergistic qualities of a system that do not result from superposition (i.e., additive effects of system components) but instead from interactions among components. Emergence results from archetypal complex processes such as self organization or self-organized criticality. Examples of emergent systems include institutions that result from the interactions among individuals (Ostrom 2005) or the relationships among economic, agricultural, and climate processes (Easterling and Kok 2002). Issues raised by the existence of complex emergent hierarchies are relevant to biocomplexity in several ways: the role of emergence in subjectivity; reconciling simplicity and complexity in scale; and the potential for sudden shifts in complex systems to change apparent scale levels.

Emergent hierarchies lie towards the constructionist pole of the scale continuum because identifying emergent phenomena can be subjective. An emergent phenomenon is one that exhibits a structure that may not be explained by lower level dynamics and typically persists for a longer period of time than the average lifetimes of entities upon which it is built (Crutchfield 1994). The related notion of 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: 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: 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: 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 Union of Concerned Scientists (2004a; 2004b) 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 (

Figure 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 multiscalar 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 ‘flat ontologies’ that entirely displace hierarchical scale or network scale with a non-scalar structure of flows (cf. Graham 1992; Marston et al. 2005).

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

4.3 Complex constructionist scales

Complex scale has several points of contact with constructionist and network scales. There is a good deal of correspondence between self organization, emergence, and the manner in which social construction and networks channel knowledge, discourse, and power (Cilliers 1998). The evolution of knowledge in the complex ecology of human thought are akin to

complex emergence; “knowledge, representation, information, cognitions of any kind, are material consequences of this same [complex] ecology.” (Smith and Jenks 2005: 142).

Emergence and complex emergent hierarchies in particular are powerful templates for the manner in which self organization or self-organized criticality create protean structures and hierarchies in both of knowledge and material systems (Thrift 1999; Nowotny 2005). Emergent hierarchies and their attendant scale levels manifest the instabilities, emergence, supervenience, shifting equilibria, unpredictability, and path dependence on which many features of network and constructionist scales are predicated. As noted above, human-environment phenomena as different as economies and ecologies are (or at least act like) complex systems driven by interactions among constituent entities that dynamically define scale. This capacity for sudden structural change points to the role of subjectivity in analysis and the potential for actors to manipulate spatial, temporal, and organizational levels.

Complex sensitivity and nonlinearity usefully complement constructionist scale because they upset the notion of scalar hierarchies in which small scales are merely the context for large-scale processes; instead, a local action may directly affect those at a larger scale without moving through intermediary scales. Scale jumping, for example, is the process by which an actor influences events at another scale without working through intermediary levels (Smith 1993). Protestors demonstrating against environmental damage caused by globalization, for instance, use international coalitions to by-pass regional and national political scales to leap onto the global stage (Glassman 2002). In protests around the globe, Greenpeace Canada has similarly used the icon of the hungry polar bear, which faces shorter hunting seasons as the polar ice melts earlier each year (Slocum 2004). The potential for a small change at one level to lead to large changes in others has metaphorical and actual relevance for human-environment systems that

increasingly rely on technological networks to almost instantly trade information (McLennan 2003). In the extreme, scale in a network is mutually constituted, where scale levels such as the global and local are simultaneously defined by one another (McGuirk 1997).

4.4 Summary: constructionist perspectives

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

5 Lessons of the scale continuum

The existence of the realist-constructionist scale continuum makes it difficult, perhaps impossible, to justify a single *a priori* theoretical framework to understand scale for 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: 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 hierarchal 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: 1021) teams are ingrained

in the US National Science Foundation Biocomplexity program, for example, but in practice teams for most projects tend towards to 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 work could benefit social science in general and constructionist research on networks in particular, while itself gaining from greater engagement with these fields.

In sum, we must strike a balance between accepting seemingly apparent scales of observation and explanation and recognizing their purposeful construction for social, economic,

and political ends. Realist scales provide an organizing principle for a variety of systems. Realist hierarchies and hierarchy theory leave some room for observer objectivity but neither addresses many of the corollaries of social constructionism, particularly when dealing with complex human-environment systems. In terms of raw subject matter, movement along the continuum from realism to constructionism seems more necessary as one goes from physical and biological systems through ecological and human-environment systems to the social and policy domains. Physical systems are not immune to social constructionism, but the relative absence of explicit human decision making and intentionality in the system of study makes them more amenable to realist perspectives on scale. In terms of scientific practice, however, social constructionism is very applicable to the messy human research enterprise (in and of itself) and its focus on a world in which few nominally ‘natural’ systems remain untouched by human activity.

Acknowledgements

This work is supported in part by the National Aeronautics and Space Administration Earth System Science Fellowship program (ESS 99-0000-0008), NSF doctoral dissertation improvement grant (DDI 9907952), and the University of Minnesota’s College of Liberal Arts and the McKnight Land-Grant Professorship Program. This work is partially an outgrowth of the Southern Yucatán Peninsular Region (SYPR) project, the principal sponsors of which have been NASA-LCLUC (Land Cover and Land Use Change) program (NAG5-6046, NAG5-11134, and NNG06GD98G), Center for Integrated Studies of the Human Dimensions of Global Environmental Change, Carnegie Mellon University (NSF SBR 95-21914), and NSF-Biocomplexity (BCS-0410016). The author gratefully acknowledges the assistance of the editor and anonymous reviewers. Responsibility for the opinions expressed herein is solely that of the

author.

References

- Agarwal, A. and Narain, S., 1991. *Global Warming in an Unequal World: A Case of Environmental Colonialism*. New Delhi, Centre for Science and Environment.
- Ahl, V. and Allen, T. F. H., 1996. *Hierarchy Theory: A Vision, Vocabulary, and Epistemology*. New York, Columbia University Press.
- Allen, T. F. H. and Starr, T. B., 1982. *Hierarchy: Perspectives for Ecological Complexity*. Chicago, Illinois, University of Chicago Press.
- Arthur, W. B., 1999. Complexity and the economy. *Science* 284 (5411), 107-09.
- Bak, P., 1996. *How Nature Works: The Science of Self-Organized Criticality*. New York, Copernicus Books.
- Bell, K. P. and Irwin, E. G., 2002. Spatially explicit micro-level modelling of land use change at the rural-urban interface. *Agricultural Economics* 27 (3), 217-32.
- Blaut, J. M., 1999. Maps and spaces. *Professional Geographer* 51 (4), 510-15.
- Boguna, M., Pastor-Satorras, R., Diaz-Guilera, A. and Arenas, A., 2004. Models of social networks based on social distance attachment. *Physical Review E (Statistical, Nonlinear, and Soft Matter Physics)* 70 (5), 56122.
- Bousquet, F. and Le Page, C., 2004. Multi-agent simulations and ecosystem management: a review. *Ecological Modelling* 176 (3-4), 313-32.
- Brenner, N., 2001. The limits to scale? Methodological reflections on scalar structuration. *Progress in Human Geography* 25 (4), 591-614.
- Cash, D. W. and Moser, S. C., 2000. Linking global and local scales: designing dynamic assessment and management processes. *Global Environmental Change-Human & Policy Dimensions* 10 (2), 109-20.

- Castells, M., 1996. *The Rise of the Network Society*. Oxford, Blackwell.
- Castree, N., 1995. The nature of produced nature. *Antipode* 27 (1), 12-48.
- Cernusca, A., Bahn, M., Chemini, C., Graber, W., Siegwolf, R., Tappeiner, U. and 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, 167-78.
- Cilliers, P., 1998. *Complexity and Postmodernism: Understanding Complex Systems*. New York, Routledge.
- Cox, K. R., 1998. Spaces of dependence, spaces of engagement and the politics of scale, or: looking for local politics. *Political Geography* 17 (1), 1-23.
- Crawford, T. W., 2005. Spatial fluctuations as signatures of self-organization: a complex systems approach to landscape dynamics in Rondônia, Brazil. *Environment and Planning B: Planning & Design* 32 (6), 857.
- Crutchfield, J. P., 1994. Is anything ever new? Considering emergence. In: Cowan, G. A., Pines, D. and Meltzer, D. E. (Eds.), *Complexity: Metaphors, Models, and Reality*. Reading, Massachusetts, Addison-Wesley pp. 515-31.
- Csanyi, G. and Szendroi, B., 2004. Structure of a large social network. *Physical Review E (Statistical, Nonlinear, and Soft Matter Physics)* 69 (3), 36131.
- Delaney, D. and Leitner, H., 1997. The political construction of scale. *Political Geography* 16 (1), 93-97.
- Demeritt, D., 2001. The construction of global warming and the politics of science. *Annals of the Association of American Geographers* 91 (2), 307-37.

- Dowlatabadi, H. and Morgan, M. G., 1993. A model framework for integrated studies of the climate problem. *Energy Policy* March, 209-21.
- Easterling, W. E., 1997. Why regional studies are needed in the development of full-scale integrated assessment modeling of global climate change processes. *Global Environmental Change* 7, 337-56.
- Easterling, W. E. and Kok, K., 2002. Emergent properties of scale in global environmental modeling - are there any? *Integrated Assessment* 3 (2-3), 233-46.
- Escobar, A., 1996. The deconstruction of nature. In: Peet, R. and Watts, M. (Eds.), *Liberation Ecologies: Environment, Development, and Social Movements*. London, Routledge pp. 46-68.
- Feyerabend, P., 1993. *Against Method*. London, Verso.
- Geist, H. and Lambin, E., 2002. Proximate causes and underlying driving forces of tropical deforestation. *Bioscience* 52 (2), 143-50.
- Giampietro, M., 1994. Using hierarchy theory to explore the concept of sustainable development. *Futures* 26 (6), 616-25.
- Gibson, C., Ostrom, E. and Ahn, T.-K., 2000. The concept of scale and the human dimensions of global change: a survey. *Ecological Economics* 32 (2), 217-39.
- Glassman, J., 2002. From Seattle (and Ubon) to Bangkok: the scales of resistance to corporate globalization. *Environment and Planning D* 20 (5), 513-33.
- Graham, J., 1992. Anti-essentialism and overdetermination - a response to Dick Peet. *Antipode* 24 (2), 141-56.
- Haggett, P., 1965. *Locational Analysis in Human Geography*. London, Edward Arnold.
- Harvey, D., 1969. *Explanation in Geography*. London, Edward Arnold.

- Herod, A., 1991. The production of scale in United States labour relations. *Area* 23 (1), 82-88.
- Herod, A. and Wright, M. W., Eds., 2002a. *Geographies of Power. Placing Scale*. Malden, Massachusetts, Blackwell.
- , 2002b. Theorizing scale. In: Herod, A. and Wright, M. W. (Eds.), *Geographies of Power. Placing Scale*. Malden, Massachusetts, Blackwell pp. 17-24.
- Holland, J., 1992. *Adaptation in Natural and Artificial Systems: An Introductory Analysis with Applications to Biology, Control, and Artificial Intelligence*. Cambridge, Massachusetts, MIT Press.
- Holling, C. S., 1995. Sustainability: the cross-scale dimension. In: Murasinghe, M. and Shearer, W. (Eds.), *Defining and Measuring Sustainability*. Washington, D.C., The World Bank pp. 65-75.
- Jenerette, G. D. and Wu, J., 2000. On the definitions of scale. *Bulletin of the Ecological Society of America* 81 (1), 104-05.
- Jonas, A. E. G., 1994. The scale politics of spatiality. *Environment and Planning D* 12, 257-64.
- Jones, K. T., 1998. Scale as epistemology. *Political Geography* 17 (1), 25-28.
- Jones, S., 2002. Social constructionism and the environment: through the quagmire. *Global Environmental Change* 12, 247-51.
- Jordan, G. J. and Fortin, M.-J., 2002. Scale and topology in the ecological economics sustainability paradigm. *Ecological Economics* 41 (2), 361-66.
- Kelly, P. F., 1999. The geographies and politics of globalization. *Progress in Human Geography* 23 (3), 379-400.
- Kimble, G. H. T., 1951. The inadequacy of the regional concept. In: Stamp, L. D. and Woodrige, S. W. (Eds.), *London Essays in Geography*. London, Longman pp. 151-74.

- Lam, N. and Quattrochi, D. A., 1992. On the issues of scale, resolution, and fractal analysis in the mapping sciences. *Professional Geographer* 44, 88-98.
- Lee, C., 2004. Emergence and universal computation. *Metroeconomica* 55 (2-3), 219-38.
- Lefebvre, H., 1974. *The Production of Space*. Cambridge, Blackwell.
- Leitner, H., Pavlik, C. and Sheppard, E., 2002. Networks, governance and the politics of scale: interurban networks and the European Union. In: Herod, A. and Wright, M. W. (Eds.), *Geographies of Power. Placing Scale*. Malden, Massachusetts, Blackwell pp. 274-303.
- Levin, S. A., 1992. The problem of pattern and scale in ecology: the Robert H. MacArthur Award Lecture. *Ecology* 73 (6), 943-1967.
- Liverman, D., 1990. Drought impacts in Mexico. *Annals of the Association of American Geographers* 80 (49-72).
- Malanson, G., 1999. Considering complexity. *Annals of the Association of American Geographers* 89 (4), 746-53.
- Mandelbrot, B. B., 1982. The many faces of scaling: fractals, geometry of nature, and economics. In: Schieve, W. C. and Allen, P. M. (Eds.), *Self-Organization and Dissipative Structures: Applications in the Physical and Social Sciences*. Austin, Texas, University of Texas Press pp. 91-109.
- Manson, S. M., 2001. Simplifying complexity: a review of complexity theory. *Geoforum* 32 (3), 405-14.
- Manson, S. M. and O'Sullivan, D., 2006. Complexity theory in the study of space and place. *Environment and Planning A* 38 (4), 677.
- Marceau, D. J. and Hay, G. J., 1999. Remote sensing contributions to the scale issue. *Canadian Journal of Remote Sensing* 25 (4), 357-66.

- Marquet, P. A., 2000. Ecology: invariants, scaling laws, and ecological complexity. *Science* 289 (5484), 1487-91.
- Marston, S. A., 2000. The social construction of scale. *Progress in Human Geography* 24 (2), 219-42.
- Marston, S. A., Jones, J. P., III and Woodward, K., 2005. Human geography without scale. *Transactions of the Institute of British Geographers* 30 (4), 416-32.
- 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, 481-98.
- McLennan, G., 2003. Sociology's complexity. *Systems Research and Behavioral Science* 37 (3), 547-65.
- McMaster, R. B. and Shea, K. S., 1992. *Generalization in Digital Cartography*. Washington, D.C., Association of American Geographers.
- Michener, W. K., Baerwald, T. J., Firth, P., Palmer, M. A., Rosenberger, J. L., Sandlin, E. A. and Zimmerman, H., 2001. Defining and unraveling biocomplexity. *Bioscience* 51 (12), 1018-23.
- Miller, B., 1997. Political action and the geography of defense investment: geographical scale and the representation of the Massachusetts Miracle. *Political Geography* 16 (2), 171-85.
- Murdoch, J., 1997. Towards a geography of heterogeneous associations. *Progress in Human Geography* 21, 321-37.
- Nicolson, C. R., Starfield, A. M., Kofinas, G. P. and Kruse, J. A., 2002. Ten heuristics for interdisciplinary modeling projects. *Ecosystems* 5, 376-84.
- 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.

- O'Neill, R. V., DeAngelis, D. L., Waide, J. B. and Allen, T. F. H., 1986. A Hierarchical Concept of Ecosystems. Princeton, New Jersey, Princeton University Press.
- O'Sullivan, D., 2004. Complexity science and human geography. *Transactions of the Institute of British Geographers* 29 (3), 282-95.
- Ostrom, E., 2005. *Understanding Institutional Diversity*. Princeton, New Jersey, Princeton University Press.
- Phillips, J. D., 1999. *Earth Surface Systems: Complexity, Order, and Scale*. Malden, MA, Blackwell.
- Pimm, S. L., 1984. The complexity and stability of ecosystems. *Nature* 307, 321-26.
- Polsky, C. and 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), 133-44.
- Popper, K. R., 1959. *The Logic of Scientific Discovery*. London, Hutchinson.
- Pratt, A. C., 1991. Discourses of locality. *Environment and Planning A* 23, 257-66.
- Prigogine, I. and Allen, P. M., 1982. The challenge of complexity. In: Schieve, W. C. and Allen, P. M. (Eds.), *Self-Organization and Dissipative Structures: Applications in the Physical and Social Sciences*. Austin, Texas, University of Texas Press pp. 3-39.
- Richardson, K., 2005. The hegemony of the physical sciences: an exploration in complexity thinking. *Futures* 37, 612.
- Ruddick, S., 1996. Constructing difference in public places: race, class and gender as interlocking systems. *Urban Geography* 17 (2), 132-51.
- Sawyer, R. K., 2002. Nonreductive individualism, part I: supervenience and wild disjunction. *Philosophy of the Social Sciences* 32 (4), 537-59.

- Schneider, S., 2001. A constructive deconstruction of deconstructionists: a response to Demeritt. *Annals of the Association of American Geographers* 91 (2), 338-44.
- Schroeder, R. A. and Suryanata, K., 1996. Gender and class power in agroforestry systems. In: Peet, R. and Watts, M. (Eds.), *Liberation Ecologies: Environment, Development, Social Movements*. London, Routledge pp. 188-204.
- Sheppard, E., 1995. GIS and society: towards a research agenda. *Cartography and GIS, Special Contents: GIS and Society* 22 (1GIS), 5-16.
- , 2002. The spaces and times of globalization: place, scale, networks, and positionality. *Economic Geography* 78 (3), 307-30.
- Sheppard, E. and McMaster, R., 2004. *Scale and Geographic Inquiry: Nature, Society and Method*. Oxford, United Kingdom, Blackwell.
- Simon, H. A., 1961. Aggregation of variables in dynamic systems. *Econometrica* 29, 111-38.
- 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), 413-43.
- Smith, J. and Jenks, C., 2005. Complexity, ecology and the materiality of information. *Theory Culture Society* 22 (5), 141.
- Smith, N., 1984. *Uneven Development: Nature, Capital, and the Production of Space*. Oxford, Blackwell.
- , 1993. Homeless/global: scaling places. In: Bird, J., Curtis, B., Putnam, T. and Tickner, L. (Eds.), *Mapping the Futures: Local Cultures, Global Change*. New York, Routledge pp. 88-119.
- Staeheli, L. A., 1994. Empowering political struggle: spaces and scales of resistance. *Political Geography* 13, 387-92.

- Stewart, P., 2001. Complexity theories, social theory, and the question of social complexity. *Philosophy of the Social Sciences* 31 (3), 323-60.
- Swyngedouw, E., 2000. Authoritarian governance, power, and the politics of rescaling. *Environment and Planning D: Society and Space* (18), 63-76.
- Tate, N. J. and Atkinson, P. M., 2001. *Modelling Scale in Geographical Information Science*. Chichester, United Kingdom, John Wiley and Sons.
- Thrift, N., 1999. The place of complexity. *Theory, Culture and Society* 16 (3), 31-69.
- Torrens, P. M. and O'Sullivan, D., 2001. Cellular automata and urban simulation: where do we go from here? *Environment and Planning B* 28 (2), 163-68.
- Turner, M. G., 1989. Landscape ecology: the effect of pattern on process. *Annual Review of Ecology and Systematics* 20, 171-97.
- UCS, 2004a. *Scientific Integrity in Policymaking: An Investigation into the Bush Administration's Misuse of Science*. Cambridge, Massachusetts, Union of Concerned Scientists.
- , 2004b. *Scientific Integrity in Policymaking: Further Investigation into the Bush Administration's Misuse of Science*. Cambridge, Massachusetts, Union of Concerned Scientists.
- Urry, J., 2003. *Global Complexity*. Cambridge, United Kingdom, Polity.
- Verburg, P. H., Soepboer, W., Limpiada, R., Espaldon, M. V. O., Sharifa, M. and Veldkamp, A., 2002. Land use change modelling at the regional scale: the CLUE-S model. *Environmental Management* 30 (3), 391-405.
- Walker, B. H., 1994. Landscape to regional-scale responses of terrestrial ecosystems to global change. *Ambio* 23 (1), 67-73.

- Walsh, S., Moody, A., Allen, T. R. and Brown, D. G., 1997. Scale dependence of NDVI and its relationship to mountainous terrain. In: Quattrochi, D. A. and Goodchild, M. F. (Eds.), *Scale in Remote Sensing and GIS*. New York, Lewis Publishers pp. 27-55.
- Wessman, C. A., 1992. Spatial scales and global change: bridging the gap from plots to GCM grid cells. *Annual Review of Ecology and Systematics* 23, 175-200.
- White, R. and Engelen, G., 1993. Cellular automata and fractal urban form: a cellular modelling approach to the evolution of urban land-use patterns. *Environment and Planning D: Society and Space* 25 (8), 1175-99.
- Wiens, J. A., 1989. Spatial scaling in ecology. *Functional Ecology* 3 (4), 385-97.
- Wilbanks, T. J. and Kates, R. W., 1999. Global change in local places: how scale matters. *Climatic Change* 43 (3), 601-28.
- Woodgate, G. and Redclift, M., 1998. From a sociology of nature to environmental sociology: beyond social construction. *Environmental Values* 7, 3-24.
- Wu, J. and Qi, Y., 2000. Dealing with scale in landscape analysis: an overview. *Geographic Information Sciences* 6 (1), 1-5.
- Zimmerer, K. S., 2000. Rescaling irrigation in Latin America: the cultural images and political ecology of water resources. *Ecumene* 7 (2), 150-75.

Figures

Figure 1: Epistemological scale continuum

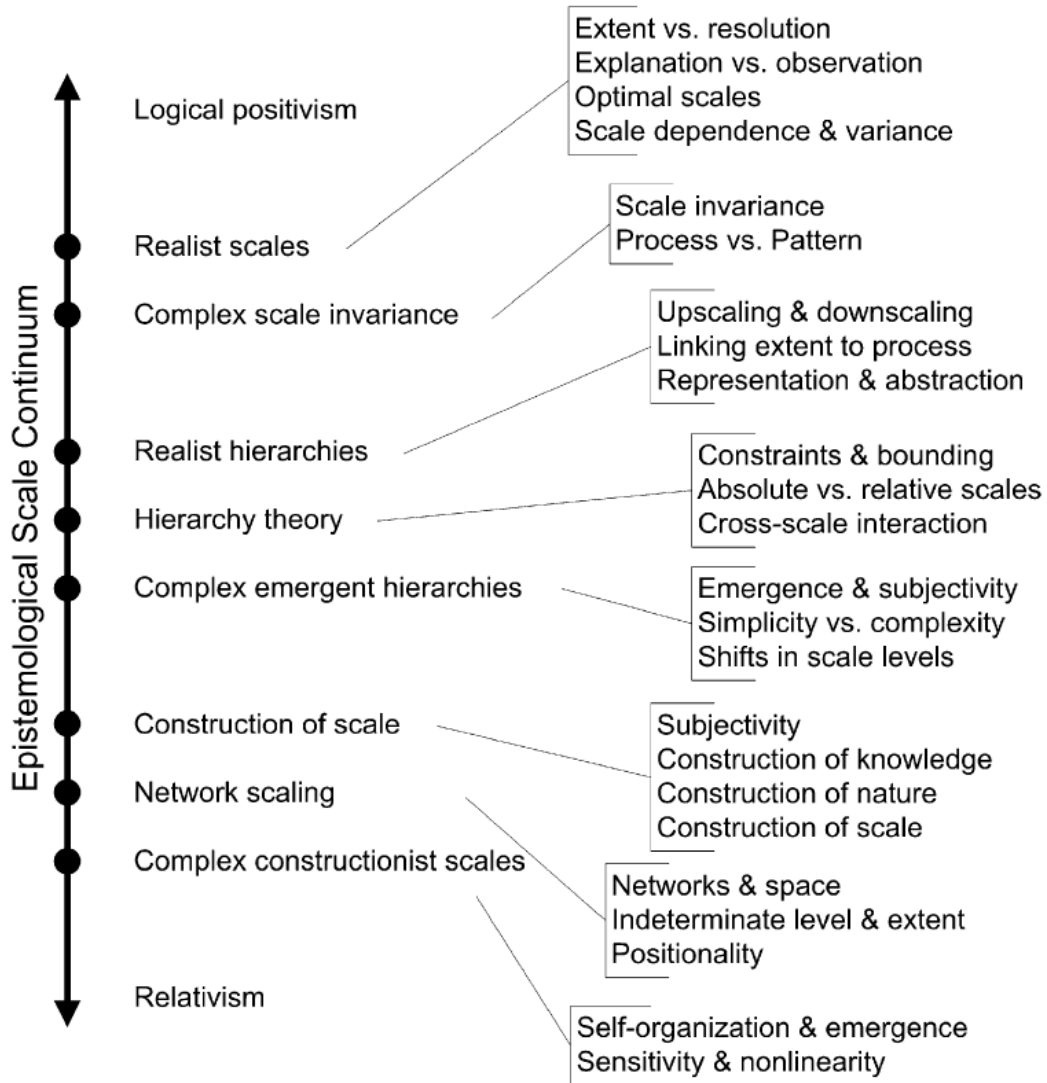


Figure 2: Scale dependence for forests

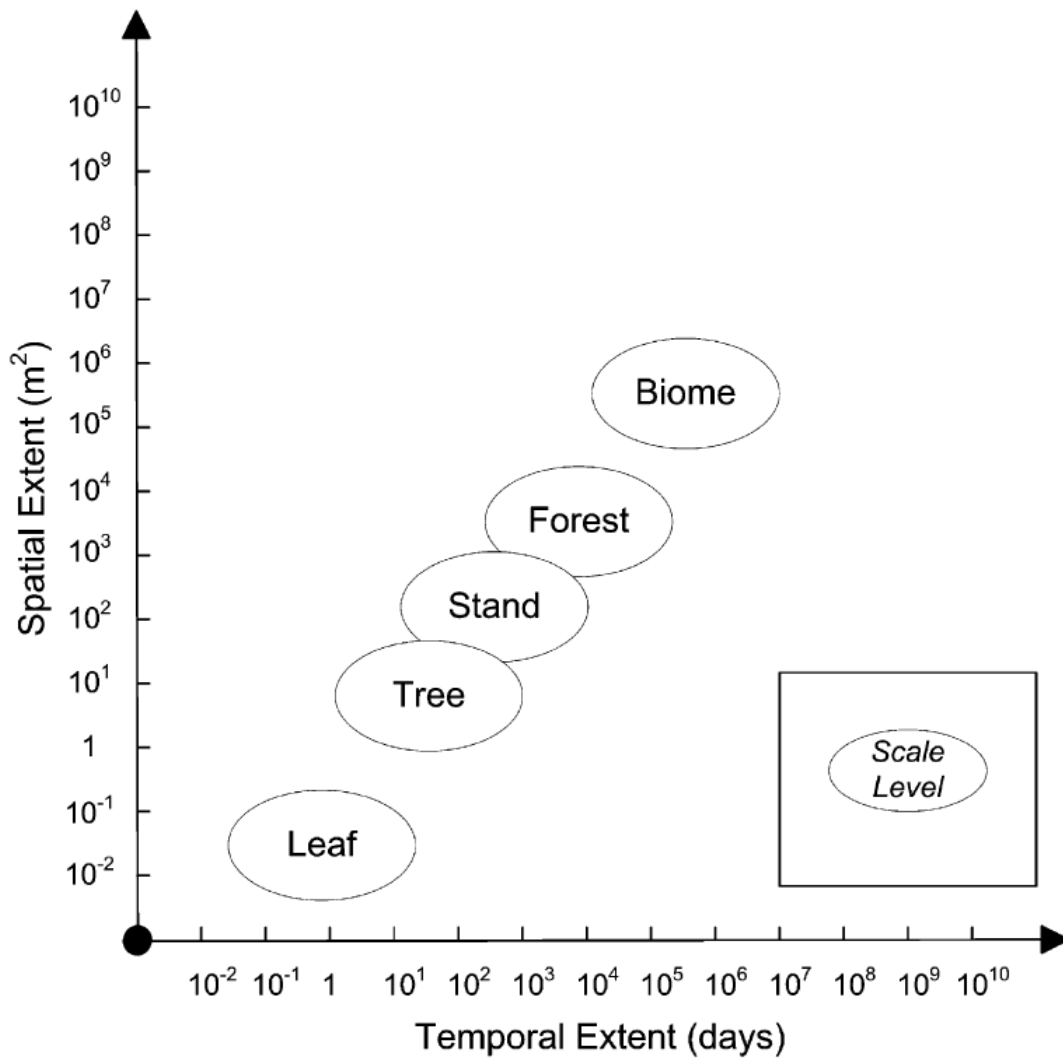


Figure 3: Space-time scaling and predictability

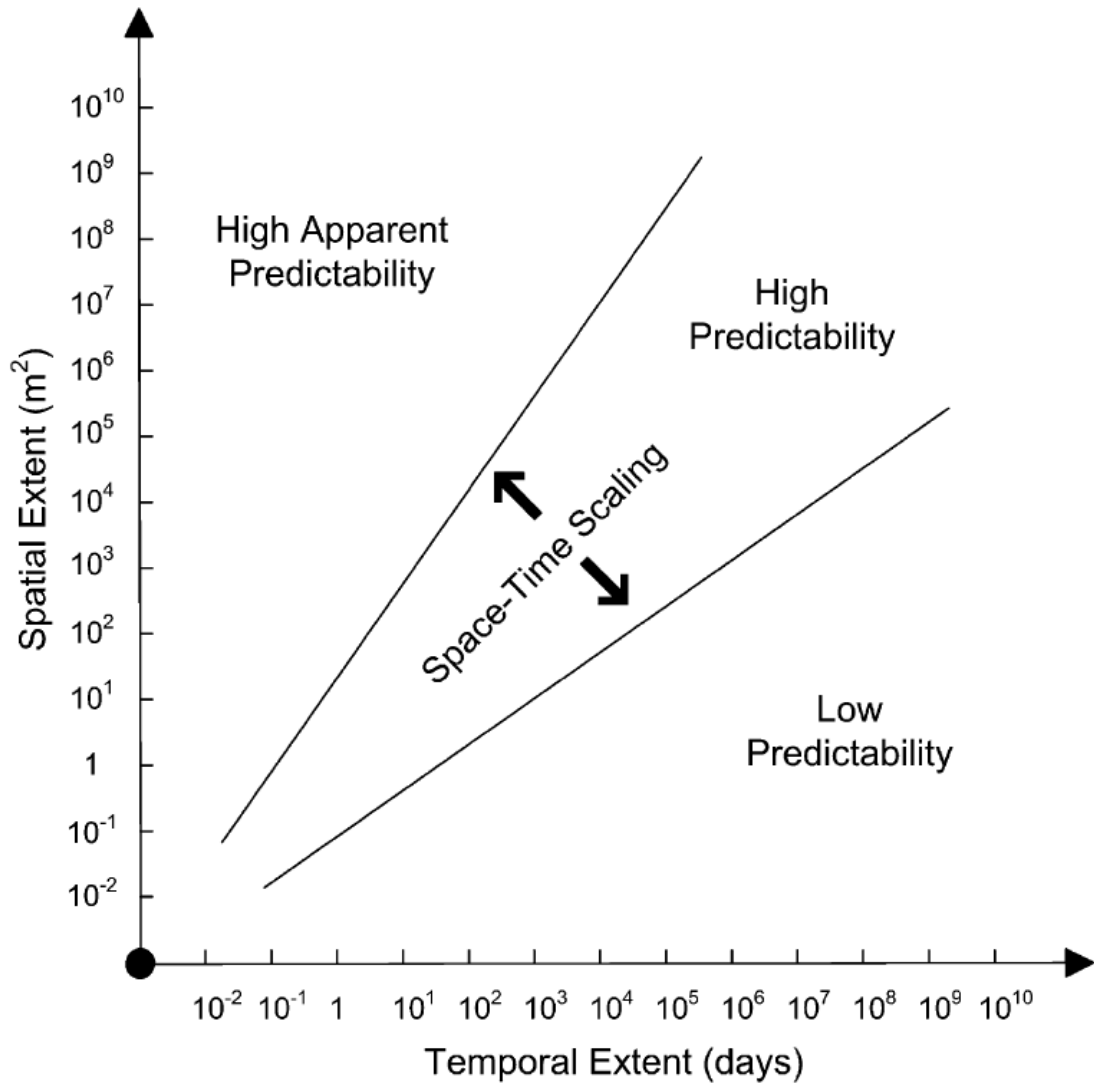


Figure 4: Relative hierarchical scales, boundaries, and state variables

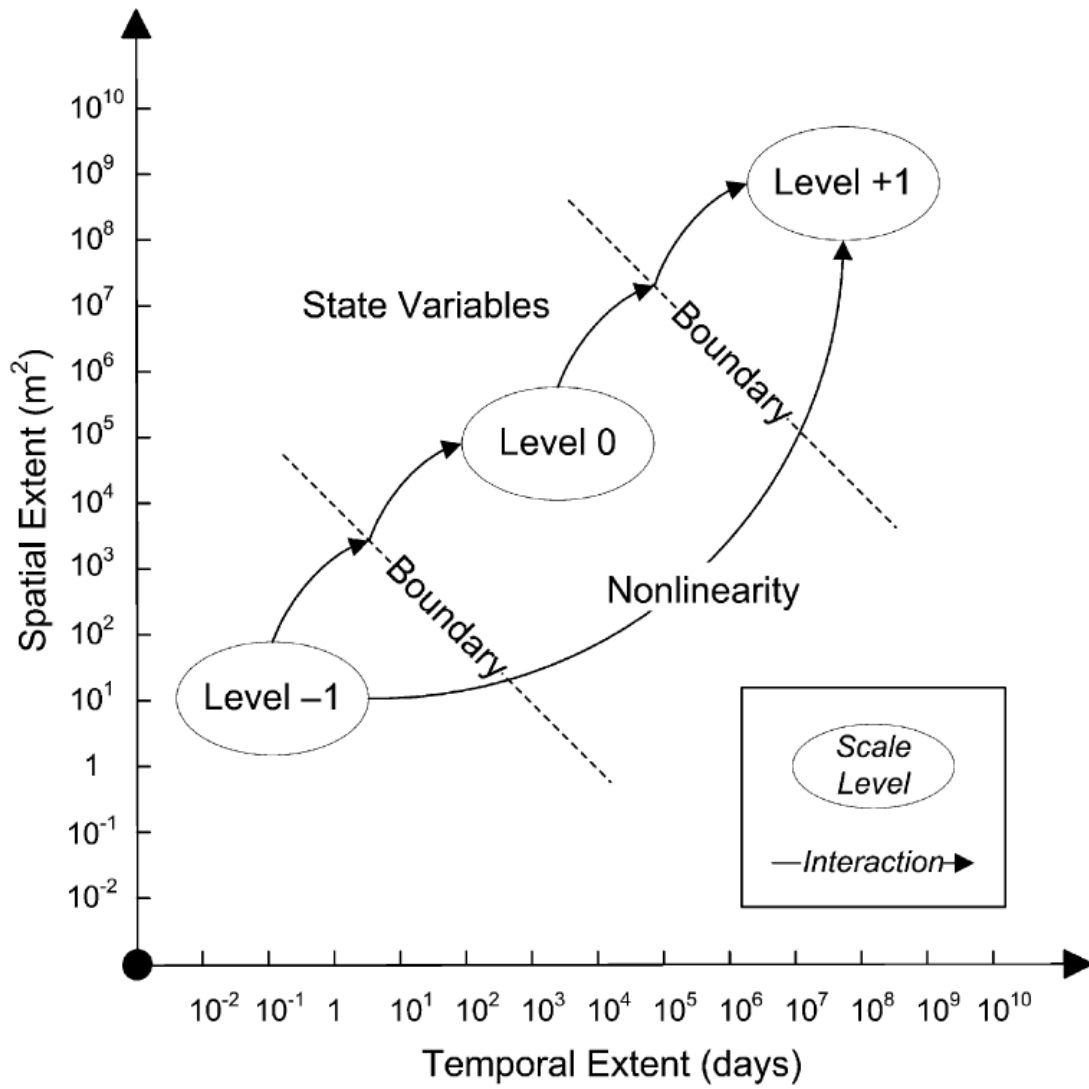


Figure 5: Network scales for a single household

