

COMPLEX ADAPTIVE SYSTEMS: CROSS-SCALE STRUCTURE AND
RESILIENCE

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Shana M Sundstrom

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COMPLEX ADAPTIVE SYSTEMS: CROSS-SCALE STRUCTURE AND RESILIENCE

Shana M Sundstrom, Ph.D.

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Adviser: Craig R. Allen

This dissertation is focused on scaling and resilience of complex adaptive systems, including ecological and economic systems. In particular it is concerned with the textural discontinuity hypothesis (hereafter called the discontinuity hypothesis), which describes how the distinct spatial and temporal scales of processes that shape systems in turn generates distinct spatial and temporal scales in system structure and entities interacting with that structure; the cross-scale resilience model, which uses the discontinuity hypothesis as the foundation of a theory about specific system features that drive ecological resilience; panarchy and adaptive cycles, which articulate how system dynamics at the above-mentioned scales change over time and how feedbacks across those scales informs system behavior; and the notion of spatial regimes in ecological structure. I both expand existing frameworks to accommodate non-ecological complex systems, and test my hypotheses in a variety of economic and ecological systems.

Some general findings of my analyses are that the objective identification of scale domains in many types of complex systems can be useful for understanding how pattern and process shape structure and impact system-level resilience. Economic systems, for example, as expressed by Gross Domestic Product, fall into distinct, non-random size classes that suggest there are scale-specific processes generating basins of attraction. I expand the cross-scale resilience model to incorporate abundance, a

species and community attribute that is mechanistically related to the provision of function and resilience. The coral reef fish communities of the Hawaiian archipelago were analysed to see if their cross-scale resilience differed amongst coral dominated and macroalgal and turf dominated reefs, with the surprising result that the macroalgal-turf communities were more resilient. In a twist on classic regime shift theory, which typically focuses on temporal shifts within a single ecosystem, I used a novel information theory method to successfully detect spatial boundaries and transition zones between types of ecological systems by using animal community data. Finally, I argue why the adaptive cycle may be a result of endogenous processes in complex adaptive systems, and is not just a convenient metaphor for cycling behavior and dynamics.

PREVIEW

DEDICATION

To Sterling, for always thinking I'm smarter than I actually am, and unconditionally supporting me throughout this process.

PREVIEW

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PREVIEW

PREFACE

“Nature is an endless combination and repetition of a very few laws”

(Ralph Waldo Emerson, Essay, Lectures and Orations. London,
William S. Orr and Co. 1851).

It is increasingly recognized that the systems of most interest to humans, including ecosystems, are complex adaptive systems and need to be investigated and understood as such. A well known physics professor once told me that if we can make an airplane fly through the air then we can remedy climate change. It is easy to see now the problems with conflating two categorically different kinds of systems and having the same expectation regarding their behavior, but at the time I could only walk away frustrated by the logical flaw I could feel but not articulate. An airplane is a complicated but non-complex mechanical system where part A + part B + part C = an airplane, and its functioning as such is predictable and reliable. The climate is a complex adaptive system, and by definition is neither predictable nor ‘reliable’ in its long-term behavior.

There is no singular definition of a complex adaptive system (CAS), and given the breadth of system types encompassed by this term this is only appropriate. Within this dissertation, my definition of a CAS changes in emphasis as I navigate from ecological to economic and back again to ecological systems. My primary motivation in this dissertation was to explore some concepts that have as their starting

assumptions the lens of complex adaptive systems. These concepts are part of a collective of ideas that fall under the umbrella of ecological resilience. They are all the brainchild of C.S. Holling and his colleagues, and when viewed as a package operate as a relatively comprehensive framework currently existing for understanding systems as complex adaptive systems. This is not to say that ecological resilience encompasses *all* concepts useful for investigating CAS's—far from it. But it is an appealing framework because of the richness of interconnected ideas that allows a researcher to systematically examine concepts central to ecology, such as scales, stability, and thresholds, with the assumptions of complex adaptive systems theory.

In short, because these concepts will be elaborated at length (and perhaps ad nauseum) in the following chapters this dissertation focused on the following: the textural discontinuity hypothesis (hereafter called the discontinuity hypothesis), which describes how the distinct spatial and temporal scales of processes that shape systems in turn generates distinct spatial and temporal scales in system structure and entities interacting with that structure; the cross-scale resilience model, which uses the discontinuity hypothesis as the foundation of a theory about specific system features that drive ecological resilience; panarchy and adaptive cycles, which articulate how system dynamics at the above-mentioned scales change over time and how feedbacks across those scales informs system behavior; and the notion of spatial regimes in ecological structure (Figure 1).

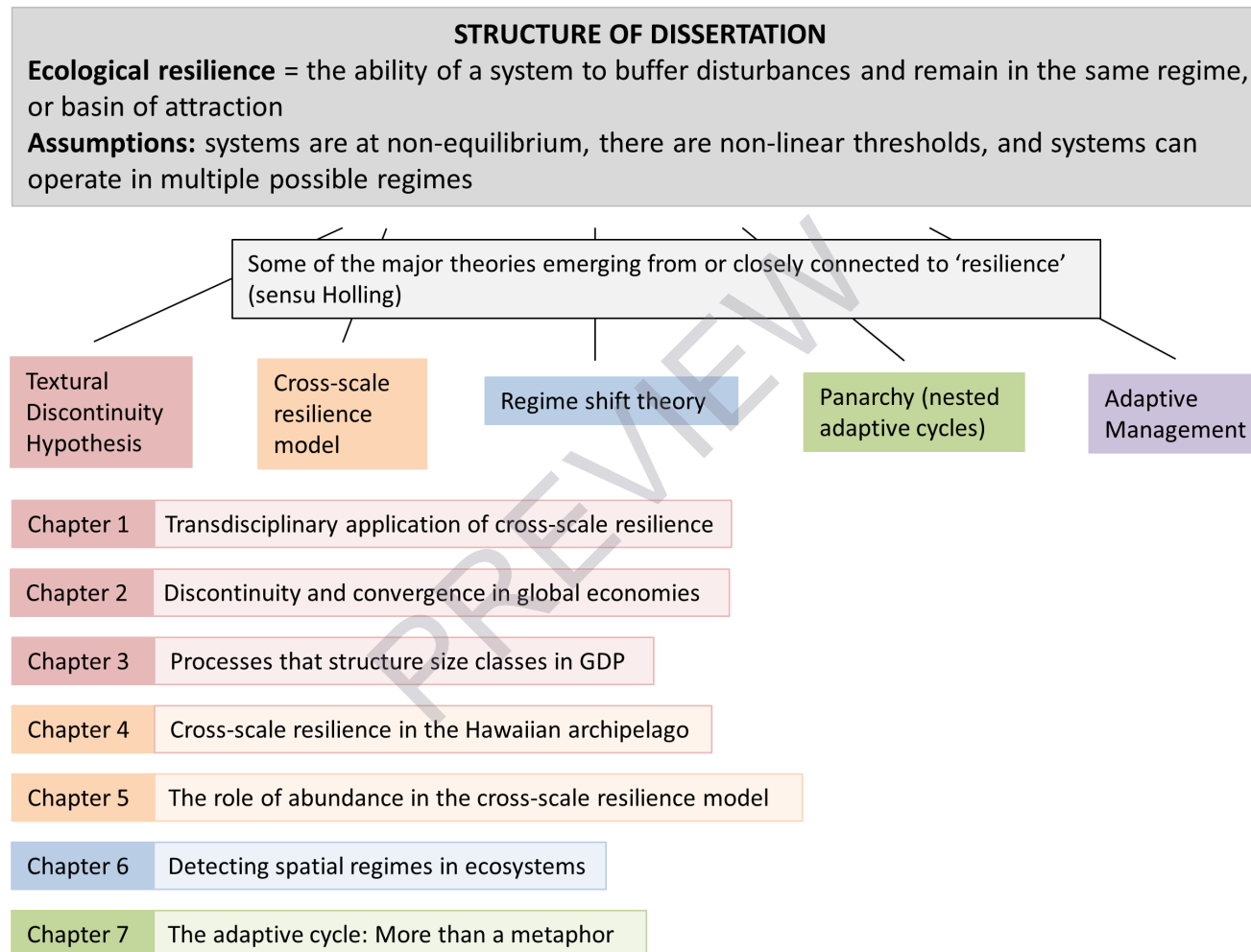


Figure 1 Relationship of dissertation chapters to extended theory of ecological resilience

In Chapter 1, “Transdisciplinary application of cross-scale resilience”, I articulate how the objective identification of scale domains in complex adaptive systems via the discontinuity hypothesis could be utilized in other fields, such as social-ecological resilience, economics, and anthropology. In Chapter 2, “Discontinuity and convergence in global economies”, I apply the discontinuity hypothesis to global cross-national economic systems, using Gross Domestic Product (GDP) to test whether there are scale domains, which can also be understood as basins of attraction, in GDP. In Chapter 3, “Processes that structure size classes in GDP”, I test whether a suite of socio-political-cultural traits associated within economics with GDP are possible explanatory variables/processes for the scale domains found in GDP. In Chapter 4, “Cross-scale resilience in the Hawaiian archipelago”, I compare the cross-scale resilience of coral reef fish communities in the Hawaiian archipelago. In Chapter 5, “The role of abundance in the cross-scale resilience model”, I discuss the implications of expanding the cross-scale resilience model to incorporate abundance. In Chapter 6, “Detecting spatial regimes in ecosystems”, I use Fisher Information to test the location of ecological boundaries (spatial regimes) between ecosystems based on bird community structure, and compare it to the location of boundaries given static eco-region maps traditionally used by agencies, managers, and researchers. In Chapter 7, “The adaptive cycle: More than a metaphor”, I argue that the adaptive cycle and nested adaptive cycles (called a panarchy) may represent endogenous system dynamics of complex adaptive systems as opposed to a useful metaphor for system behavior, and I provide a variety of metrics by which this could be tested. And finally, in the Conclusion, I provide a brief summary of the implications of this body of research.

CHAPTER 1 TRANSDISCIPLINARY APPLICATION OF THE CROSS-SCALE RESILIENCE MODEL

Introduction

Scientists often have a poor understanding of the system-level behavior and dynamics of complex systems, such as ecosystems, economies, or integrated social-ecological-economic systems, whereas they are more likely to have a highly refined understanding of the components of complex systems, such as species or the behavior of individuals in an economy. The essence of a complex system, however, is that its behavior cannot be deduced from simply aggregating knowledge of the components. This fundamental constraint compels the need for tools that allow us to track the impact and consequences of localized changes or disturbances on system-level behavior and dynamics over time and space. The field of resilience science in ecology has studied resilience as an emergent system-level feature of complex ecological and social-ecological systems, and has developed a tool for quantitatively assessing ecosystem resilience, called the cross-scale resilience model. We argue that the cross-scale resilience model can be applied to other types of complex systems.

Once the provenance of ecology (Lovelock 1992), artificial life (Langton 1986), and genetics (Kauffman 1995; Serra et al. 2007), the application of complex adaptive systems theory to new fields has broadened considerably, from health care (data flows and human interactions) (Tan et al. 2005), food and water security (Villa et al. 2014), software development (Batra et al. 2011), business (Mason 2007), legal

systems (Ruhl 2014), medical research (Greek & Hansen 2013), engineered systems such as electrical grids and traffic management (Zhang et al. 2008; Haghnvis & Askin 2012), urban water systems (Kanta & Zechman 2014) and many more. Scientists are embracing a more complex view of system dynamics, and moving beyond long-held assumptions of linear equilibrium behavior for many different types of systems. Understanding universal, or at least broadly applicable, rules of complex systems behavior would assist the challenging task of understanding the ‘wicked problems’ society faces, such as rapid environmental and social change including climate change, economic and socio-cultural challenges, biodiversity loss, and the degradation of social-ecological systems (Vitousek et al. 1997; Millenium Ecosystem Assessment 2005).

Comparative analyses of complex systems have, in fact, demonstrated commonalities among distinctly different types of systems (Schneider & Kay 1994; Holling 2001; Lansing 2003; Foster 2005; Bullmore et al. 2009). Both biological and non-biological complex systems appear to evolve and be structured by similar principles, leading to a limited set of possible topological structures, organization, dynamics and behavior that are to some extent universal across system types (Watts & Strogatz 1998; Gunderson & Holling 2002; Barabási 2009; Bullmore et al. 2009). Levin (1998) proposed that the essential elements of a complex adaptive system (CAS) can be reduced to three elements: “sustained diversity and individuality of components; localized interactions among the components; and an autonomous process, where based on the results of local interactions, a subset of the components is selected for replication or enhancement (p. 432).” From these essential elements flow the other key features of a CAS: adaptation and introduction of novelty (Allen &

Holling 2010), non-equilibrium dynamics as a result of the dispersed and local nature of selection, the absence of top-down global control, and the emergence of hierarchical organization and other emergent phenomena (Levin 1998). Of these features, hierarchical organization and the emergence of resilience is our focus. Resilience is the ability of a system to remain organized around the same set of processes, structures, and functions (Holling 1973).

Within ecology, two parallel avenues of research have examined properties of CASs and their implications for system stability and resilience. The first, network theory, has uncovered rules of topological structure regarding the ways nodes are connected to each other using graph theory (Barabási 2009; Cumming et al. 2010), and examined the extent to which different topologies are resilient to random or targeted node loss (Srinivasan et al. 2007; Dunne & Williams 2009; Uden et al. 2014). In ecosystems, nodes are frequently modelled as species, connected to each other in food webs that generate emergent properties of information storage (such as genetic material), material and energy flow, resilience, and adaptive capacity (Montoya & Solé 2003; Jørgensen & Fath 2004; Pascual & Dunne 2005; Barabási 2009). Network theory has been widely applied to understand the effect of topological properties like connectance on the function and resilience of a broad array of CASs, from the internet, to social systems, and the brain (Barabási 2003, 2007; Pascual & Dunne 2005). However, network theory does not yet account for hierarchy and scaling in a non-arbitrary way when it considers scaling at all. Any scales identified are typically user-defined levels, as in when food-webs are stratified by trophic level (Bascompte et al. 2005).

The second research avenue, that of ecological resilience (Holling 1973), was inspired by the multi-scalar and hierarchical organization of ecological systems. In particular, the discontinuity hypothesis was developed as a mechanistic explanation for the way species' interactions with the hierarchical, scaled nature of their environment structures communities (Holling 1992). The cross-scale resilience model extended the discontinuity hypothesis by providing a testable hypothesis for how system-level resilience can emerge from species' interactions with environmental structures and processes that vary with scale (Peterson et al. 1998). This model has provided one of the few quantitative measures of resilience available to date (Allen et al. 2005; Stow et al. 2007; Angeler et al. 2013a), despite the widespread uptake of the resilience concept. We propose that the cross-scale resilience model may describe fundamental patterns in CASs resulting from dynamics that are general to other types of hierarchical CASs. Here we discuss some of the relevant theory underpinning ecological resilience, the discontinuity hypothesis, and the cross-scale resilience model, discuss recent examples from non-ecological systems, and then propose some systems for which we believe a cross-scale resilience analysis would be fruitful. We expect that a broader application of the cross-scale resilience model to different types of CASs will not only offer possibilities to increase our mechanistic understanding of the organization of ecological, social, and economic systems, but also help provide insight into management and policy challenges under fast-changing environmental and social baselines. Shared principles amongst systems has the pleasing consequence that theory, modeling and tools developed within one field for a particular type of CAS may be pertinent to another field, creating powerful opportunities for shared learning and collaboration.

Resilience

The development of resilience theory has received considerable attention in recent years (Gunderson & Holling 2002; Carpenter & Brock 2004; Folke et al. 2004; Allen et al. 2005; Cumming 2011; Walker & Salt 2012). Ecological resilience is the ability of a system to remain organized around the same set of processes, structures, and functions (Holling 1973). The degree of resilience in a system is a measure of how much disturbance the system can buffer without moving into an alternative regime (Peterson et al. 1998). This is a distinctly different view of resilience than the more traditional engineering resilience, which defines resilience as the return time to equilibrium after a system has experienced a disturbance (Holling & Meffe 1996). Engineering resilience presumes a single steady state, which is at odds with our current understanding of the dynamics of CASSs. In practice, this means that once a CAS has shifted from Regime A to Regime B, an engineering view of resilience would incorrectly assume that the system would eventually rebound to Regime A without substantial intervention. Resilience theory has demonstrated that breaking the feedbacks that maintain the system in Regime B can be very difficult (Scheffer et al. 2001).

Resilience theory is built on an understanding of social-ecological systems as CASSs, thus it assumes non-linear dynamics, and multiple possible basins of attraction governed by different regimes (i.e., different sets of processes). The ability to identify regime thresholds and provide early warnings of regime shifts is a vigorous area of current research (Folke et al. 2004; Biggs et al. 2009; Scheffer et al. 2012). Regime shifts are often abrupt, non-linear transitions between basins of attraction that occur when the threshold for a critical system driver is exceeded. When the resilience of a

system is reduced, systems are more vulnerable to a potential regime shift. Fold-bifurcation threshold dynamics are common in ecological systems, where even a small change in conditions can trigger an abrupt regime shift if a bifurcation threshold is passed, and hysteresis, or the inability of a system to move backward and return to a previous regime, is possible (Scheffer et al. 2001; Scheffer & Carpenter 2003).

Regime shifts in ecosystems epitomize the practical relevance of resilience research because the outcomes of regime shifts are uncertain, and frequently have negative consequences in the form of reduced ecosystem provisioning or increased poverty (Moberg & Folke 1999; Crépin et al. 2012).

The relevance of resilience theory to other types of CASs is possible in part because order and pattern can emerge from the dynamics of self-organization in the absence of natural selection, merely from local interactions between agents (Kauffman 1995). Thus, although natural selection and evolution have corollaries in other fields--businesses as the objects of natural selection, or the evolution of CASs such as civilization, economies, or cities (see (Tainter 1988; Beinhocker 2006), the emergence of higher-order phenomena such as resilience from lower-order localized interactions is not dependent on genetic-based natural selection (van den Bergh 2007). It is increasingly clear that economies and other types of social systems have dynamics more appropriately described by the science of CASs than that of simple, linear dynamics, and tools like the discontinuity hypothesis and the cross-scale resilience model can be used to explore commonalities and differences in the basic dynamics of different types of CASs (Tainter 1988; Beinhocker 2006).

The discontinuity hypothesis

The discontinuity hypothesis describes hierarchy and scaling in ecological systems as a result of structuring processes that occur over limited ranges of spatial and temporal scales. In ecological systems, some processes occur with high frequency and at small spatial scales, while others are slow and operate at large spatial extents, creating hierarchy and heterogeneity. Because the characteristic rate and extent of key structuring processes differ sufficiently, they create scale domains or ranges of scale over which patterns change monotonically or not at all. For example, Wiens (1989) describes the scaling of transpiration, which is regulated by stomatal mechanisms at the scale of a leaf, but by climate at the scale of vegetation regions. Likewise, the processes that regulate the turnover of a pine needle differ fully from those that determine the location and extent of the boreal forest (Holling 1992). Scale domains are separated from each other by a non-linear transition (a discontinuity) to the next set of structuring processes (Wiens 1989; Holling 1992).

The discontinuity hypothesis is based on our understanding that species perceive and interact with their environment at scales that are relative to their body size, and persistence depends in part on how well a species' body mass allows it to take advantage of the resources available at a specific scale (Peters 1983; Holling 1992; Fisher et al. 2011). Animal body mass distributions for a given ecosystem consist of groups of similarly-sized species that exploit resources at similar scales. That is, each body mass group mirrors a specific scale of structure and resource availability in the ecosystem, such that the number of body mass groups indicates the number of scale domains present. These body mass groups are separated by gaps, which reflect a scale break (discontinuity), or transition to a new scale domain.

Countless animal communities have been tested for discontinuities with affirming results (Holling 1992; Havlicek & Carpenter 2001; Lambert 2006; Allen et al. 2006; Nash et al. 2013b).

The discontinuity hypothesis relates to a general problem in ecology and other scientific disciplines regarding the quantification of scale in complex systems in non-arbitrary ways (Gibson et al. 2000; Nash et al. 2014a). There have been few tools available for identifying the fundamental scales present in a system rather than defining levels of organization based on observer bias. Wiens (1989) wrote, “we need non-arbitrary, operational ways of defining and detecting scales” and went on to ask, “How may we recognize domains of scale in a way that avoids arbitrary imposition of preconceived scales or hierarchical levels on natural variation?” The strength of the discontinuity analysis is that it is a tool for identifying the available scales of structure in a system without imposing human preconceptions. There are a variety of methods for detecting discontinuities, such as Bayesian classification and regression trees (BCART), Monte Carlo approaches (such as the Gap Rarity Index), and hierarchical cluster analysis (Allen & Holling 2002; Allen et al. 2005). These methods are used on rank-ordered body mass data for all the species in an ecological community (such as all the birds, mammals, or herpetofauna). Body mass can be obtained from general handbooks, as the patterns of aggregations and discontinuities in a system are highly robust to geographic variation and gender differences in body size (Sundstrom 2009). Alternatively, discontinuities have been found by identifying where the fractal dimension of ecological structure changed abruptly, indicating that different structuring processes are dominant (Li 2000; Nash et al. 2013b). Time series modeling has also been used to identify temporal frequency patterns of groups of