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Review

Evaluating ecological resilience with global sensitivity and uncertainty analysis

Stephen G. Perz[a,*], Rafael Muñoz-Carpena[b], Gregory Kiker[b], Robert D. Holt[c]

[a] Department of Sociology and Criminology & Law, University of Florida, Gainesville, FL, USA
[b] Department of Agricultural and Biological Engineering, University of Florida, Gainesville, FL, USA
[c] Department of Biology, University of Florida, Gainesville, FL, USA

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ABSTRACT

Concern about catastrophic tipping points has motivated inquiry to better understand ecosystem dynamics in the presence of human action. This requires that we confront multiple challenges in the evaluation of complex systems. One challenge is that resilience has proven difficult to quantify; another issue is that the value of model complexity relative to system complexity is disputed; and finally, local methods for assessing uncertainty are inadequate for more complex models. We address these three challenges simultaneously by proposing a means of evaluating ecological resilience via employment of global sensitivity and uncertainty analysis and comparing models of varying complexity. We suggest that probability distribution functions in output from global sensitivity and uncertainty analysis can be interpreted in terms of ball-and-cup diagrams used in systems theory to visualize ecological resilience. This permits quantification of ecological resilience in terms of the probability of whether a system will remain in a pre-existing state or shift to a different state. We outline the methods for using global sensitivity and uncertainty analysis to evaluate ecological resilience and provide examples from recent research. We highlight applications of these methods to assessment of ecosystem management options in terms of their ramifications for ecological resilience.

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* Corresponding author at: 3219 Turlington Hall, University of Florida, PO Box 117330, Gainesville, FL 32611-7330, USA. Tel.: +1 352 294 7186; fax: +1 352 392 6568.
E-mail address: sperz@ufl.edu (S.G. Perz).

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1. Introduction

Human action increasingly affects global ecosystems (Millennium Ecosystem Assessment, 2005; Intergovernmental Panel on Climate Change, 2007), pushing them toward potentially catastrophic "tipping points" (Scheffer, 2009; Scheffer et al., 2009), beyond which systems are unable to return to their initial states. This concern has prompted calls for greater attention to research and education concerning tipping points and broader issues of resilience in complex dynamic systems (AC-ERE, 2009; Stafford et al., 2010). Key to such efforts is the analysis of social–ecological interactions (Pickett et al., 2005), particularly through applications of dynamic simulation models (Liu et al., 2007) which capture key processes that can shift social–ecological systems from one state to another.

Three lines of inquiry have sought to understand complex systems for the sake of anticipating and avoiding radical changes in socio-ecological systems. First, there is a growing literature on the measurement and evaluation of resilience. A priority in the resilience literature has been to develop methods to identify the conditions under which complex systems remain in a pre-existing state or surpass a tipping point and thereby shift to a different state, as opposed to exhibiting non-catastrophic dynamics (e.g., Holling, 1996; Gunderson and Pritchard, 2002; Cumming et al., 2005; Scheffer, 2009). Second, increasing computing power has stimulated interest in the relationship between model complexity and system behavior (e.g., Nihoul, 1994; Snowling and Kramer, 2001; Ascough et al., 2008). There, inquiry has focused on the significance of model complexity for model output, due to debate over the question of whether more complex models are more likely to reveal the potential for transitions among multiple system states (e.g., Waldrop, 1992; Scheffer, 2009). And third, there is growing concern among modelers about how best to evaluate the implications of interacting sources of uncertainty in models, a concern that has prompted development of new methods to evaluate model uncertainty for its effects on model output (Saltelli et al., 2000, 2004, 2008). Parallel to concerns among modelers are similar preoccupations among ecosystem managers who must make decisions under conditions of uncertainty about system dynamics and tipping points. These three areas of research are in fact interrelated, and each highlights challenges to the assessment of complex systems for ecosystem management.

Section 2 of this paper therefore reviews the literatures on these lines of inquiry. In the process, we combine contributions from engineering and ecology (Gattie et al., 2007; Schulze, 1996). From engineering, we draw insights concerning complexity in model design and the evaluation of uncertainty in model predictions; and from ecology, we employ the concept of ecological resilience applied to understanding complex dynamics in social–ecological systems. We begin by reviewing relevant literature on three topics: (1) the evaluation of ecological resilience, (2) the relationship of model and system complexity, and (3) the relationship of model complexity and uncertainty. We then propose a means of unifying these literatures using global sensitivity and uncertainty analysis (Saltelli et al., 2000, 2004) to evaluate ecological resilience. This review motivates the first of our three main arguments: analysis of model uncertainty permits assessment of ecological resilience, including the identification of different system states. In particular, we suggest that changes in model inputs map onto changes in model outputs, which can be interpreted in light of ecological resilience. This argument integrates work on resilience and uncertainty; however, implementation requires a concrete methodology to put this integration into practice.

Section 3 therefore outlines the methods of global sensitivity and uncertainty analysis (GSA/UA) as a means for evaluating ecological resilience. Sensitivity and uncertainty analyses are complementary and usefully implemented together, so we refer to their joint operation as GSA/UA. We show how output from GSA/UA for a given model indicates in probabilistic terms the range of possible values for an indicator of system states, which in turn provides quantitative information about uncertainties in important simulated system components as well as insights into the ecological resilience of the system.

For "proof of concept," Section 4 of the paper illustrates the implementation of GSA/UA by reviewing three previously published mechanistic dynamic models of ecosystems. To each, we apply GSA/UA in order to highlight its utility for quantitatively assessing model uncertainty and ecological resilience, and to show its value in applied contexts such as ecosystem management. Our first example models the effects of climate change and sea level rise on coastal habitats for shorebird populations; in this example, the application of GSA/UA reveals high probabilities of observing multiple possible system states. Furthermore, as climate change occurs, the relative probabilities associated with different system states change over time, which suggests dynamic shifts in the system and its ecological resilience. This substantiates our first argument and permits conclusions about model uncertainty and ecological resilience in terms of the probability of observing different system states. The second example focuses on phosphorus concentrations and vegetation dominance in a wetland ecosystem and compares models of varying complexity. This provides an illustration of our second central argument: increasing model complexity can raise the probability of observing multiple and quite distinct system states. The third example takes up the question of how GSA/UA of ecosystem models can be applied as a practical tool in ecosystem management for ecological resilience. We present a population model for an endangered species and evaluate management decisions using a Monte Carlo filtering procedure in GSA/UA to reflect management strategies in order to see if the resulting model output indicates reduced probabilities of observing undesirable system states. This provides an illustration of our third main argument, that GSA/UA has applications to ecosystem management for ecological resilience by permitting observation of the probabilities of different system states under specific management regimes defined by subsets of distributions in uncertain model inputs.

Given this review of case studies of GSA/UA applied to ecosystem models, we conclude in Section 5 by suggesting that GSA/UA provides a basis for the quantitative evaluation of ecological resilience. In particular, we discuss the use of GSA/UA to support ecosystem management, notably as a tool to respond to concerns about uncertainty in adaptive management (Gregory et al., 2006).

2. Literature review: resilience, complexity and uncertainty

2.1. Resilience in social–ecological systems

In systems theory, resilience is typically depicted in terms of "system states" subject to "disturbances" that can cause shifts among states (Carpenter and Brock, 2004; Holling, 1996; Gunderson and Pritchard, 2002; Ludwig et al., 1997; Scheffer, 2009). Complex systems are often characterized as having multiple possible system states, and encompassing processes that push the system toward one state or another, called "system attractors." Resilience thought often invokes a "ball-and-cup" analogy that allows visualization of the behavior of complex systems, where system state (the position of the ball) is defined by the shape of a "basin of attraction" (the cup) in which the system may move. Fig. 1 (top panel) illustrates the ball-and-cup analogy. Basins of attraction reflect the tendencies of system attractors and define the possible states of a system.