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ORIGINAL PAPER

Managing for resilience: early detection of regime shifts in complex systems

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Abstract The broad implications of catastrophic regime shifts have prompted the need to find methods that are not only able to detect regime shifts but more importantly, identify them before they occur. Rising variance, skewness, kurtosis, and critical slowing down have all been proposed as indicators of impending regime shifts. However, these approaches typically do not signal a shift until it is well underway. Further, they have primarily been used to evaluate simple systems; hence, additional work is needed to adapt these methods, if possible, to real systems which typically are complex and multivariate. Fisher information is a key method in information theory and affords the ability to characterize the dynamic behavior of systems. In this work, Fisher information is compared to traditional indicators through the assessment of model and real systems and identified as a leading indicator of impending regime shifts. Evidenced by the great deal of activity in this research area, it is understood that such work could lead to better methods for detecting and managing systems that are of significant importance to humans. Thus, we believe the results of this work offer great promise for resilience science and sustainability.

Keywords Regime shift · Leading indicator · Fisher information · Resilience · Environmental management

Introduction

Complex systems are multivariate and often characterized by nonlinear dynamics. While these systems are not implicitly designated by multiple regimes, many complex systems do in fact display this structure (Garmestani et al. 2009a). A regime can be identified by the variables that define the system, and the periodicities associated with that regime (Fath et al. 2003). The range of possible movements within a dynamic regime that can occur without generating a regime shift is the domain of attraction (Ludwig et al. 2002). Over time, resilient systems exhibit self-organized patterns with a particular degree of dynamic order. However, it is possible for a system to shift from one regime to another resulting in a temporary loss of dynamic order denoting system reorganization (Karunanithi et al. 2008). These regime shifts are typically associated with significant consequences (e.g., declining fish stocks, loss of water quality, economic downturn).

Threshold methods (e.g., TITAN) and models are being explored as tools to aid in identifying thresholds in ecological systems (Baker and King 2010; Cuffney et al. 2011; King and Baker 2011; Qian and Cuffney 2012). Results from these efforts are compelling as they provide insight on change point identification in trends related to individual taxa and highlight the importance of model alternatives. Although thresholds and regime shifts appear to be quite closely related concepts, these phenomena are quite distinct. In particular, thresholds are defined as a point where small changes in underlying system variables produce large scale system wide responses and result in sudden and dramatic changes in key properties and system quality (Groffman et al. 2006). On the contrary, regime shifts do not require abrupt tipping points but can be the result of long periods of system reorganization. However, while

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