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Regime shifts in coupled socio-environmental systems: Review of modelling challenges and approaches☆

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ABSTRACT

Increasing attention to regime shifts, critical transitions, non-marginal changes, and systemic shocks calls for the development of models that are able to reproduce or grow structural changes that occur over time periods perceived as abrupt. This paper highlights specific modelling challenges to consider when exploring coupled socio-environmental systems experiencing regime shifts. We explore these challenges in the context of four modelling approaches that have been applied to the study of regime shifts in coupled socio-environmental systems: statistical, system dynamics, equilibrium and agent-based modelling. When reviewing these modelling approaches we reflect on a set of criteria including the ability of an approach (1) to capture feedbacks between social and environmental system, (2) to represent the sources of regime shifts, (3) to incorporate complexity aspects, and (4) to deal with regime shift identification. Many of the modelling examples considered do not provide information on all these criteria, which receive a lot of attention in empirical studies of registered regime shifts. This suggests a need to develop a common modelling terminology in the domain of modelling for resilience and regime shifts. When discussing strengths and weaknesses of various modelling paradigms we conclude that a hybrid approach is likely to provide most insights into the processes and consequences of regime shifts. Challenges and frontier directions of research for designing models to study regime shifts in coupled socio-environmental systems are outlined.

1. Introduction

Large-scale natural disasters, destruction of vital ecosystem services, colonisation by invasive species, and socio-economic crises are currently at the top of the international agenda. Such events interrupt the functioning of economic, ecological, or coupled socio-environmental systems (SES), and may lead to a persistent change in system structure. Even in the absence of external disturbances, in the contemporary highly interconnected world, coupled SES are more vulnerable than they would otherwise be (Helbing, 2013).

In various disciplines, regime shifts, critical transitions, non-marginal changes, and systemic shocks are closely-related terms used to denote a structural change, often with a perceived sense of abruptness. Specifically, in the resilience literature a '*regime shift*' is a change from one system state to another, although this concept applies to cases where the transition occurs over any timescale, abrupt or otherwise (Walker and Meyers, 2004; Folke, 2006; Carpenter et al., 2011). The term is mainly used in ecology to describe significant, persistent changes in ecosystems – typically with vital consequences for socio-economic systems – which occur due to a switch in the dominant feedbacks that drive the system into a new regime (Biggs et al., 2009). The switch in the dominant feedbacks happens either as a results of a major external shock, or because the feedbacks dominating in the old regime are gradually eroding, passing a threshold after which new feedbacks prevail. As such, it is not unreasonable to apply the concept of regime shifts to socio-ecological or social systems (Schluter et al., 2012; Mueller et al., 2014; Lade et al 2013), despite the fact that the latter has its own vocabulary to describe analogous phenomena. Specifically, the socio-economic literature uses the term '*non-marginal change*', which is contrasted with gradual marginal change. Non-marginal change is a major change in the structure of

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Table 1
System states and drivers of change: a regime shift occurs in boxes III and IV; no regime shift in boxes I and II, due to system's resilience.

	Current regime is maintained	Regime shift
Disturbance	**I**. Recovery back to the same state	**III**. New state driven by exogenous disturbance
Gradual change	**II**. Remain in the same system state	**IV**. New state driven by endogenous or exogenous gradual change

an economy, shifting a socio-economic system onto a radically different trajectory, as opposed to its gradually moving along the same trend (Stern, 2008). Coupled SES are expected to experience major irreversible changes with non-marginal economic effects in a climate-changed world. Despite this, the majority of economic tools are designed to study exclusively marginal changes – i.e. small variations around a particular path. In economics '*structural change*' refers to a long-term fundamental shift in the functioning of markets and economic structure, moving them into a different state. Abrupt structural change is often linked to macro-economic cycles, such as Kondratieff waves, which under a Schumpeterian interpretation could feature 'creative destruction' during downturns, and are accompanied by observed shifts in the time series of socio-economic data (Medhurst and Henry, 2011). The term '*systemic shock*' is used in financial and environmental economics domain to refer to a major shift in a system state when normally uncorrelated markets and processes become correlated (OECD, 2003; Bhansali, 2008). Systemic shocks are global changes in the functioning of systems on which society depends. They may be driven either by micro-level gradual changes or external disturbances (e.g. natural hazards) (Filatova and Polhill, 2012). The resilience literature also uses the term '*critical transitions*', which are fundamental shifts experienced by systems when they pass bifurcations (Scheffer et al., 2012). A critical transition to a contrasting system state occurs when a system is approaching a catastrophic bifurcation – a tipping point – around which even small perturbations lead to a large change in system level variables. Positive feedbacks play a vital role in such transitions as they trigger a self-propagating shift to a different state (Scheffer, 2009). Thus, a critical transition is a special type of regime shift, which may occur without any major external shocking event (Andersen et al., 2009).

In this paper we use the term 'regime shift' as it is the most all-encompassing concept to describe the phenomena in which we are interested. A regime shift may be driven either by a disturbance or a gradual change (Table 1). '*Disturbance*' is an exogenous forcing in the form of a hazard event (e.g. hurricane, disease, fire) or in the form of an extreme change in an input variable (e.g. level of precipitation). After a disturbance, the system may either recover back to the same state (Table 1, I) or may shift to a new state[1] (Table 1, III), depending on the magnitude, rate of change, duration and frequency of the disturbance as well as the resilience of the system itself. (Gunderson and Holling, 2002; Folke, 2006; Scheffer, 2009). Turner and Dale (1998) review the differences between large infrequent and small frequent disturbances. According to Lake (2000) a disturbance may be in the form of a pulse (short-term and sharp), a press (a sharply-arising and maintained disturbance), or a ramp (a disturbance steadily increasing over time and space without an endpoint). Collins et al. (2011) simplify these ideas to two important kinds of disturbance: long-term sustained press disturbances and discrete, rapid short-term pulse disturbances.

A regime shift may also occur due to gradual changes in the system's components (Table 1, IV), which up to a critical point do not cause a shift in system state (Table 1, II). Regime shifts arising from gradual changes in explanatory variables (exogenous or endogenous drivers of response variables) have become especially apparent in a time of collapse of ecosystems, financial crises, housing bubbles, and climate change. In all these cases it is difficult to identify a single disturbance that caused a regime shift. Instead, it was gradual overfishing that led to the near-extinction of species and destruction of coral reefs (de Young et al., 2008); the slow accumulation of CO_2 and other green-house gases that caused climate change and its adverse consequences (IPCC, 2007; Stern, 2008); economic agents one-by-one adopting seemingly rational rules that caused structural changes in financial markets and economy (Anand et al., 2011); and the gradual spread of expectations among individuals of receiving a dividend from housing asset investments as housing prices grow annually driven by an increasing demand that was itself caused by those expectations (Arce and Lopez-Salido, 2011). Often a regime shift occurs when a system is moved towards a threshold by a combination of gradual changes and the shift is precipitated by a disturbance that would otherwise not be as harmful (Biggs et al., 2009).

Moreover, a regime shift may arise not only from gradual changes in a single variable, but from the interactions among processes operating at different spatial and temporal scales. As Carpenter and Turner (2000) point out, the time periods of changes in ecosystems span several orders of magnitude. A further complication is that the emergence of regime shifts from the bottom up in complex SES is embedded in heterogeneous spatial landscapes. The initial spatial correlation of site conditions and domino-effect responses across neighbouring cells strongly affect the consequent evolving patterns of a dynamic adaptive system (Scheffer, 2009). The effects of interactions among different processes across several variables are captured by concept of the 'perfect storm'. Here, the values of each of the variables taken individually might not be thought extraordinary, but collectively they form a highly unusual set of circumstances sufficient to cause a regime shift.

From a complex adaptive systems perspective, SES are seen as constantly changing, co-adapting, and perpetually out of equilibrium (Arthur et al., 1997; Folke, 2006). Marginal changes when a system gradually moves along a certain trend are quite "convenient" for decision-makers (and modellers), as prediction of future states can with a certain confidence rely on the historic trends and historic data. In other words, we know with a reasonable degree of certainty that with a unit change in driving variable(s) the response variable is likely to change in a predictable direction with a predictable extent. However, a growing body of literature suggests that it is common for complex SES to experience abrupt sudden shifts from one system state to another (Kinzig et al., 2006; Stern, 2008; Scheffer, 2009; Anand et al., 2011; Vespignani, 2012). A system experiencing a regime shift transforms into a system with new properties, structure, feedbacks, and underlying behaviour of components or agents. Macro variables of interest then do not change marginally with a gradual change in independent variables: there is a shift in the trend observed. These altered internal dynamics often prevent or impose a significant barrier to returning to the previous regime, and hence the possibility of regime shift occurring over relatively short timescales is of interest to decision-makers whose power and influence may be adversely affected. The

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[1] A system *state* is not a steady-state or equilibrium, but rather a regime characterized by a certain system's structure, properties and functionalities (Folke, 2006).

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