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Modelling systemic change in coupled socio-environmental systems

J. Gary Polhill [a], [*], Tatiana Filatova [b], Maja Schlüter [c], Alexey Voinov [b]

[a] *The James Hutton Institute, Aberdeen, UK*
[b] *University of Twente, Enschede, The Netherlands*
[c] *Stockholm Resilience Centre, Stockholm University, Stockholm, Sweden*

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ABSTRACT

Abrupt systemic changes in ecological and socio-economic systems are a regular occurrence. While there has been much attention to studying systemic changes primarily in ecology as well as in economics, the attempts to do so for coupled socio-environmental systems are rarer. This paper bridges the gap by reviewing how models can be instrumental in exploring significant, fundamental changes in such systems. The history of modelling systemic change in various disciplines contains a range of definitions and approaches. Even so, most of these efforts share some common challenges within the modelling context. We propose a framework drawing these challenges together, and use it to discuss the articles in this thematic issue on modelling systemic change in coupled social and environmental systems. The differing approaches used highlight that modelling systemic change is an area of endeavour that would benefit from greater synergies between the various disciplines concerned with systemic change.

1. Introduction

The collapse of ecosystems and the global financial crisis have much more in common than one may think at the first glance (Scheffer, 2009). Not only may these abrupt systemic changes be driven by internal and external processes of a similar nature, the system's reactions and early warning signals that indicate such changes may also share the same characteristics (Scheffer et al., 2009). While there has been much attention to studying regime shifts in ecological and economic systems independently, the attempts to do so for coupled socio-environmental systems (SES) are scarcer. (We deliberately use the term socio-environmental systems here, with a view to being as general as possible, though social-ecological systems are very much in view.) Understanding systemic change in coupled systems requires insights not only into the processes at macro and micro levels in both socio-economic and environmental subsystems but also into the role of feedbacks between them. Models can be instrumental here. This special issue aims to elicit and discuss the challenges of modelling systemic changes in coupled SES and point towards ways to address them by presenting recent examples of simulation models of systemic change. We begin our introduction to the issue using three challenges (terminology, structural change and subjectivity) as a basis for introducing systemic change in coupled socio-environmental systems.

1.1. *Terminology and definitions*

One of the first obstacles in the study of systemic change in SES is terminology.[1] Various disciplines in both the environmental and social sciences have engaged with relevant ideas – regime shift, structural change, non-marginal change, transition theory to name a few – and each claims ownership over their tokens. While ordinary mortals squabble over land and resources, in academia the territories are linguistic. For the purposes of introducing this thematic issue, we use the term *systemic change*, and include in Box 1 a brief glossary of terms. As modellers, we are interested in *systems* (though even this term is claimed), whether they are represented or analysed using equations, probability distributions, algorithms or any other formal approach. *Systemic changes* involve

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[1] Indeed, the concept of coupled socio-environmental systems is itself the subject of debate with different terminology in different disciplines. Here we mean systems that include people embedded in dynamic, evolving environments (such as ecosystems) that they depend on but also affect.

* Corresponding author.
E-mail address: gary.polhill@hutton.ac.uk (J.G. Polhill).

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Box 1
Glossary

The definitions here apply to the terms as they are used in this paper. Due to the diversity of disciplines involved in the area, authoritative or normative definitions are infeasible.

Coupled systems – distinct systems that can be modelled in their own right that are linked together.

Domain of attraction – a region of state space a system is inclined to inhabit.

Feedback – a mechanism, process or signal that loops back to influence the SES component emitting the signal or initiating the mechanism or process (Biggs et al., 2015).

Ontology – the entities, attributes, relationships and processes that are explicitly represented in the model's formulae, variables and algorithms.

Regime – the configuration of a social-ecological system, i.e. its self-organizing processes and structures (Biggs et al., 2015).

Regime shift – a substantial reorganization in system structure, functions and feedbacks that often occurs abruptly and persists over time (Crepin et al., 2012).

Social-ecological systems – complex, integrated systems in which humans are embedded in nature (Berkes and Folke, 1998).

Socio-environmental systems – tightly linked social and ecological, biophysical or spatial systems that mutually influence each other (based on SESYNC http://www.sesync.org/).

Systemic change – a fundamental change in the behaviour and/or structure of a system, be it the language used to describe the states it could possibly have, 'significant' changes to the expressions in that language indicating the states it does have, or changes in the descriptions of the processes by which the system moves from one state to the next.

Theoretical model – a conceptual, abstract model, not necessarily fitted to data.

fundamental changes to the way in which a system is structured, covering such things as:

- new classes of entity being formed, or new types of relationship between them;
- the introduction of new processes and changes in feedback loops;
- changes to the set of exogenous variables to which the system is sensitive;
- other changes to the relevance of variables in or affecting the system;
- the reorganisation of networks of interaction, possibly entailing different interaction topologies;
- abrupt (step-wise) changes in functions or parameters describing the system.

All these may be needed to represent exogenous change, or endogenous evolution that comes as a result of the formation of new institutions, rules or norms governing behaviour.

If we conceive systemic change as going from one system α to another, β, then in comparison with models of system α exclusively, models simulating systemic change from α to β entail, to some degree or another, redefinition of system boundaries and pathways through which the social system interacts with its environment. Differences between the two kinds of model may also include appropriate temporal and spatial system resolutions and extent.

Systemic changes may arise through exogenous disturbances to a system or emerge endogenously either through the behaviour of the system itself, or through gradually accumulated responses of the system to relatively small exogenous perturbations (Walker and Meyers, 2004; Biggs et al., 2009; Carpenter et al., 2011). Systemic changes may be coupled with a collapse in existing (formal and informal) institutions, loss of key hubs in interaction networks, irrelevance of prior classification criteria, or entities no longer interrelating in a particular way. To consider a rather extreme example, the French revolution involved the collapse of the monarchy, the execution of much of the aristocracy, the irrelevance of feudal social stratification, and with that, at least in principle, an end to social interactions based on a presumption of inequality. Since such changes may themselves be seen as disturbances, a systemic change can also be understood as the propagation and amplification of a disturbance throughout the system, leading to a long-term change in the way the system is organised. All these issues pose challenges for modelling, not least because, in extreme cases, they may involve a fundamental shift in the vocabulary used to describe the system, which will be reflected in the model's ontology. For example, in equation-based models systemic change implies that not only parameters' or variables' values change but the entire functional forms used to relate them in the model transform, possibly with new variables and new processes being introduced and old ones being deleted.

More formally, a model of a system may be conceived as a triplet consisting of (L) a formal language describing the possible states it can have, (E) expressions in that language describing the specific state it currently has (such as, the existence of a particular entity, values the entity has for its variables, and the other entities it interacts with), and (P) algorithms for computing subsequent state(s) of the system given previous state(s). Systemic change as represented in the model is a change to combinations of L, P, and 'major changes' to E, each of which will be referred to as ΔL, ΔP and ΔE systemic changes respectively. In the case of ΔE, a systemic change occurs when a significant number of the entities in the system are replaced with new entities, but ones of the same types, interacting in the same way as before. In ΔP, the systemic change affects the way the system evolves. In ΔL, it is the whole vocabulary used to describe the system that changes. (See Box 2.) Notably, systemic changes are not necessarily associated with a 'shock' or disturbance – they can occur through the gradual evolution of the system, so are also relevant to those who do not believe in discontinuities in natural systems (the *natura non facit saltus* axiom). Gradual changes in a system's elements and micro-level processes may drive a system over a critical point when irreversible and significant macro-level structural changes occur.

1.2. Change in structure

Another major challenge for modelling systemic changes is that they – by definition – involve fundamental changes in system behaviour and structure that are often unknown beforehand. The promise of predictive modelling, however, is based on the assumption that the trend along which a system was developing in the past can be, with acceptable confidence, extrapolated into the future. We build our models based on what we know about the systems in the past. This is well recognized for statistical or data-