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Structural Loop Analysis of Complex Ecological Systems☆

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ABSTRACT

Ecosystems are complex and dynamic making them challenging to understand. We urgently need to assess human impacts on ecosystems which cause changes in structural feedbacks producing large, hard to reverse changes in state and functioning. System dynamics has proven to be a useful and versatile methodology for modelling complex systems given the comparative ease with which feedback loops can be modelled. However, a common issue arises when models become too large and structurally complex to understand the causal drivers of system behaviour. There is a need for an intermediate level of analysis capable of identifying causal driving structures and dynamics, regardless of model complexity. This study investigates Loop Eigenvalue Elasticity Analysis, a structural analysis technique commonly used in business and economic system dynamics models, and evaluates its utility for identifying feedback loop structures responsible for behavioural changes in complex ecological systems. The approach is demonstrated by analysing a simple lake system model that has been extensively studied in the past for its capacity to undertake critical transitions between alternative stable states. We show how the dominance of feedback loops can be tracked through time building influence over the system's behaviour decades prior to the actual collapse in the system. We discuss our findings in the context of studying complex ecosystems and socio-ecological systems.

1. Introduction

Socio-ecological system models represent the interconnected nature of society and the environment. These systems are complex, able to exhibit emergence and self-organisation, with behaviours arising endogenously through non-linear dynamics (Güneralp, 2006). A defining characteristic of socio-ecological systems is multiple feedback loops which collectively form the internal structure of the system (Meadows, 2009), but disentangling and prioritising those feedbacks in order to understand system behaviour and develop effective policy is no simple task. Indeed, a necessary condition for labelling a system a socio-ecological system is that of a feedback loop operating between social and ecological elements. It is such feedback loops that are often the primary drivers of emergent system behaviour (Sterman, 2001). Here, we use the term 'driver', in the context of structural feedback loops, to mean the main endogenous cause of a system's behaviour. Systems may exhibit strong non-linear dynamics which are explored with the concepts of critical transitions between alternative stable states, regime shifts, and tipping points with potentially hard or effectively impossible to reverse changes in state due to properties of hysteresis (Scheffer, 2009; Carpenter, 2005). Consequently socio-ecological systems are hard to understand, hard to predict and difficult to manage (Meadows, 2009). Maintaining socio-ecological systems in desirable states and understanding why their behaviours change through time is fundamental for economic growth, poverty alleviation and general wellbeing (United Nations, 2015; Scheffer, 2009).

Process based, mechanistic, bottom up modelling has been used to understand socio-ecological systems (Verburg et al., 2016). System dynamics is one methodology that can be used to increase our understanding of such systems. System dynamics models are structural representations of dynamic real world systems. They take a resource based view of the world, characterising a system through a set of stocks and flows in order to represent its structure. Stocks are often, but not only, material goods, and flows are pathways of material between stocks (Ford, 2010).

System dynamics has an established track record of being applied to ecological and socio-ecological modelling (e.g. Ford, 2010; Meadows, 2009; Dyson and Chang, 2005; Saysel et al., 2002; Vezjak et al., 1998).

Abbreviations: LEEA, Loop Eigenvalue Elasticity Analysis; SILS, Shortest Independent Loop Set; PLUM, Phosphorus Loops in (U)Soil and (M)Sediment model; DDWA, Dynamic Decomposition Weights Analysis

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Powerful and intuitive software packages such as Vensim (Ventana Systems, Inc., 2006) and STELLA (isee systems, 2016), the exchange of established models and modelling libraries allows potentially very complex systems to be represented with models that produce output via computationally efficient numerical integration schemes. While this has allowed a wide range of system dynamic models to be developed, it has, at times, produced models that are difficult to assess with regards to their overall utility in increasing our understanding of real world systems. Such models can be challenging to parameterise, validate and interpret (Voinov and Shugart, 2013). The risk is that some system dynamics models are essentially black box representations of the target system making them effectively as hard to interpret as their real world counterparts (Voinov and Shugart, 2013).

In this study, we investigate a methodology that could increase our understanding, and potentially prediction, of large changes in system structure and functioning through a quantitative analysis of feedback loops as endogenous determinants of system behaviour. Rather than searching system-level properties and variables for statistical properties of impending critical transitions (Scheffer, 2009; Scheffer and Carpenter, 2003), we instead focus on the structural properties of the system which drives such behaviour.

We are motivated to understand how these sub-processes function collectively in producing system behaviour. One analogy is that if the system dynamics model is an organism that we can observe via its output, then we seek to understand the processes that drive such behaviour by peering within the model in order to identify 'organs' and 'physiological processes'. This analysis can be used in conjunction with evaluation of the system output, the system's stability, and identification of the most important components with respect to specific behaviours. In this study we investigate the mechanisms responsible for generating stability and instability within a system, how these change through time, whether stability or instability is dominated by an individual driver or generated by several, and how these drivers change in dominance as a system undergoes a transition between alternative stable states.

The technique explored within this study is known as Loop Eigenvalue Elasticity Analysis (LEEA). LEEA expands on the knowledge gained from linear stability analysis and graph theory, identifying a set of feedback loops within a system's structure known as the Shortest Independent Loop Set or SILS (Oliva, 2015; Oliva, 2004), which are collectively responsible for generating stability and instability within the system. A description of SILS, what it does and, and how it is applied can be found within the Supplementary information Section 1 of this paper. LEEA then structurally analyses the loop set, identifying which feedback loops are dominating the system's behaviour at any point in time, generating a hierarchy of the influential feedback loops of the system.

Exploring ecosystem dynamics through the study of feedback loops has already shown potential to improve our mechanistic understanding of critical transitions and stability within lake systems (Kuiper et al., 2015). While the methodology of Kuiper et al. (2015) focusses primarily on food webs, their motivations of finding feedback loops within a lake ecosystem in order to determine stability and critical transitions between two regimes is similar to this study.

Previous research has demonstrated that LEEA can increase understanding of system behaviour and causal drivers across a range of model systems (Oliva, 2015; Kampmann, 2012; Kampmann and Oliva, 2008; Güneralp, 2006; Güneralp, 2005). Thus far the method has only seen limited use in the field of socio-ecology in the context of agriculture (Bueno, 2013; Bueno, 2012) and the Baltic cod fishery as a potential practice to be undertaken after conducting generalized modelling (Lade et al., 2015). Here we extend this work and evaluate LEEA in the context of critical transitions and regime shifts, implementing loop analysis of a small lake model which can undergo critical transitions between clear and turbid states as a consequence of human drivers.

A full explanation of the limitations of the LEEA technique, along with many solutions to these limitations has been addressed by Güneralp (2006). Efforts to make the technique more automated have been conducted by Sergey Naumov and Rogelio Oliva and can be found online (Naumov and Oliva, n.d.).

1.1. The Model

The model chosen to demonstrate the application of LEEA has been developed from Carpenter (2005) which formulated a simple model of a shallow lake, Lake Mendota in Wisconsin, USA, using empirical data for soil, lake and sediment phosphorus levels. The model was bistable as increasing phosphorus input in the lake produced a critical transition with a sudden shift from a clear to a turbid state. Shallow lakes are classic examples of bistable systems, capable of discrete transitions from clear to eutrophic conditions (Wang et al., 2012) and their properties are relatively well known (Carpenter et al., 2011; Carpenter, 2005; Ludwig et al., 2003; Scheffer and Carpenter, 2003; Scheffer, 1998) with current theories attributing many eutrophic regime shifts to large influxes of phosphorus through anthropogenic activity such as fertiliser runoff from farms in the lake catchment area. The model has been chosen for two principle reasons: 1) the main focus of the model's dynamic behaviour is a critical transition, allowing for an investigation of feedback loop behaviour around the point of a critical transition. 2) The model is relatively simple, allowing for a quantitative account of LEEA to be presented, and assessment of LEEA's utility for the analysis of such systems.

2. Background

2.1. Lake Eutrophication

Lake Mendota is a shallow freshwater lake surrounded by agricultural fields which receive ample supplies of phosphorus fertiliser. Soil erosion leads to excess phosphorus from the fertiliser, not taken up by vegetation, to be washed into surrounding streams and rivers, eventually leading to the lake. This process concentrates phosphorus runoff from the lake's catchment area into lake water where the excess of nutrients causes algal blooms to form. The formation of these blooms leads to plant death by blocking sunlight, fish death by generating anoxic conditions and phosphorus recycling from the lake sediment, which increases the already high levels of phosphorus in the system (Scheffer, 2009; Scheffer and Carpenter, 2003; Scheffer, 1998). Combined, these events can cause a lake to undergo a critical transition from a nutrient poor, high biodiversity, clear water state to a nutrient rich, low biodiversity, eutrophic state.

Lake Eutrophication is not only detrimental for the lake biota and biodiversity, it can have adverse effects on the system's provision of ecosystem services. Provisioning services are impacted primarily through the collapse of fisheries. Cultural services such as recreation and tourism are also affected (Dodds et al., 2009; Scheffer, 2009). Attempts to return a eutrophic lake to its previous clear conditions require the levels of phosphorus in the lake to be reduced but these systems can have large hysteresis loops, making them very challenging to recover (Carpenter et al., 1999). If nutrient levels are reduced sufficiently, the lake becomes capable of undergoing a reverse critical transition, returning to its former low nutrient, clear state, however such a reverse in conditions may take many years (McCrackin et al., 2017; Wang et al., 2012).

2.2. Feedback Loops

Feedback loops can emerge in systems as coincidental structures when multiple interactions form between components that link an output back to its original source. Feedback loops are capable of existing in one of two forms, positive or negative. Positive feedback loops are known for generating reinforcing behaviour in a system and are