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Modelling future safe and just operating spaces in regional social-ecological systems

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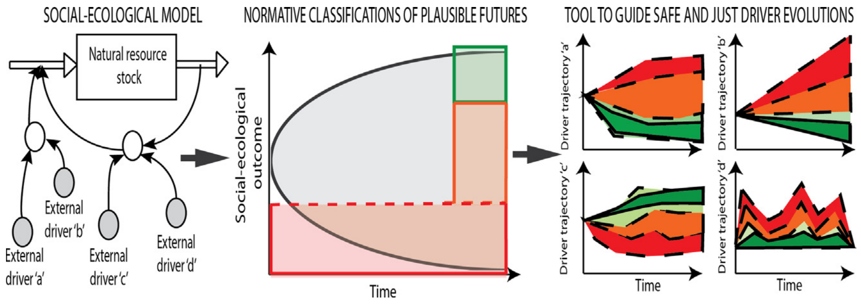
HIGHLIGHTS

- The first *future* safe and just operating spaces of a real social-ecological system
- Systems modelling explores resilience to driver interactions, feedbacks and management.
- Resilient causal pathways are traced back from pre-defined safe and just futures.
- Decommonisation extends Chilika's resilience to fishery intensification pathways.
- Decision-makers should target the “core space” of the safest driver interactions.

GRAPHICAL ABSTRACT



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ABSTRACT

Shaping social-ecological systems towards sustainable, desirable and equitable futures is often hampered by complex human-natural feedbacks, emergence and nonlinearities. Consequently, the future of systems vulnerable to collapse is uncertain under plausible trajectories of environmental change, socioeconomic development and decision-making. We develop a modelling approach that incorporates driver interactions and feedbacks to operationalise future “safe and just operating spaces” for sustainable development. Monte Carlo simulations of fish catch from India's Chilika lagoon are compared to conditions that are ecologically and socioeconomically desirable as per today's norms. Akin to a satellite-navigation system, the model identifies multidimensional pathways giving at least a 75% chance of achieving the desirable future, whilst simultaneously diverting the system away from undesirable pathways. Critically for regional governance, the driver limits and trade-offs associated with regulating the resource are realised. More widely, this approach represents an adaptable framework that explores the resilience of social-ecological interactions and feedbacks underpinning regional sustainable development.

1. Introduction

The challenges facing Earth's contemporary social-ecological systems (SESs) call for integrated, holistic and dynamic assessments of sustainability (van der Leeuw et al., 2011). However, predicting the future of SESs is associated with spatiotemporally complex processes like human population growth, climate change and natural resource use. Consequently, achieving aspirational futures such as the United Nation's Sustainable Development Goals and the Convention on Biological Diversity's “Aichi targets” is complicated by interplay between short-term policies, medium-term socioeconomic demands, long-term environmental trends and multiscale uncertainty about the future.

Empirical datasets have traditionally uncovered the complexities of real SESs, such as historical legacies, interdependencies and nonlinearities

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(Dearing et al., 2015). Yet, there is growing recognition that decision-makers benefit from complementing empirical data with modelled assessments that capture the complex processes driving social-ecological functions (Letcher et al., 2013; Schlüter et al., 2012). Ultimately, social-ecological models aim to test hypotheses about past causes of environmental degradation and provide virtual platforms to test strategies for management without the need for potentially harmful in situ experiments.

The non-analogous challenges facing SESs in the 21st century demand modelling techniques that move beyond statistical-based forecasts, optimisation and cost-benefit analysis, to process-based models for persistence, adaptability and resilience (Letcher et al., 2013; Verburg et al., 2016). For instance, unprecedented rates of regional interconnectivity are undermining resilience to cross-scale processes, such as “roving bandits” that sequentially exploit marine fish stocks (Berkes et al., 2006), and the effects of climate change on hydrological baselines and extremes (Milly et al., 2008). Moreover, the strengths of reinforcing and balancing feedback structures are known to evolve as systems adapt to stresses (Liu et al., 2007). Rather than assuming unidirectional relationships, as common amongst integrated assessment models used to estimate the socioeconomic impacts of climate change (Weyant, 2017), it is critical to capture feedbacks driving SESs towards abrupt ecological changes. Feedback sensitivity may be tested by probabilistic simulations that stress the system over a spectrum of future scenarios, with their iterative nature helping to improve model performance by repeatedly comparing outputs to new observations (Dietze et al., 2018). In turn, rather than narrowly forecasting the most likely future trajectory, normative scenarios can identify broad pathways leading to desirable futures whilst avoiding system limits (Bai et al., 2016). Although established in theory, the practical application of these concepts to real SESs is limited.

The conceptual framework of this research aims to bring together and advance three research areas in SESs science. First, with regards to operationalising desirable futures (Carpenter et al., 2015a), the planetary boundaries concept represents a complex systems framework describing a “safe operating space” (SOS) of nine Earth system limits which once transgressed weakens the chances of persisting stable Holocene environmental conditions (Rockström et al., 2009). Whilst there is debate over the global threshold values, interdependencies and implications for biodiversity (Brook et al., 2013; Montoya et al., 2018), the heuristic has been downscaled to identify coupled boundaries of regional biophysical limits and foundations of social wellbeing (Dearing et al., 2014; Raworth, 2012). To date, these “safe and just operating spaces” (SJOS) have been empirically defined in China (Dearing et al., 2014) and South Africa (Cole et al., 2017), showing how socioeconomic development can force ecosystem services (e.g. air quality, soil stability, biodiversity) beyond environmental thresholds and envelopes of historical variability. Therefore, this work aims to build on the empirical studies by converting the SJOS concept into a forward-looking tool that identifies driver-based SJOSs for regional social-ecological systems, defined by: (i) the future dynamics, interactions and limits of drivers underpinning regional social-ecological functions, (ii) the effects of non-stationary driver interactions, feedbacks and trade-offs, and (iii) the internal leverage points available to regional governors to shape system resilience.

Second, this study aims to build on previous attempts to model safe spaces of experimental (Carpenter et al., 2015b) and real systems (Hossain et al., 2017). In particular, the model of rice produce in Bangladesh (Hossain et al., 2017) is solely dependent on user-defined damage functions and statistical driver-response relationships that might breakdown under nonstationary environmental conditions. Here, a model of a real SES is built with a systems-based approach using empirical observations, qualitative records and insights from stakeholder interviews to capture the dynamics of the key stocks, flows and feedbacks (Graphical abstract, panel 1). Once the model's skill is verified against historical data, the model is simulated forward under a spectrum of socioeconomic and biophysical scenarios to understand the likelihood of achieving safe and just futures from today (Graphical abstract, panel 2). Outcome trajectories are then traced back to their causal driver pathways to understand the resilience of the system to cross-scale processes, feedbacks and management options (Graphical abstract, panel 3).

In doing so, the third contribution of this research is building on the systems models that test resilience against a single temporally dynamic driver (Bueno and Basurto, 2009; Moxnes, 2000), and/or assume that the natural environment remains static whilst socioeconomic drivers vary over time (BenDor et al., 2009; Martins et al., 2015). Identifying SJOSs of multiple interacting drivers works towards overcoming three barriers resisting the use of SJOSs in regional decision-making, namely (a) the need for systems to transgress safe spaces before sustainable limits can be empirically observed, (b) the identification of a “core SJOS” of the least riskiest pathways of the most influential drivers, and (c) the development of a modelling approach that delivers realistic and robust governance options with respects to system complexities and uncertainties (Anderies et al., 2004).

On top of exploring the issues surrounding the future persistence of India's Chilika lagoon (i.e. the fourth aim of this paper), the system acts as the vehicle to develop and test this modelling framework. Section 2.1 introduces the study site, Section 2.2 details the parameterisation of the systems model, before Sections 2.3, 2.4 and 2.5 describe the external future scenarios, internal governance scenarios and definitions of safe and just futures, respectively. Section 3.1 simulates the future fish catches and their causal driver trajectories (Section 3.2), before identifying driver-based SJOSs that represent interacting signposts to maintain SESs inside sustainable limits (Section 3.3).

2. Material and methods

2.1. The Chilika lagoon fishery system

The Chilika lagoon is Asia's largest brackish water ecosystem, covering 1000 km^2 of India's Bay of Bengal coastline (Fig. 1). The fishery was valued at US$25-million/year in 2015, supporting 35,000 fishers and 200,000 livelihoods in the preparation, marketing and distribution of fish (Kumar and Pattnaik, 2012). Fish catch quadrupled between the 1930s and the late-1980s, but reversed from an average of 7200 tonnes/year during the 1980s to 3100 tonnes/year during the 1990s. Since 2005, catches have averaged 12,000 tonnes/year following the opening of a new tidal outlet in 2000 between the lagoon and the Bay of Bengal.

The history of multidecadal growth, collapse and recovery reflects Chilika's dynamic biophysical, socioeconomic and institutional settings. Chilika receives freshwater inputs from both the Lower Mahanadi catchment (LMC) and the Western Catchments (WC) on the lagoon's western flank (Kumar and Pattnaik, 2012) (Fig. 1), split 75:25 in favour of the LMC. Brackish ecosystem conditions are primarily maintained by the transgression of marine waters via the principal tidal outlet at Satapada. The location of the tidal outlet is dynamic, driven by the deposition of terrestrial sediment and northwards littoral drift along the Bay of Bengal (Chandramohan et al., 1993). In turn, it is estimated that 70% of the fish stock annually migrate to (anadromous species) or from (catadromous species) the lagoon via Satapada to complete reproduction cycles (Kumar et al., 2011). The 1990s fishery collapse is blamed on the unchecked northward drift and sedimentation of the now defunct “Magarmukh” outlet, whereby the reduced tidal range constrained fish migration, freshened water salinity to ~4 parts per thousand (ppt) and promoted the growth of freshwater vegetation which blocked fishing grounds (Kumar et al., 2011).

Concurrently, the active fisher population has increased from 7000 in the 1940s to 35,000 at present, split 60:40 between traditional and non-traditional communities (Kumar and Pattnaik, 2012). Non-traditional fishers introduced outboard motors in the early-1980s