EDITORIAL

Sustainability of complex social-ecological systems: methods, tools, and approaches

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Social-ecological systems (SES) are nested, multilevel systems in which ecological and social elements interoperate through regular bidirectional interactions and feedback loops (Gunderson and Holling 2002; Holling 2001; Folke 2006). They are characterised by complex and dynamic interdependencies, between social and ecological sub-systems (Liu et al. 2015), which remain poorly understood. However, understanding the dynamics of complex SES interactions is essential for supporting both human well-being and the sustainable management of resources (Gain et al. 2019a). Failure to recognise such complex interdependencies and dynamics has led to severe environmental problems (Gain et al. 2019b) and developmental challenges, such as climate change impacts, biodiversity loss, resource scarcity, and resource degradation. The interconnectedness of complex problems cannot be assessed with traditional disciplinary approaches alone. Instead, inter- and trans-disciplinary approaches are required to deal with such sustainability challenges.

Within the last decade, significant progress has been made with respect to analysing SES. Specifically, SES have recently emerged as a prominent analytical framing to investigate pressing sustainability issues in the Anthropocene (de Vos et al. 2019; Rockström et al. 2009). A number of frameworks have been developed to study SES, including the social-ecological system framework (SESF) (Ostrom 2007, 2009;

McGinnis and Ostrom 2014), the vulnerability framework (Turner et al. 2003) and the driver-pressure-state-impact-response (DPSIR) framework (Gari et al. 2015; EC 1999; Lewison et al. 2016). To foster a better understanding of the dynamics and complexity of social-ecological interactions, a variety of assessment methods including both quantitative and qualitative approaches (e.g., system dynamics modelling, network analysis, agent-based modelling, multi-criteria analysis/indicator-based aggregation, and integrated assessment/decision support systems/coupled model frameworks) are now available (An 2012; Filatova et al. 2013; Lippe et al. 2019; Belton and Stewart 2002). Despite this progress, the operationalization of the conceptual frameworks through applying innovative methods and tools to allow for the sustainable development of SES is still an active field of investigation.

The goal of this Topical Collection is to analyse the sustainability of SES at different scales by using recently available innovative methods, tools and approaches. The Topical Collection emerges from a 2-day workshop in Kiel, Germany (26–27 September 2018), involving key interdisciplinary researchers in the field of SES. This Topical Collection comprises papers spanning areas from theories to quantitative methods that contribute to analysing multiple sustainability challenges of complex SES at different regional contexts.

This article is part of the Topical Collection on *Sustainability of social-ecological systems*

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Baggio et al. (2019) study the role of social learning and inter-jurisdictional networks (linking socio-political and ecological processes) in order to reduce biodiversity loss. They present a theoretical multiplex network model that mimics multiple political jurisdictions making decisions affecting species migration across a landscape. Direct application of the model is described based on two cases (i.e., the removal of fences in the Great Limpopo Transfrontier Park, in southern Africa, and cooperation to solve regional environmental dilemmas in Arizona). The results indicate that maintaining heterogeneity in learning and knowledge approaches and sharing this knowledge lead to increasing species coexistence and, hence, reducing biodiversity loss in times of fragmented ecological landscape.

Bodin et al. (2019) investigate how and why pre-established social networks facilitate effective collaborations in addressing natural hazards. Empirically investigating with crisis responders of large-scale wildfires in Sweden and Canada, they analyse factors that shape actors' ability and willingness to form new social ties with other actors. In addition, they also assess the propensity to activate pre-existing social ties. By using social network analysis, they find that pre-existing ties comprised a considerable proportion of all ties. Using exponential random graph models, the results show that actors who are working with (or have previously worked with) a common third actor are more likely to activate pre-existing social ties. They conclude that the tie formation and activation differences can be attributed to diverging organisational contexts varying in their reliance upon self-organising versus command-and-control approaches.

Hossain et al. (2020) present a case of participatory modelling in the Bangladesh delta in which the concept of complex social-ecological systems (SES) is adopted for capturing dynamic properties for long-term sustainability and human well-being. Shared conceptual system dynamics (SD) models are developed with stakeholders and feedback loops are identified for the ecological and social sub-systems. Results allow exploring the relationships between water availability with crop, fish, shrimp and forest production. Moreover, they explore the relationships between biophysical thresholds (i.e., river discharge, air temperature and soil salinity) and social impacts, which may put SES resilience at risk and increase the likelihood of regime shifts.

Adams et al. (2020) investigate the relationship between ecosystem services and poverty in different SES of the delta coastal region of Bangladesh. They focus on three dimensions: economic contribution of provisioning ecosystem services to households' livelihood mix, social-ecological systems producing different bundles of ecosystem services, and material wealth versus reported life satisfaction. The approach is a large-scale household survey and variables are analysed with logistic random intercept models. The approach allows characterising, among other things, the linkages between SES types and life satisfaction (a measurement of subjective well-being) and material poverty.

Ferdous et al. (2020) explore the "protection paradox" in the Jamuna River floodplain in Bangladesh whereby the protection of the coastal floodplain can lead to increases in flood damages due to over reliance on protection and reduced preparedness. Using primary and secondary data on population density, human settlements and flood fatalities, they compare two urban areas and two rural areas with different flood protection levels and find that higher levels of flood protection are associated with higher increase in population density over the past decades as well as assets exposed to flooding. The results of the study indicate that flood mortality rates associated with the 2017 flooding in Bangladesh were lower in the areas with lower protection level, thus highlighting the unintended consequences of structural flood protection and their relevance for the establishing sustainable policies of disaster risk reduction and adaptation to climate change in rapidly changing environments.

Balbi et al. (2020) also focus on the inherent complexities and internal interdependencies of dynamic SESs. In particular, they explore the role of behavioural features of human agents in driving the outcomes in terms of food security, by proposing a game theory model to explore the role of cooperation and diversity at the community level in southern Malawi. The model simulates cropping strategies, by considering cooperation, as driven by other-regarding preferences, and conformation, as the tendency to converge to similar choices, as opposed to differentiation driving to crop diversity. Results show that cooperation is only necessary for community success when the community converges on similar crop planting choices, while differentiation can succeed with or without cooperation. Based on the results, the authors suggest that the sustainability of the whole community can be reached through different pathways and—food—exchange mechanisms within and beyond the system boundaries.

Martin et al. (2020) extend an existing bistability model for shallow lakes focusing on the predator-prey relationship between two fish species by explicitly introducing vegetation as an additional state variable. This is done to understand the social-ecological interactions in lake restoration and specifically to determine the time required to restore lakes from turbid to clear states as a result of restoration measures that operate at different time scales. Restoration scenarios are used to demonstrate that combined measures are effective to restore lake environments while single restoration measures may not achieve a change in the state of the lake. The paper emphasises that balancing short-term improvements and long-term influences on the systems' state is critical.

Lazar et al. (2020) employ an integrated assessment model, the Delta Dynamic Integrated Emulator Model (ΔDIEM), to explore the outcomes of four contrasting adaptation trajectories on the southwest coast of Bangladesh. Their results show

different trade-offs between the four trajectories: embankment rehabilitation reduces flood risk, but at a high economic cost and also enhances waterlogging; planned and unplanned migration combined with limited infrastructure management and governance can result in significant abandonment. On the other hand, building elevation through sedimentation has the potential for increased environmental and economic sustainability but raises equity issues. Despite their results being sensitive to factors such as sea level rise and socio-economic development, they conclude that integrated assessment tools that link the environment, people and policy choices are important for highlighting the complex interactions occurring in a dynamic delta environment and can be used to support informed management, development and adaptation.

For analysing the sustainability of complex social-ecological systems, innovative methods and approaches that are able to account for and represent interactions between the various system components are essential. These approaches are evolving rapidly, supported by the increasing availability of data on physical and socio-economic parameters. In order to support the analysis of social-ecological systems and promote scientific understanding, this Topical Collection brings together eight examples of diverse tools and methods spanning areas from theories to quantitative methods. We hope that the Topical Collection will contribute to the analysis of multiple sustainability challenges of complex SES in different regional contexts.

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