An Integrated Framework to Study Ecological Tipping Points in Social-Ecological Systems

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Abstract

Sudden regime shifts or tipping points pose a major threat to various ecosystems and people's livelihoods worldwide. However, tipping points are still hard to predict and often occur without warning. To avoid dramatic social-ecological consequences, it is crucial to understand tipping point behaviour and to identify early warning indicators. Previous studies have hardly implemented an integrated social-ecological approach, which has led to a fragmented understanding and oversimplification of tipping point phenomena. Against this background, we present a systemic research framework that harmonizes ecological and social perspectives to gain a mechanistic understanding of tipping point behaviour. We utilize a social-ecological systems (SES) approach to identify drivers, consequences, and feasible preventive strategies. Our proposed framework consists of a retrospective, a comparative and a prospective perspective; each of them utilizes interdisciplinary studies in both sub systems at multiple scales. The research framework was developed by the members of NamTip, an inter- and transdisciplinary research project aiming to understand and manage desertification tipping points in Namibia's semi-arid rangelands. The NamTip project represents a practical implementation of the research framework, that uses an integrated, social-ecological study design combining the threefold approach with dynamic modelling. This includes analyses of time-series and archival data, experimental and observational studies, as well as scenario development and exploration of decision-making with local farmers. After the initial practical implementation and with our ongoing evaluation, we are convinced that such an ambitious and complex framework will guide the way to a profound understanding of tipping point phenomena and feasible management options.

Introduction

Climate change coupled with societies' increasing demand for natural resources are a cause of major concern for ecosystem stability and health. When vulnerable ecosystems can no longer cope with environmental change, they might experience drastic regime shifts, or tipping points (Milkoreit et al., 2018). Ecological tipping points may have dramatic consequences for nature and people, such as the loss of biodiversity and critical ecosystem services. Unfortunately, they are difficult to predict, and often come as unwelcome surprises (Milkoreit et al., 2018). Until now, only few attempts have been made to better understand tipping point behaviour from an integrative social-ecological perspective (Kéfi et al., 2016).

The art of studying ecological tipping points

Over the last decade, researchers have used different approaches to study ecological tipping points. These include the use of mathematical models (Plagányi et al., 2014), observational studies (Clark et al., 2013), historical ecological records (Lamentowicz et al., 2019), and remote sensing techniques (Krishnamurthy R et al., 2020). As stated by Scheffer et al. (2009), only a smart combination of these different approaches in a unified framework will enhance our capacity to anticipate critical transitions. In this context, a social-ecological systems (SES) perspective is helpful (Schlüter et al., 2014). Due to the complexity of integrative studies, however, research with an SES perspective has tended to oversimplify either the social or the ecological subsystem of an SES (Lauerburg et al., 2020; Schlüter et al., 2014). At this point, we argue that an integrative SES perspective can yield valuable insights into ecological tipping point behaviour, if an effort is made to take a holistic approach from the onset of the project (Dearing et al., 2015). Such an approach should integrate natural and social science research as well as local stakeholders to achieve a better understanding of complex interactions (Linstädter et al., 2016).

Here we present a novel, integrated research framework for studying ecological tipping points in coupled SESs. By using an interdisciplinary project on ecological tipping points in dryland grasslands as an example, we demonstrate the strengths of our integrated SES approach.

A methodological framework for tipping point research

Characteristics of the study design

An SES is characterized by dynamic interactions and feedbacks between the social and ecological subsystems which occur between societal actors with different ecosystem functions. Therefore, a study approach is required that ensures an examination in equal depth on both subsystems to avoid an overrepresentation of one single subsystem (Linstädter et al., 2016; Schlüter et al., 2014). For this purpose, scales and indicators need to be carefully pre-defined and applied complementarily in both subsystems in order to understand processes at the individual, community, and landscape level (Kéfi et al., 2016; Linstädter et al., 2016).

Scheffer et al. (2009) defined early warning signals as general indicators for tipping points, which requires long-term observational studies. For practical reasons however, this is rarely feasible. Following recommendations of Likens and Lindenmayer (2012), we propose a set of three alternative approaches to study ecological tipping points. Specifically, we propose combining (1) a retrospective view on tipping point behaviour with (2) a comparative and (3) a prospective approach. A retrospective – or historical – perspective allows a closer view on previous tipping point behaviour by collating different types of social and biophysical records, such as ecological time series, environmental archives, and oral histories (Dearing et al., 2015). In contrast, a comparative perspective allows studying tipping point dynamics via a space-for-time substitution (Pickett, 1989). Finally, a prospective – or experimental – approach enables studies of tipping point processes in the critical time window before a tipping point is crossed. Prospective approaches are however difficult to perform in the social subsystem of a coupled SES, as system manipulations are for ethical reasons not feasible.

Means of Integration

Studying ecological tipping points in real-world social-ecological systems requires inter- and transdisciplinary work. This in turn presupposes the integration of methods, knowledge, and modes of thinking from different scientific disciplines (Linstädter et al., 2016). For this purpose, careful deliberations across the teams regarding the different components of the study during the planning phase are crucial (Jahn et al., 2012). Alongside this process, the input of non-academic experts and stakeholders is essential to achieve transdisciplinarity (Liehr et al., 2017). Research activities should be structured on a modular basis for the integration of empirical research, reflecting the different disciplinary parts of the study as well as their respective contributions to the studied tipping point.

Besides the three empirical approaches outlined above, dynamic modelling offers an alternative solution to study tipping point phenomena. Generally, it allows one to substitute or complement data acquisition if time-series are not available and experimentation turns out to be difficult (Carpenter and Brock, 2006). However, dynamic modelling is also useful if empirical data are available: it encourages work at the intersections of different conceptual references, facilitates a common understanding of key variables, and provides a structure to relate different datasets to each other. Throughout the planning and implementation process, the validity and value of multiple ways of knowing – including local ecological knowledge – must be acknowledged (Yeh, 2015).

Practical example: Desertification tipping points in Namibian rangelands

The practical implementation of our framework is presented by the NamTip project. This project aims to better understand the social-ecological mechanisms that lead to the crossing of a desertification tipping point (DTP) in Namibia's semi-arid grasslands. With its transdisciplinary approach, this project addresses ecological and socio-economic processes at different spatial and temporal scales. It uses an integrated, social-ecological study design combining retrospective, comparative and prospective methods with dynamic modelling.

Retrospective approach

Due to the difficulty of detecting early-warning signals for tipping points in real time, annual net primary production (ANPP) is used as a key proxy to understand DTP behaviour retrospectively, as it has been shown that ANPP changes prior to a DTP. Moreover, social factors of DTPs are studied from the historical perspective including the exploration of the interconnections between local and broader social, political, and economic processes. Through literature and archival research, past and recent policies affecting rangeland management are also analysed (Menestrey Schwieger and Mbidzo, 2020). Furthermore, we conduct land use and land cover change analysis over the past 60 years based on historical aerial photographs to explore underlying land use history leading to today's rangeland conditions.

Comparative approach

From an ecological perspective, the comparative approach aims to replace a time-series analysis with a temporal gradient analysis. Here, we study the ecosystem structure and function along differently managed grazing gradients, using spatial phenomena to understand and model temporal processes. At several farms and communities, transects are laid out from water points and paddocks in the direction to the camp or open grassland to study how different ecosystem components change along transects. The comparative approach in the social subsystem contrasts case studies within and across the two main land tenure systems in the region (freehold and communal land). This way, we assess the divergences and similarities in terms of management practices and institutions, perceptions regarding DTPs, as well as the different socio-economic effects of DTPs, including 'best practices' for avoiding DTPs (de Vos et al., 2019).

Prospective approach

The ecological approach aims to use experimental manipulations that simulate future scenarios of drylands crossing DTPs. With a full factorial field experiment ("TipEx") we intend to push semi-arid savannah rangeland beyond a tipping point by imitating severe drought and grazing – two relevant drivers of desertification (Adeel and Kalbermatten, 2005). During the experiment, we record ecological parameters to evaluate the treatment effects in a synthetic analysis of ecosystem responses. From a social perspective, we employ two methodological approaches to explore the decision-making processes of communal and freehold farmers in the face of future DTPs. By means of scenario development and implementation (Rounsevell and Metzger, 2010), we assess farmers' strategies to cope with DTPs under circumstances that are difficult to observe (or which lie in the future). We also employed a decision-making game to complement this approach. Here farmers are confronted with a specific set of socio-political, economic, and environmental circumstances under which they must take management decisions in the face of desertification.

Synthesis and dynamic modelling

Early-warning indicators of system shifts are the basis for proactive management strategies, which need to be realistic and match local conditions and capabilities. Thus, we perform an interdisciplinary synthesis of local and scientific knowledge to explore early-warning indicators and management options. Furthermore, results of the empirical examinations and the interdisciplinary synthesis are integrated in an agent-based simulation model. The model explores the dynamics of coupled rangeland SESs in time and space under different processes of global change. It is specifically designed to capture feedback processes between ecosystem dynamics and farmers' management strategies. This gives us a mechanistic understanding of the emergence of a DTP (including early-warning indicators) and how livelihoods of farmers are affected under changing system conditions.

Conclusion and outlook

The proposed framework for studying ecological tipping points in social-ecological systems combines tools and methods from previous tipping point studies or SES studies in a novel, highly integrated way. It allows a more holistic view on tipping points and can be applied in various ecosystems. The application of this framework within the NamTip project has been successful and accompanied by achievements, but has had its challenges as well. The social and ecological subsystem studies found common denominators and applicable

scales, although a full evaluation and feasibility check is still ongoing. We encourage researchers aiming at a full understanding of a tipping point phenomenon to conduct similar efforts concerning their study framework.

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