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Research

Capturing emergent phenomena in social-ecological systems: an analytical framework

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ABSTRACT. Social-ecological systems (SES) are complex adaptive systems. Social-ecological system phenomena, such as regime shifts, transformations, or traps, emerge from interactions among and between human and nonhuman entities within and across scales. Analyses of SES phenomena thus require approaches that can account for (1) the intertwinedness of social and ecological processes and (2) the ways they jointly give rise to emergent social-ecological patterns, structures, and dynamics that feedback on the entities and processes that generated them. We have developed a framework of linked action situations (AS) as a tool to capture those interactions that are hypothesized to have jointly and dynamically generated a social-ecological phenomenon of interest. The framework extends the concept of an action situation to provide a conceptualization of SES that focusses on social-ecological interactions and their links across levels. The aim of our SE-AS (social-ecological action situations) framework is to support a process of developing hypotheses about configurations of ASs that may explain an emergent social-ecological phenomenon. We suggest six social-ecological ASs along with social and ecological action situations that can commonly be found in natural resource or ecosystem management contexts. We test the ability of the framework to structure an analysis of processes of emergence by applying it to different case studies of regime shifts, traps, and sustainable resource use. The framework goes beyond existing frameworks and approaches, such as the SES framework or causal loop diagrams, by establishing a way of analyzing SES that focuses on the interplay of social-ecological interactions with the emergent outcomes they produce. We conclude by discussing the added value of the framework and discussing the different purposes it can serve: from supporting the development of theories of the emergence of social-ecological phenomena, enhancing transparency of SES understandings to serving as a boundary object for interdisciplinary knowledge integration.

Key Words: *action situation; agency; complex adaptive systems; emergence; explanation; intertwindness*

INTRODUCTION

Social-ecological systems (SES) are complex adaptive systems (CAS) that are constituted by interactions between diverse people and elements of diverse ecosystems (Berkes and Folke 1998, Folke et al. 2016). These interactions give rise to patterns, structures, and dynamics that feedback on the processes that generated them in a continuously evolving manner (Levin et al. 2013). When studying social-ecological phenomena such as regime shifts, transformations, or sustainable governance, we are thus faced with the challenge of unraveling how dynamic interactions among and between human and nonhuman elements of a SES jointly generate the emergent phenomenon of interest. Empirical work on adaptive governance, resilience, and transformation has illustrated how complex interactions give rise to system-level patterns, which in turn affect local interactions (Folke et al. 2003, Olsson et al. 2004, 2008, Enfors 2013, Österblom and Folke 2013). This growing body of detailed, descriptive understanding of SES provides a rich empirical knowledge base, however, we lack tools to synthesize this knowledge into possible explanations of the social-ecological interactions and processes that may have generated an emergent social-ecological phenomenon.

Social-ecological systems are complex adaptive systems composed of networks of relations and interactions between humans and nonhuman entities (Bodin and Tengö 2012; for an animated clip on SES as complex adaptive systems, see http://www.seslink.org). These interactions can be interactions between people (social-social), for instance in social networks, communities, or policy making arenas; between people and biophysical entities (social-ecological), for instance when a farmer plants a crop, or an organization implements a conservation area, or when marshlands provide protection to settlements against spring tides; and between biophysical entities (ecological-ecological), for instance when one species preys on another. This network of social-ecological interactions, which continuously adapts and evolves, produces macro- or system-level SES outcomes such as a landscape pattern and can lead to SES changes such as a regime shift or transformation. Emergent novel system-level properties or dynamics, at the same time, create new conditions to which actors and biophysical entities may adapt, in a continuously evolving process. Explanations of SES dynamics and phenomena thus need to pay attention to microlevel interactions and macrolevel outcomes alike because they both shape the evolution of a system.

The complex adaptive and multilevel nature of SES that give rise to emergent, often unexpected and highly uncertain SES behavior has long been recognized (Levin et al. 2013, Folke et al. 2016). The governance challenges that arise from this complexity have received much attention (Duit and Galaz 2008, Mahon et al. 2008, Levin et al. 2013). The causal processes through which the interplay between local interactions of people and ecosystems with system-level social or ecological structures and processes produce emergent SES phenomena are, however, less known (Carpenter et al. 2009, Levin et al. 2013, Fischer et al. 2015). We define emergence as the generation of novel properties or functionalities that cannot be explained by their constituting elements alone, e.g., outcomes that are more than the sum of their

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parts (Page 2015, Moore et al. 2018). This novelty is the result of a continuous process in which interactions among and between individual people and ecosystems generate emergent outcomes that change the context of future human actions and ecosystem dynamics. For instance, the collapse of the Baltic cod stocks in the 1980s was brought about, among other things, by the interplay between individual fishers' perceptions of cod availability, their harvesting activities, and emerging institutional (subsidies), economic (cod prices), and ecological (shift in food webs) outcomes (Lade et al. 2015).

Interactions between humans and nature have been at the core of SES research for a long time, but doing justice to this interdependence when analyzing SES still remains a challenge (Fischer et al. 2015). Approaches and methods that facilitate an analysis of SES without giving prominence to either the social or ecological domains are still rare (Binder et al. 2013). Human-environment interactions are the focus of studies of coupled human-nature systems (Kramer et al. 2017), socio-environmental systems (Turner et al. 2016), or social-ecological systems (Fischer et al. 2015), among others. These studies conceptualize interactions (or links, connections, or relations, etc.) in fundamentally different ways. The meanings differ in the degree to which the social and ecological are viewed as merely linked or part of a single, integrated system. On the more loosely connected side of the spectrum are one-or two-way links between human systems and ecosystems, e.g., human action as drivers of ecosystem dynamics (Tilman 2001), nature providing benefits to people (Díaz et al. 2015), or biophysical factors having an impact on institutional change (Cole et al. 2014). In a more embedded perspective, human-nature interactions have been conceptualized as constituted through mind, experience, or place (Ives et al. 2017), and explored as the role of humans in the generation of coproduced ecosystem services (Fischer and Eastwood 2016). Finally, an increasing number of studies abandon any distinction between social and ecological, and see social-ecological relations, not entities, as the fundamental elements of SES (Dwiartama and Rosin 2014, Cooke et al. 2016, West et al. 2018, Mancilla García et al. 2019).

In the field of social-ecological systems research, as a subfield of human-environment research, the idea of linking social and ecological systems (Berkes and Folke 1998) across spatial and temporal scales (Gunderson and Holling 2002) has evolved into what is now called the "intertwined" nature of social-ecological systems (Folke et al. 2016) in a bid to better capture dynamic social-ecological interactions across scales. Most frameworks in use today, however, have not followed this development and still stop short of providing analytical concepts or tools to study SES as intertwined networks of human and nonhuman elements (but see Bodin and Tengö, 2012 for an example of social-ecological networks). Many treat the social and the ecological as two separate subsystems that are connected through links such as ecosystem services (Nassl and Löffler 2015) and take either an ecocentric or an anthropocentric perspective (Binder et al. 2013, Partelow and Winkler 2016). This limits the possibility of accounting for the embeddedness of humans in ecosystems, which manifests itself in the many, continuously evolving relations and interactions between humans and elements of their biophysical environment. These interactions can be of different types, from the extraction of natural resources for material benefits, or the consumption choices of consumers that affect resource exploitation (Crona et al. 2016), to the intangible benefits received through knowing, interacting, perceiving, or living within ecosystems (Russell et al. 2013), or the meaning and attachment associated with a place (Stedman 2016).

We propose an analytical framework to address the two gaps highlighted above: (1) to study the processes that give rise to emergent social-ecological phenomena and (2) to better capture the intertwined nature of SES that underlies them. The aim of the framework is to enhance understanding of causes of emergent SES phenomena by integrating existing knowledge into possible explanations that can then be tested in field campaigns or through modeling. Such an understanding can provide insights for SES governance, for example by identifying which configurations of social-ecological interactions may be more likely to enable transitions toward sustainability. The framework supports mapping knowledge about key social-ecological interactions and the emergent structures and processes they give rise to into configurations that are assumed to have generated a phenomenon of interest. Our use of the term "interaction" refers to interactions between human and nonhuman actors/entities not between variables or systems. It views humans and nature as deeply intertwined through a multitude of interactions and ways in which people relate to, are shaped by, and interact with nonhuman elements of a SES and how, vice versa, the nonhuman elements are affected by and affect people. We use the term social-ecological phenomenon to refer to an empirical observation one wants to understand and explain, such as the collapse of the Baltic cod stocks or a poverty trap. Our ambition is that the framework, which we call the social-ecological action situations (SE-AS) framework, be used:

- as an analytical tool to make explicit and map existing knowledge about social-ecological interactions and emergent processes and structures that may have generated a phenomenon of interest;
- to support the development of possible explanations of emergent social-ecological phenomena, which can inform a field study, an experiment, or the development of a computational model;
- as a boundary object to facilitate a process of integrating knowledge about key interactions from the ecological and social domains into an explanation of social-ecological change.

The framework and its underlying conceptualization of SES build on resilience thinking's understanding of SES as complex adaptive and tightly intertwined systems (Folke et al. 2016) and the concept of an action situation as an interaction context shaped by the participants and rules of interaction from Ostrom's Institutional Analysis and Development framework (IAD; Ostrom 1990). A key conceptual advance of our work is the introduction of two new types of action situations (AS), namely a social-ecological and an ecological AS. Social-ecological action situations capture relations and interactions between humans and nonhuman entities that are core causes of SES phenomena. Ecological action situations capture interactions between components of ecosystems that can constrain or enable social-ecological action situations. Our framework, however, goes beyond merely extending the action situation concept by establishing a way of analyzing SES that is significantly different to the IAD or the SES framework (Ostrom 2007, McGinnis and Ostrom 2014). These differences lie in how we emphasize the dynamics of social-ecological interactions and their emergent outcomes that jointly bring about a SES phenomenon of interest.

We have developed the framework over several years, refining it through application to our own and published studies from the literature (see below; Appendix 1; R. Martinez Peña, K. Orach, and M. Schlüter, *unpublished manuscript*), reviews of other frameworks, and the development of dynamical systems and agent-based models that explore possible explanations for observed SES phenomena (Lade et al. 2013, 2015, 2017, Wijermans and Schlüter 2014, Martin and Schlüter 2015, Schill et al. 2016, Lindkvist et al. 2017). For simplicity, we analyzed situations in which social-ecological interactions are particularly prominent, i.e., situations of natural resource use, uses of ecosystems for recreation or spiritual activities, or as sinks for pollution.

FRAMEWORKS AND ANALYTICAL APPROACHES FOR ANALYSIS OF SOCIAL-ECOLOGICAL SYSTEMS (SES)

Before introducing the SE-AS framework, we briefly discuss the ability of a few selected, well-known frameworks to capture emergence and the intertwined nature of SES. We distinguish between frameworks that focus on system-level variables and those that incorporate individual actors and their agency at a microlevel. We acknowledge that there are many different frameworks for social-ecological systems' analysis, but a review would lie beyond the scope of this paper (see Binder et al. 2013 for a comparison of 10 established frameworks for the analysis of SES).

Many frameworks or methods for analysis of SES that originate in the natural sciences focus on the system-level and describe the SES through aggregate state variables. This is most common in approaches based on dynamical systems theory. They describe interactions between aggregate state variables that determine the development of the system over time, its equilibrium configurations (alternative stable states), the stability of these configurations, and thresholds between them. They commonly assume that the change in state variables is following a deterministic causal relationship and that microscale interactions can be aggregated to a consistent behavior of a macrolevel state variable. Causal loop diagrams (Sterman 2001) and dynamical systems models are a common methodology to study the dynamics of SES at the system level. We argue that although they are very useful to understand critical feedbacks and their implications for SES dynamics, the conceptualization of SES at the macrolevel alone has limitations with respect to capturing emergent characteristics of CAS, i.e., unexpected outcomes resulting from heterogeneity of individual or collective actors and ecosystem components and their interactions.

One of the most prominent and commonly used frameworks in SES research originating in the social sciences is the SES framework (Ostrom 2007, 2009, McGinnis and Ostrom 2014). Contrary to the system-level frameworks, it focusses on interactions between resource users, particularly the factors that enable self-organization for sustainable resource use. The framework is based in collective action theory and is a collection of variables characterizing the resource, the resource system, the resource users, and the governance system that have empirically been shown to affect collective action and sustainable common pool resource use. It is diagnostic in that it aims to support the identification of sets of interacting biophysical, institutional, and community variables that may affect how groups self-organize to develop institutional arrangements for natural resource management. Its core is the action situation, i.e., a situation in which groups of boundedly rational individuals participate in a strategic interaction, which was proposed by Ostrom as the focal unit of analysis in the institutional analysis and development framework (IAD; Ostrom 2005). Although an action situation in the IAD represents a social interaction context that is defined by the participating actors and their attributes, the focus of an analysis is generally on the rules that govern their interactions and less on the agency of diverse actors participating in those action situations or the social networks that structure their interactions.

Resilience thinking is based on a view of social-ecological systems as complex adaptive systems of humans embedded in the broader ecosystem (Berkes and Folke 1998). It acknowledges the importance of both agency and structural factors such as institutions, but often uses approaches that tend to focus either on one or the other. Transformative agency, for instance, is at the core of recent developments in the study of transformations (Westley et al. 2013), although system-level feedbacks and institutions are key aspects considered in the study of regime shifts and adaptive governance, respectively (Chaffin et al. 2014). Consequently, studies apply different frameworks and approaches suitable for the respective focus. Frameworks, approaches, or tools, such as the resilience assessment, developed to apply resilience thinking to real world problems (Walker and Salt 2012) often only list the social and the ecological side by side without making the dynamics between them explicit. Finally, social-ecological networks are an approach that uses network theory to study social-ecological interactions (Janssen et al. 2006, Bodin and Tengö 2012). The core unit of analysis is a social-ecological network motif composed of social and ecological nodes that can be connected in various ways. Social-ecological and ecological interactions are explicitly considered and inferences made about the consequences of certain structural characteristics for emergent SES behavior. However, because of its static nature, the approach cannot capture the continuous change and evolution that characterize SES as complex adaptive systems.

Contrary to commonly used frameworks, findings of inductive empirical work on SES dynamics and emergence of adaptive or transformative governance show the intricate interplay of agency, social networks, organizations, and institutions (e.g., Folke et al. 2003, Olsson et al. 2004, 2008, Österblom and Folke 2013). Frameworks and theory development that capture the links between microlevel interactions and emerging macrolevel structures and processes that codetermine the behavior of SES are lagging behind. With the SE-AS framework, we want to address this gap by building on Ostrom's concept of the action situation from the IAD and networks of adjacent action situations (McGinnis 2011*b*), but go beyond this work by incorporating relations between and agency of human and nonhuman entities and interactions across multiple levels.

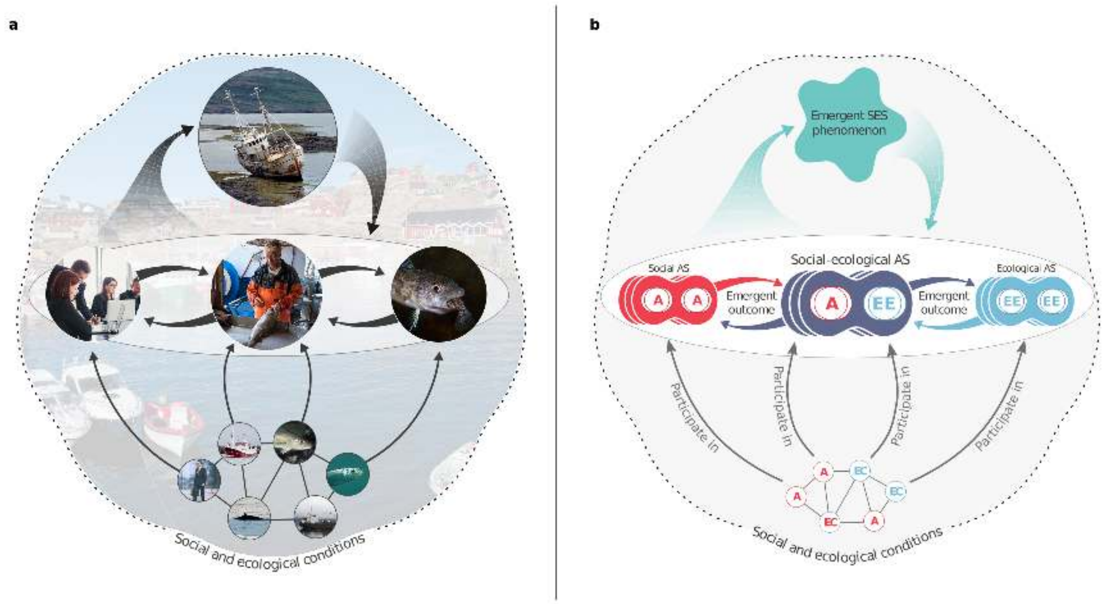


Fig. 1. The emergence of a social-ecological phenomenon (emergent SES phenomenon) from social-ecological interactions. (a) The collapse of a fishery (a type of regime shift, top picture) emerges from interactions between fishers and the fish through fishing (middle circle), policymakers that devise incentives and regulations (left circle), and different fish and other species that interact through a food web (right circle). The framework is used to abstract these action situations from the many relations and interactions between actors and ecosystem components in a given SES, represented by the network of actors and ecological entities at the bottom of the figure. Emergent outcomes from one AS, such as regulations, affect interactions in another AS, e.g., fishing. (b) The generic SE-AS framework. The eclipse in the middle represents a configuration of AS that are hypothesized to have generated the emergent SES phenomenon of interest. There can be multiple social, social-ecological, and ecological AS in a configuration. This configuration is developed by identifying those social-ecological, social, and ecological AS from the many interactions in the SES (network in the bottom) that are considered relevant from a theoretical or empirical perspective. The emergence of the phenomenon results from a continuous process of local interactions that shape emergent outcomes to which they subsequently adapt (green arrows).

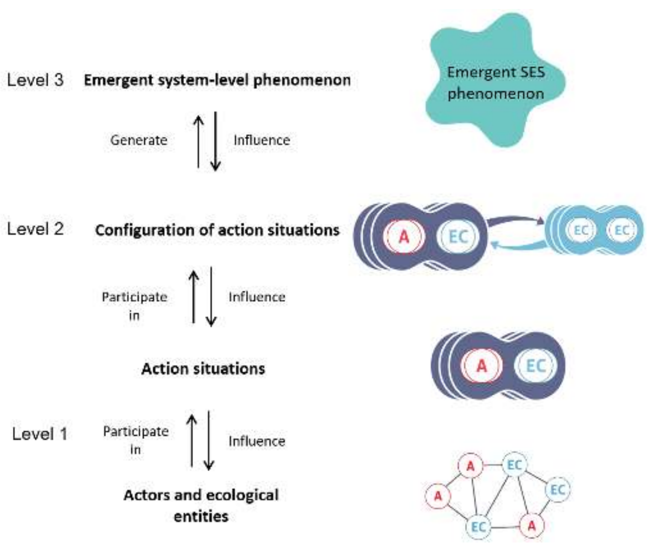
ANALYZING SOCIAL-ECOLOGICAL SYSTEMS (SES) AS MULTILEVEL COMPLEX ADAPTIVE SYSTEMS: THE SOCIAL-ECOLOGICAL ACTION SITUATION (SE-AS) FRAMEWORK

We propose the social-ecological action situation (SE-AS) framework as a complement to the above-mentioned frameworks (Fig. 1). The main elements of SE-AS are action situations that are linked through emergent outcomes. The framework is composed of multiple layers (Fig. 2). At the lowest level are interactions between individual or collective actors and ecological entities that are structured by social networks or spatial structures (Fig. 1, networks at the bottom; Fig. 2, networks of actors and ecological entities). The interactions and contexts that are considered relevant for understanding the emergence of a phenomenon from a theoretical or empirical perspective are selected and represented as ASs (Fig. 2, level 1). An AS is characterized by its participating actors and the rules, networks, space, etc. that structure their interactions. Outcomes of one AS may affect the rules, structures, or participants of another AS. These mesolevel influences of one AS on another are represented by links between AS (Fig. 2, level 2). A harvesting rule that emerges from a rule-making AS, for instance, will change the rules that constrain harvesting of the regulated species within a harvesting AS. The harvesting of this species in a harvesting AS may affect the actions of fishers in another harvesting AS by changing their motivations or knowledge. Links can occur between social-ecological and social or between social-ecological and ecological AS, but never directly between social and ecological AS. For example, the fishing pressure that results from a harvesting social-ecological AS on the population of the target species may affect its competition with another species in an ecological AS, such as the harvesting of cod in the Baltic Sea affected its competition with sprat. This influence on the ecological AS together with external factors such as changes in salinity and temperature resulted in a shift of the food web from a dominance of cod to a dominance of sprat (Möllmann et al. 2009). This in turn affected the harvesting SE-AS through changes in the availability of cod (as a material interaction) or in the perception of the availability of cod (as a nonmaterial interaction). A configuration of linked ASs represents a hypothesis or possible explanation of the interactions and emergent structures that generated a social-ecological phenomenon of interest, such as the collapse of the cod fishery in the Baltic Sea (Fig. 2, level 3).

Broadening the concept of an action situation

To build the framework, we expanded on Ostrom's concept of an action situation (AS). In particular, we extended the action situation beyond a purely social interaction context (social action situation, S-AS) to two other types of contexts: one that captures interactions between humans and nonhuman entities such as fish in a lake, a field, or a particular landscape, which we call a social-ecological action situation (SE-AS); and one that captures relations or interactions between ecological or biophysical elements such as predation of one species on another or the impact of a crop on soil quality, which we call an ecological action situation (E-AS).

Fig. 2. Different levels of analysis of interactions and emergent outcomes in a social-ecological system (SES) that form the basis of our social-ecological action situations (SE-AS) framework. Framework components are actors and ecological entities organized in action situations (AS; level 1). In the second level, AS influence each other through emergent outcomes (level 2) to jointly produce the phenomenon of interest (level 3). Influence can go across all levels from bottom to top but also from top to bottom.



By extending Ostrom's concept of an action situation to social-ecological and ecological AS, we broaden the definition of actors and types of interactions. Social-ecological and ecological AS involve nonhuman entities that can affect or prevent change and interact with other ecological or human agents. Human actors and ecological entities both have agency, defined as the exercise or manifestation of the capacity to act (Schlosser 2015), albeit this agency can be of different types such as intentional behavior of humans versus responses to environmental stimuli of ecological entities. We thus treat human actors and ecological entities as ontological equals, however, acknowledge that they can have different types of agency. Human actors can respond intentionally and reflexively to changes in SES outcomes, which makes emergent outcomes contingent on individuals' cognitive processes. Ecological or biophysical entities largely respond to information or material feedback from their environment. The separation between intentional human behavior and unconscious behavior of nonhumans is, however, fuzzy as much human behavior is considered to be executed without conscious deliberation, whereas nonhuman animals may also show intelligent, social, and proactive behavior. The SE-AS framework does not prescribe any particular position with respect to the ontological differences between human and nonhuman actors/entities or the degree of agency of ecological entities but rather encourages researchers to make explicit the particular position they take in an analysis.

Our broader conception of the action situation also goes beyond Ostrom's AS by not prescribing any particular model of human behavior such as the boundedly rational actor (McGinnis et al. 2011) and recognizing that actors are diverse in their interests, motivations, and beliefs, interact within social or social-ecological networks, and can deliberately choose to change or not comply with the rules that structure interactions. The framework is not intended to prescribe a particular view of whether outcomes are determined by the rules that govern interactions or agency of the participants or both. We encourage researchers to critically reflect on the assumptions made regarding human behavior when analyzing a SES.

Social action situations (S-AS)

A social AS is defined by the participating human actors, their capacities, rules, and structures that govern their interactions (Ostrom 1990; Table 1). An actor in an action situation is an individual that has a position, certain information, and a degree of control. The interactions of participating actors are governed by sets of rules, such as positioning rules that define the positions actors have in the given action situation and hence influences the actions they can take. Interactions among participants produce outcomes such as a new rule for harvesting or a change in an existing rule. At the same time, the rules that structure a social AS may be adjusted reflexively based on evaluations of outcomes (McGinnis 2011*a*). We broaden the concept of a social AS proposed by Ostrom by emphasizing the need to consider agency of individuals resulting from diverse motivations and goals of participating actors, which may lead to actions that are not prescribed by the external rules. Outcomes are thus the result of actions and interactions that are enabled and constrained by rules and diverse agency, interests, and goals of participating actors.

Social-ecological action situations (SE-AS)

A social-ecological AS is defined by the participating human actors and ecological entities, their capacities, and the social and biophysical rules and structures that govern their interactions. Human actors in social-ecological AS can be individuals, groups, or organizations, such as resource users, farmers, a monitoring agency, a community, tourists, or citizens, that have a relation or interaction with components of an ecosystem. Ecological entities can be any component of an ecosystem, such as a fish population in a coastal area, a field, or a nature reserve, that affects and is affected by human actors.

Human actors in a SE-AS can have diverse needs, interests, values, knowledge, beliefs, skills, access, and opportunity sets, etc. that influence their actions and interactions with the ecological entities (Boons 2013). Ecological entities can have attributes such as spatial distribution, growth rates, quality, etc. that influence their effect on human actors and actions. The relations and interactions between human actors and ecological entities can be material, for instance human actors extract resources or pollute them;

Table 1. Types of social-ecological, social, and ecological action situations (social action situations expand from McGinnis and Ostrom 2014). The list is not intended to be comprehensive but a starting point for identifying action situations.

Name	Description	Examples of (emergent) outcomes
Social-ecological action situations (SE-AS)		
Cultivating/ Harvesting	Cultivating crops, harvesting natural resources such as fish, timber, grass	Resource conservation/collapse, land-use patterns, changes in biochemical or physical flows, societal well-being, experiences, adaptive capacity, cultural practices, information
Converting	Changing sea or landscapes through technology (e.g., building a dam) or by restoring or converting use to protect ecosystems (e.g., protected areas/reserves)	Changes in biochemical or physical flows, species abundance and composition, habitats, protection from environmental hazards, land-use patterns, adaptive capacity, aesthetic values
Recreating	Spending time in nature, enjoying (physically, psychologically)	New spaces such as parks and recreational areas, new trails, appreciation of nature, health, nature-related values in society
Cultural activities	Performing cultural or spiritual activities in nature	Land-use patterns, e.g., patches of sacred forest, cultural values, emotional well-being, health, conservation
Ecological monitoring	Observing or measuring ecological conditions	Information, understanding, perceptions
Polluting	Introducing substances into ecosystems	Changes in ecosystem state, biochemical flows, economic outcomes
Social action situations (S-AS)		
Rule making [†]	Developing an operational rule, e.g., the level at which individuals can harvest a common pool resource; developing collective choice rules that determine who is involved in decision making	Rules, policies, regulations, norms, subsidies
Information sharing	Sharing information or knowledge between actors	Social learning, shared experiences, innovation, development of trust, norms
Deliberating	Communicating, exchanging observations and views, reflections, assessing outcomes, persuading each other	Common understanding, consensus, trust, innovation
Conflicts	Engaging in actions that aim to harm other actors	Loss of trust
Investing	Allocating financial resources to restore, conserve, or convert sea or landscapes	Support for social-ecological interactions
Lobbying	Influencing political actors to follow one's own interests	Change in rules or lack of change, money flows
Networking	Creating and maintaning social ties	New knowledge, access to information or assets, trust, coordination, pooling resources
Social monitoring	Monitoring compliance of others	Compliance with regulations or norms; punishment
Evaluating	Evaluating outcomes of action situations	Understanding, learning, change in values
Competing	Aiming to do better than other actors, may involve interfering with their activities to reduce their performance	Individualism, social groups
Trading	Exchanging goods or services between two or more actors, selling products at markets	Demand, income
Ecological action situations (E-AS)		
Predation	Individuals of one species prey on another	Species abundance, food web structure, habitat structure
Competition	Individuals of the same or different species compete for a limited food resource or space	Species abundance, food web structure, habitat structure
Facilitation	Individuals of one species facilitate growth or reproduction of another species	Species abundance, food web structure
Infection	One organism infects another organism with a disease	Spread of virus, epidemic
Species-habitat interaction	Generation of offspring, facilitated by suitable ecological environment	Species abundance
Vegetation-soil interaction	Vegetation growth stabilizes soil Soil quality affects vegetation growth and vice versa	Stabilized soils, erosion control, change in water flows, increased nutrients, soil quality

[†] Note that this action situation is called "Harvesting" in McGinnis and Ostrom (2014).

ecological entities feed or flood humans. They can also be nonmaterial, e.g., human actors perceive, manage, or are attached to ecological entities, and ecological entities soothe, protect, or are attached to humans (Table 1). Several conceptualizations and typologies of human-nature interactions have recently been proposed such as a distinction between material and symbolic coupling (Manuel-Navarrete 2015) or material, experiential, cognitive, emotional, and philosophical human-nature connections (Ives et al. 2018). The SE-AS framework does not prescribe a particular conceptualization of human-nature interactions.

Interactions lead to outcomes, which can equally be material or nonmaterial, such as a fish catch or a harvest, a perception, new knowledge, or meaning created through sense of place (Masterson et al. 2017). Outcomes can have short or long-term consequences for the actors and ecological entities of the AS and will affect them differently and in either a direct or indirect manner. A fish catch for instance may increase the well-being of fishers and the mortality of a fish population, the protection of an area for spiritual activities may increase the psychological well-being of individuals and the integrity of the ecosystem, and a monoculture may increase income but decrease soil quality. Human actors may adjust their behavior based on these outcomes (Boons 2013, Schill et al. 2015), and ecological entities may disappear or change their functioning. It is important to note, however, that human behavior is not solely determined by the outcomes of the AS, but also the result of intentionality and political processes (Manuel-Navarrete 2015). Like a social AS, a social-ecological AS is structured by social rules, such as a harvesting regulations or a monitoring protocols, but also by biophysical rules and structures such as the growth of a fish population, the spatial structure of the resource, the geography of a landscape, or physical accessibility (Epstein et al. 2013).

Ecological action situations (E-AS)

An ecological AS is defined by the participating ecological entities, their attributes, and the biophysical rules that govern their interactions. Ecological entities can be individual organisms such as a fish or a tree, groups or populations of organisms such as the cod population in the Baltic Sea, or more aggregate units such as water, soil, or vegetation in a given location. They have attributes such as spatial distribution, productivity, growth rates, quality, and integrity. They receive information or material flows, respond in one of several possible ways, and interact with other entities. Interactions between ecological entities include for instance predation, competition for resources, facilitation, or ecological, geological, or biophysical processes such as vegetation-soil interactions (see Table 1). These interactions produce outcomes such as changes in size of populations (e.g., predator-prey interactions), soil erosion, changes in the water retention capacity of the soil (e.g., processes by which trees capture water and release it gradually), or erosion (processes by which vegetation stabilizes soil). The outcomes can have short or long-term consequences for the ecological entities by changing their properties, e.g., the nutrient content of the soil, and by affecting their future development such as the growth of a fish population. An ecological AS is structured by biophysical rules (e.g., climate, abiotic conditions, food web structure) and anthropogenic impacts, which are captured in social-ecological AS.

Interactions between organisms such as predator-prey relationships are easily represented as ecological AS. Representing biophysical processes such as water or nutrient flows, which are more commonly represented as stocks and flows, can be more challenging. These biophysical processes can be captured, however, as interactions between stocks such as an interaction between soil and vegetation in a field that affects nutrient flows (the outcome). The biophysical (and social) processes that are not affected by actions within the spatial and temporal scales considered in a study are represented as external drivers.

Ecological AS are different from whole ecosystems in that they focus only on those interactions between biotic and abiotic ecological entities that are considered relevant for analyzing a particular SES phenomenon. For instance, to analyze the collapse of the cod population in the Baltic Sea the relevant interactions between cod and sprat populations were included in an ecological AS because their interactions within the food web of the Baltic Sea were considered critical for the ecological regime shift (Möllman et al. 2009). This ecological AS was thus included in our hypothesis of the causes of the cod collapse. An alternative hypothesis may also include an ecological AS that represents the impact of eutrophication on cod population dynamics.

Why three different types of AS and not just one social-ecological AS?

We propose the distinction of social-ecological, social, and ecological AS purely for analytical reasons. Ultimately, everything in SES is social-ecological because all human interactions are embedded in biophysical environments, and today's human actions influence ecosystems across all scales. Interactions between humans and their biophysical environment, however, happen at different temporal and spatial scales and can be more or less direct. An indirect interaction means that the effect of humans on ecological entities or of ecological entities on humans is transmitted through another ecological or social process. In the case of the collapse of the Baltic cod population, for example, the effect of humans on the sprat population is transmitted through changes in the abundance of cod. We thus represent the interactions between cod and sprat in an ecological action situation and link it to the social-ecological AS of cod harvesting, which affects the size of the cod population in the cod-sprat interaction. In the Baltic Sea, sprat is also fished and thus is directly affected by human action, however, in our analysis of the cod fishery collapse, we considered this interaction to not be relevant. For analytical purposes, it is thus useful to introduce social AS to capture those social interactions that, for a given phenomenon of interest and given spatial and temporal scales, are not directly affected by ecological entities and those ecological AS that are not directly affected by social entities. The SE-AS framework captures these indirect interactions through links between different types of AS. Any social or ecological AS will always be linked to and hence affected by the outcomes of a social-ecological AS.

Which social-ecological interactions are considered direct and thus included as social-ecological AS in an analysis is a choice of the analyst and depends on the research question and the temporal and spatial scales of a study. Changes in soil quality for instance can be the direct outcome of a social-ecological AS or the outcome of an ecological AS. It is not the intention to systematically capture all possible social-ecological relations and interactions present in a system but to focus on those that are considered important for generating the phenomenon of interest. It is, however, possible and encouraged to develop several different hypotheses and then explore or test them empirically or through mathematical or computational modeling.

Configurations of linked action situations at and across levels

The aggregate or emergent outcomes of one AS may affect another AS by changing its rules or influencing attributes of its participants such as beliefs, values, growth, or mortality. The outcomes of an E-AS such as the abundance of cod emerging from cod-sprat interactions, for instance, affects the interactions between fishers and cod in the harvesting SE-AS by changing the amount of available fish but also affecting fishers' perception of the availability of fish, which influences their fishing behavior. The emergent outcome of the fishing SE-AS affects the interactions between cod and sprat by changing the abundance of cod. We call such a network of ASs that are linked through their emergent outcomes a configuration of ASs.

Linked action situations have been proposed before by McGinnis (McGinnis 2011*b*), who introduced networks of adjacent AS to facilitate application of the IAD to complex policy settings such as polycentric governance systems. Two AS are adjacent to each other when outcomes generated in one help determine rules that govern interactions within the other. We propose a similar network of AS, which we call a configuration. Contrary to the network of adjacent (social) action situations, our configurations, however, also include social-ecological and ecological AS. At the same time, outcomes of one AS can not only determine rules of another AS as in McGinnis (2011) but also affect attributes of participating actors and ecological entities. Other frameworks that build on the idea of linked action situations are the management and transition framework (MTF; Pahl-Wostl 2009) and the ecology of games framework (Lubell 2013)

A configuration of AS represents a conceptual model or hypothesis about interactions and their aggregate or emergent outcomes that may have generated the SES phenomenon of interest, e.g., a regime shift or a trap, at the system level (oval in the middle of Fig. 1). At the same time, the emergent phenomenon may feedback on ASs and the links between them on the meso- and microlevels, such as the effect of the cod collapse on policymaking. This feedback, however, may happen much later than the emergence of the macrolevel phenomenon (Levin et al. 2013). Note that the levels of the SE-AS framework are relative in that the microlevel is smaller than the macrolevel. They are not considered unique (ontological) categories. The delineation of the different levels is made by the analyst for the purpose of the analysis, and is defined with respect to the phenomenon of interest, the research question, and aim of the study. We also emphasize that there may exist several mesolevels between the micro- and the macrolevels.

Finally, processes in SES are highly context dependent and the hypothesized interactions may only generate the phenomenon of interest under specific social and ecological conditions. These conditions are particular features of the political, cultural, and biophysical contexts that influence the emergent SES phenomenon but that do not change within the spatial or temporal scales at which the phenomenon takes place. They are described in Figure 1.

TYPES OF SOCIAL-ECOLOGICAL, SOCIAL, AND ECOLOGICAL ACTION SITUATIONS

We suggest six generic types of social-ecological action situations that represent common interactions between people and the biophysical environment in the context of natural resource or ecosystem management: cultivating/harvesting, converting, recreating, cultural activities, ecological monitoring, and polluting (Table 1). We have selected them because they are key social-ecological interactions across a wide range of natural and ecosystem management case studies. The list is intended to serve as a starting point for identifying types of social-ecological action situations in SES. We have classified the social-ecological AS based on the intentional or unintentional human activity involved, such as cultivating a field (cultivating), harvesting a fish stock (harvesting), collecting information on the state of the ecosystem (ecological monitoring), or polluting a river (polluting). Each generic type can be further specified into subtypes. Cultivating/harvesting, for instance, includes fishing and farming. Converting includes building infrastructure to better access a natural resource (e.g., irrigation canals), i.e., changing a landscape to protect from natural hazards or for conservation, or restoring a lake to a clear water state. The interactions between humans and ecological entities captured in AS are often of multiple types. In a fishing AS, for instance, interactions can be material when we conceptualize the extraction of fish, but can also be nonmaterial when referring to the experience of a fisher of catching fish. Many AS may represent several types of interactions.

Similarly, we suggest a list of typical social and ecological ASs. The types of social action situations build on the list of action situations in the SES framework (action situations: interactions and outcomes, McGinnis and Ostrom 2014) but were extended to include others that appeared relevant in the case studies we analyzed, such as trading. There is a multitude of social action situations that may be relevant in specific contexts and our list does not aim to be comprehensive. Similarly, we only present a selection of ecological action situations.

APPLICATION OF THE SOCIAL-ENVIRONMENTAL ACTION SITUATIONS (SE-AS) FRAMEWORK TO ANALYZE EMERGENT SOCIAL-ECOLOGICAL PHENOMENA

We illustrate the application of the framework to develop hypotheses about causes of emergent social-ecological phenomena by applying it to several cases of regime shifts and traps as well as one case of cascading global crisis. All are phenomena that pose major governance challenges and hence are of particular interest when analyzing SES. Our analysis is based on literature reviews or our own empirical research (see legend and key literature in Table 2). The aim of each application is to develop configurations of AS that represent a hypothesis of the key interactions that generated the regime shift or kept the system stuck in its current state by reinforcing existing structures and processes. We present seven case studies (Table 2), two of which are described with the remainder in Appendix 1.

An analysis of an observed SES phenomenon using the SE-AS framework begins with identifying the focal or several focal social-ecological action situations that are considered key for generating the observed phenomenon from a theoretical or empirical perspective (see Appendix 2 for a list of guiding questions for the application of the framework). The six types of social-ecological action situations defined above can serve as a guide for selecting focal action situations. In the case of the Baltic Sea cod collapse, the focal social-ecological action situation is the harvesting of cod by fishers from the Baltic Sea and the west coast of Sweden (Fig. 3). When conceptualizing the AS, one needs to identify the actors and ecological entities involved, their possible actions, attributes, and factors such as rules, biophysical factors, or social networks that structure their interactions. The level of detail about components of an AS one wants to incorporate in an analysis depends on the purpose and interest of the study. For instance,

Table 2. List of case studies that were analyzed using the social-ecological action situations (SE-AS) framework. The first two cases are presented in the main text (Baltic Cod and Pamir Mountains), the others are in Appendix 1. Cases 3,6, and 7 are based on the review of literature on the case, whereas cases 1, 2, 4, and 5 are an outcome of empirical research performed by authors (see key literature for relevant publications). Note: SES = social-ecological system.

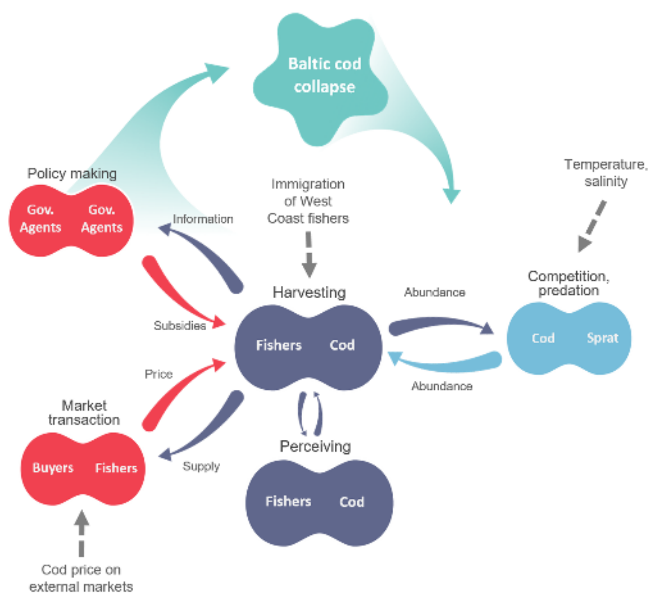
	Empirical phenomenon of interest	SES phenomenon of interest	Research question	Key literature
1	Collapse of the Baltic Sea cod populations	Regime shift	How did social factors and processes in the cod fishery contribute to the cod collapse?	Lade et al. 2015
2	Persistent poverty in the Pamir Mountains	Social-ecological trap	How did the introduction of a new seed by a donor organization contribute to the creation of a social-ecological trap?	L. J. Haider, W. J. Boonstra, A. Akobirshoeva, and M. Schlüter, *unpublished manuscript*
3	Collapse of the Newfoundland cod fishery	Regime shift	Which social and social-ecological interactions have maintained unsustainable harvesting and led to the collapse of cod?	Mason 2002
4	Restoration of lake Ringsjön, southern Sweden	Regime shift	How do social and ecological processes interplay to determine the restoration time of a tipping lake?	Martin and Schlüter 2015 R. Martin, M. Schlüter, T. Blenckner, *unpublished manuscript*
5	Small-scale fisheries in Mexico	Trap	Which microlevel mechanisms lead to a dominance of patron-client relationships in the fishery?	Lindkvist et al. 2017
6	Dryland agriculture in Tanzania	Social-ecological trap	What feedbacks maintain the trap and what leverage points for escaping the trap exist?	Enfors 2013
7	Spread of Avian influenza	Cascading crisis	What are possible social-ecological feedbacks that may precipitate an epidemic?	Galaz et al. 2011

when analyzing the collapse of the Baltic cod stocks, we considered how the decision of a Baltic Sea fisher on the amount of time spent fishing is influenced by his perception of the availability of cod, but also by the investments he has made in his fleet (sunk cost effect). His investment decisions may be influenced by a policy, such as a subsidy, that emerged from a rule-making AS. The cod stock, as the ecological component in the harvesting AS, may be influenced by previous fishing pressure as well as emergent outcomes of food web interactions of cod with sprat. These in turn are affected by temperature and salinity. The factors influencing the focal social-ecological AS are thus either emergent outcomes of other social, ecological, or social-ecological action situations or external drivers (such as temperature).

Collapse of the Baltic Sea cod populations

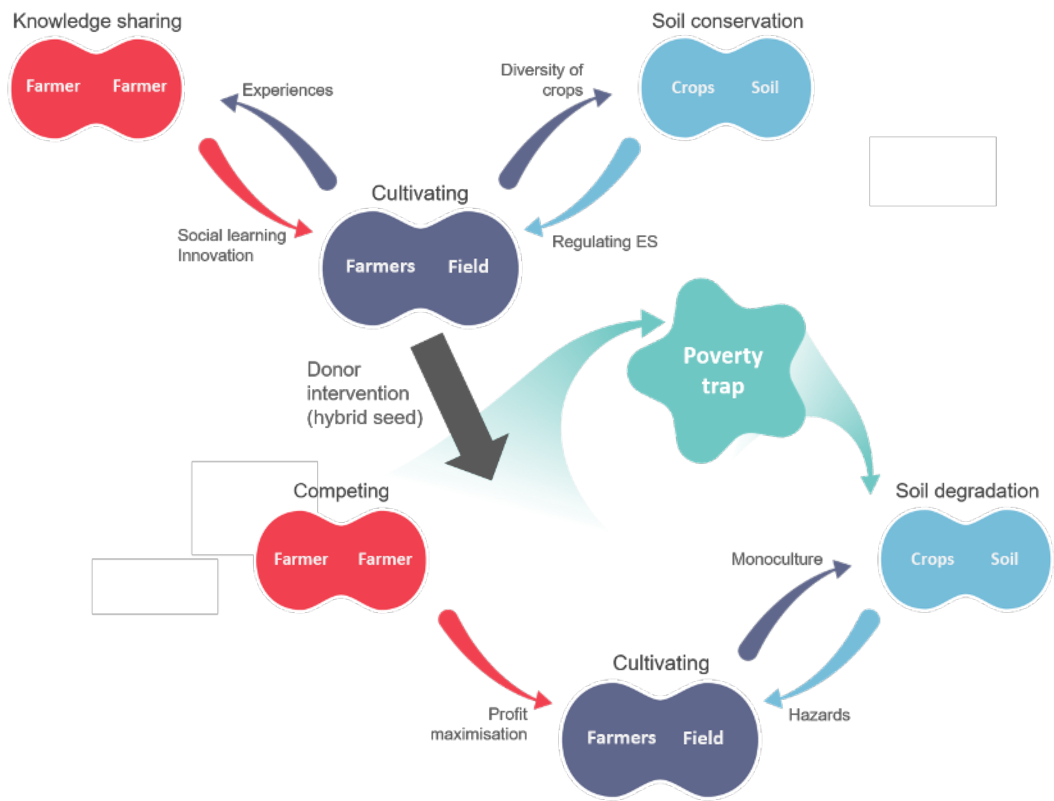
The collapse of the cod fishery in the Baltic Sea is an example of a well-studied ecological regime shift (Möllmann et al. 2009). Although the ecological drivers of the collapse, such as change in temperature and salinity are well known, the contribution of social processes to the collapse has only recently received attention (Lade et al. 2015). We applied the SE-AS framework to develop a hypothesis about the social-ecological interactions that may have accelerated or prevented the collapse (Fig. 3). The main social-ecological action situation is the harvesting of cod by fishers (fishing SE-AS). We hypothesized that fisher decision making in this social-ecological AS affected the stability of the fishery (compared to the ecosystem alone) and thereby its tendency to undergo a regime shift. Based on empirical evidence, we assumed that the decision of a fisher to spend time fishing was influenced by the perceived profitability of cod fishing, his previous catch experiences, and investments in his fishing fleet (sunk cost effect; Lade et al. 2015).

Fig. 3. Social-ecological action situations (SE-AS) representation of the configuration of social-ecological (dark blue), social (red), ecological action situations (light blue) hypothesized to have caused the cod collapse in the Baltic Sea.



We could then decompose these decision-making factors by identifying the social and ecological interactions that influenced them. A fisher's perception of cod abundance is influenced by previous catch experiences, which are the result of past social-ecological fishing interactions (perceiving AS). Fishers had a

Fig. 4. Social-ecological action situations (SE-AS) representation of the configuration of social-ecological (dark blue), ecological (light blue), and social (red) action situations hypothesized to generate a social-ecological trap and the loss of native seeds in the Pamir mountains. Traditional agriculture before development intervention (left) and after development intervention of improved seed varieties (right).



perception of high cod abundance because of a preceding cod boom. Cod abundance is influenced by food web interactions, such as the competition and predation between cod and sprat and cod and herring in ecological AS (competition, predation ASs). Because these ecological interactions have been well studied (Möllmann et al. 2009), we do not go into their details here. An actor's perception of profitability of cod fishing is influenced by the market price for cod. Market prices for cod, which were also affected by cod supply from other areas, and subsidies from the Swedish government are both considered critical factors for high fishing pressure in the 1980s. The market price emerged in a social AS from market transactions that were influenced by cod supply resulting from the fishing social-ecological AS (market transaction AS). Finally, a fisher's investments in his fleet were influenced by subsidies provided by the Swedish government. These subsidies were the result of a rule-making social AS that was influenced by information provided by the fishing AS (policymaking AS). The fishing pressure, as an outcome of the fishing interactions, was also influenced by an external driver, namely immigration of fishers from the west coast of Sweden, who were attracted by the prospect of high catches during the cod boom.

A model-based analysis of the role of these different interactions for explaining the cod collapse revealed that adaptation of fisher behavior to changing cod populations helped to delay the cod collapse until the nonlinear dynamics of the ecological interactions caused the collapse (Lade et al. 2015). Fishers responded to changing cod availability by changing their decisions with respect to time spent fishing, investment in their fleet, and in the case of the west-coast fishers whether to enter the Baltic Sea. Fishers' adaptability to changing conditions was, however, delayed by slow updating of perceptions of cod availability, sunk cost effects from investments in new fleet, and subsidies, which in interplay with the ecological dynamics, ultimately caused the collapse.

Poverty trap in the Pamirs

The Pamir Mountains of eastern Tajikistan remain one of the poorest areas of the post-Soviet nations. At the same time, they are home to a high level of agricultural biodiversity and century old traditions of cultivating a very harsh environment (Van Oudenhoven and Haider 2012). Today, development organizations have largely replaced the role of government in basic governance functions to meet social needs. However, despite a long history of interventions, poverty persists while agricultural biodiversity and knowledge about farming are in decline. We applied the SE-AS framework to analyze the poverty trap in the Pamirs, particularly to understand how the introduction of a new seed by a donor organization contributed to the creation of this social-ecological trap (Fig. 4).

The main social-ecological AS is cultivation, representing the relationship between a farmer and her field (cultivating AS). We hypothesized that the donor intervention had disrupted cultural practices that maintained the agricultural diversity that underlaid the adaptive capacity and ecological integrity of the high mountain fields (L. J. Haider, W. J. Boonstra, A. Akobirshoeva, and M. Schlüter, *unpublished manuscript*). Before the intervention, a farmer's decision about what to plant was influenced by rituals in the community, such as the joint preparation of ceremonial dishes that are based on particular local grains (left side of Fig. 4). Farming was a collective enterprise in which seeds were shared and experiences exchanged; this provided opportunities for innovation. This is represented by a social AS of knowledge sharing and cocreation among farmers through folklore, recipes, and daily practices. The diversity of crops on the fields was created by a process of coevolution in which successful innovations that were well adapted to the social-ecological environment were maintained. The agricultural practices associated with this way of farming conserved the soil and enhanced the adaptive capacity of the larger agro-ecological system critical in the harsh environment of the Pamirs (soil conservation AS).

Donor interventions promoted improved seed varieties with the primary aim to improve yields of a few staple crops, such as wheat and potatoes (right part of Fig. 4). The intention was that cash surplus for poor families would lead to livelihood diversification and therefore improved well-being. Over time however, these seed varieties failed because they were not adapted to the environmental conditions of the Pamiri landscape and required substantial fertilizer inputs that were not available. The resulting reduction of diverse plant functions, such as nitrogen fixation, water retention, and erosion control led to further soil degradation (soil degradation AS). Furthermore, because no traditional knowledge was needed for the improved seeds, the system of cultivation changed, thus also changing the social AS, leading to a loss of opportunities for social learning and innovation. This interaction is possibly replaced by a more competitive and transactional relationship between farmers (competing AS). The loss of social learning and corresponding soil degradation created a social-ecological trap from which it is difficult to escape.

Our empirical study has shown that this trap has indeed emerged in some communities in the Pamirs, where we can find an interesting transition stage of maintenance of cultural practices even though the ecological components have already been lost (L. J. Haider, W. J. Boonstra, A. Akobirshoeva, and M. Schlüter, *unpublished manuscript*). Other communities, however, resisted the introduction of the seed. The diverse responses of people to the external intervention are subject of ongoing empirical research.

DISCUSSION

Added value of the framework

The SE-AS framework is grounded in a conceptualization of SES as deeply intertwined, complex adaptive systems. It goes beyond existing frameworks by focusing on the emergence of SES phenomena from the interplay of microlevel social-ecological interactions with the emergent outcomes they generate. It puts interactions between humans and nonhuman entities at the center of an analysis. The framework structures interactions into three types of action situations (AS) that are linked through their emergent outcomes. A configuration of linked AS represents a possible explanation of the interactions and processes that generated the emergent phenomenon of interest. The AS and their emergent outcomes serve as analytical devices to focus an analysis on those interactions that are considered most relevant for the phenomenon of interest from a theoretical, observational, or empirical perspective.

The framework's primary contribution is twofold. First, it conceptualizes a SES as composed of interactions between diverse human and nonhuman entities that are constrained and enabled by interaction structures, i.e., spatial arrangements, rules, social networks, that are created and affected by those interactions. The framework supports an analysis that recognizes these evolving interactions across multiple levels as key mechanisms for the emergence of social-ecological phenomena. The SE-AS framework provides a means to structure those interactions into linked AS to develop possible explanations that account for complex causation and emergence. Social-ecological and ecological ASs allow incorporating relevant dynamics of social-ecological and ecological processes, and thus to go beyond a perspective that sees biophysical factors as static constraints to social interactions. This perspective encourages the analysts to be specific about the processes that give rise to the rules and structures that shape interactions in SES. The focus on human and nonhuman actors/entities and not variables allows accounting for different types of agency, action, and interaction of heterogeneous actors. For instance, the noncompliance of some actors with an environmental regulation delays the implementation of a policy, which can have significant nonlinear effects on those ecological interactions relevant for restoring a turbid lake (R. Martin, M. Schlüter, T. Blenckner, *unpublished manuscript*).

Second, when applying the framework, the researcher or group of researchers need to identify the ASs and links between them deemed relevant for a particular emergent phenomenon based on field studies, expert knowledge, the literature, or synthesis of empirical evidence. In so doing, the framework encourages making explicit assumptions of the participants about the relevance of different material and nonmaterial interactions for the problem at hand. The resulting hypothesis or conceptual model can then inform a field study, an experiment, or an agent-based model to test its validity and investigate selected social-ecological interactions. As our experience with some of the seven examples has shown, such an iterative process of conceptual model development and simulation modeling or empirical work can help unpack the complex causalities at play in SES and enhance understanding of social-ecological dynamics (Schlüter et al. 2019). We envision that such a process will ultimately contribute to theory development and the identification of interactions critical for management and governance.

Comparison to existing frameworks

Although building on the action situation from the IAD and SES frameworks, the SE-AS framework differs from them in three important ways. First, it puts social-ecological interactions, not social interactions, at the core of an analysis and thus shifts the focus to social-ecological relations and interactions as key explanatory elements. Treating human and nonhuman entities as equal is a first step to overcome the dichotomy between social and ecological and thus to better account for the intertwined nature of SES (Stone-Jovicich 2015). It still, however, conceptualizes human and nonhuman entities as separate entities that exist prior to any interaction, i.e., they first exist before they can interact with each other. Process-relational perspectives, on the contrary, conceive of these entities themselves as coconstituted through social and ecological relations and interactions (T. Hertz, M. Mancilla García, M. Schlüter, *unpublished manuscript*). Whether and how the framework can be used to support an analysis based on a process-relational perspective remains to be explored.

Second, the framework acknowledges the importance of social and ecological processes, such as environmental governance or food web dynamics, that may be more remote from the direct human-nature interactions in focus, but shape rules of interactions and agents' motivations and goals. These ecological and social-ecological processes may not always be visible through disciplinary framings that underlie many frameworks. In SE-AS, these dynamics can be captured through social and ecological AS that are linked to social-ecological AS through emergent outcomes. The explicit consideration of ecological AS allows the researcher to consider the ecological dynamics and their outcomes, which are reduced to a few resource system variables in Ostrom's SES framework. Recent extensions to Ostrom's SES framework that include ecology have added ecological rules that can help define how biophysical conditions may shape social interactions (Epstein et al. 2013), but they do not consider the social-ecological and ecological processes that jointly give rise to these rules in the first place.

Third, the SE-AS framework accounts for the dynamic and emergent nature of SES by focusing on those dynamic interactions within and across AS, which over time may have generated the phenomenon of interest. Simultaneous interactions within multiple AS often mutually influence each other. The food web interactions between cod and sprat, for instance, are constantly affected by the interactions between fishers and cod. The resulting cod abundance thus is shaped by ecological and social-ecological dynamics alike. An analysis that treats ecological processes as external conditions, drivers, or a fixed rate such as a population growth rate would miss these important intertwined dynamics. An explanation developed in SE-AS, however, does not specify causality beyond the constellation of actors and interactions because this can only be explored through an empirical study, an agent-based model, or an experiment.

The framework differs from causal loop diagrams by its focus on actors and their interactions and not on aggregate variables and the flows that connect them. Actors or ecological entities in an AS can be heterogeneous and their interactions may be structured by social networks or physical space. The level of detail at which an AS is represented depends on the focus of an analysis. Furthermore, a possible explanation developed in SE-AS does not assume deterministic causal relationships between interacting entities or AS the way that causal loop diagrams normally do. Instead, a configuration of AS defines the actors, ecological entities, their attributes, interactions, and rules considered to be important elements of a causal explanation of the phenomenon of interest. Agricultural practices in the Pamirs, for instance, are considered to emerge from social interactions in knowledge exchange AS that are influenced by a social-ecological AS of cultivation and biophysical and institutional settings in a way that cannot be reduced to simple causal relationships on the micro- or macrolevels. The focus of the framework is on the interactions that give rise to an emergent outcome, rather than deterministic relationships between variables. Causal relationships in SES are difficult to analyze and need to be explored in field studies, experiments, or through modeling.

The SE-AS framework leaves room for different interpretations of reality. Outcomes of an AS, for example, can be determined by structural features of the AS, or by the agency of its participating actors, or both. Because SES are complex adaptive systems, SES outcomes are most likely determined by the interplay between bottom-up self-organized processes with emergent top-down structural constraints. In SES, "parts and whole ... co-constitute one another with a relationship of 'reciprocal causality' between local and global levels" (Thompson and Varela 2001:421). Others have highlighted the need for understanding the relationship between strategies actors use and the broader system dynamics that shape the context in which they operate, thus indicating the need to take the links between microlevel agency and macrolevel system structure or dynamics into account (Westley et al. 2013). The SE-AS framework does not prescribe a particular view about the causes of SES outcomes, the model of human behavior, or the role of agency versus structure. It is, however, the responsibility of the researcher to be transparent about the particular position on these issues she takes when using the framework.

Applications

We have developed the framework as a tool to (1) organize empirical knowledge about social-ecological interactions; (2) make explicit assumptions about their relevance for SES outcomes; and (3) facilitate interdisciplinary collaboration across domains to develop social-ecological explanations of SES phenomena. The framework thus serves different roles from supporting the analysis of causes of a phenomenon of interest for building SES theory, to enhancing transparency of models of SES, and serving as a boundary object for knowledge integration. The framework is flexible with respect to the level of abstraction and detail of an analysis because each AS can be unpacked to the depth necessary for a particular research question. Our application of the framework to the seven case studies has shown that the process of identifying key components and their interactions makes explicit assumptions about the causes of SES patterns and dynamics. It supports a process of disclosing and discussing different assumptions about the key mechanisms and processes that generate an observed phenomenon. For instance, biodiversity and human well-being in the Pamirs may be maintained when (1) the cultivation of fields is connected to social interactions that maintain and cocreate knowledge and practices suitable for the local landscape, or (2) the cultivation of fields is supported by knowledge exchange with external actors. Although the challenge of identifying key elements and reducing complexity is always an empirical one, our framework and the types of action situations we have introduced can help structure a problem situation and organize available knowledge in a clear and transparent way.

Decisions on which AS to include in an analysis, which processes to represent at the microlevel, which heterogeneities matter, and where to set system boundaries are difficult and depend on the question or phenomenon of interest. They need to be made in a transparent manner. In many cases, knowledge about a phenomenon is not sufficient to specify all relevant actors, biophysical entities, and interactions. We have developed the framework to support discussions in interdisciplinary teams with the aim to elicit and integrate available knowledge across different domains. The framework may serve as a boundary object to facilitate a process of integrating different understandings about actors, attributes, and rules in the ecological and social domains into one or several possible social-ecological explanations. Note that the goal of the framework is not necessarily to find one best explanation or to integrate different understandings that may be contradictory but rather to help clarify different understandings as a basis for further exploration and learning. Contradictory or missing information or knowledge can be captured in alternative explanations that can be tested in parallel and through an iterative process of hypothesis development and testing leading to a renewed hypothesis and so forth.

Given the complexity of SES and the diversity of available disciplinary, interdisciplinary, and transdisciplinary knowledge, no single framework will be best or sufficient for their analysis and governance. On the contrary, SES research benefits from multiple perspectives and methods (Bousquet et al. 2015). With the SE-AS framework, we aim to support studies that enhance understanding of SES dynamics, particularly the mechanisms at and across different levels that bring about emergent system-level change. We hope that our framework will be used to develop strategies and measures that may prevent an undesirable change or enable a desired one, such as a transformation toward sustainability. The SE-AS framework offers a step toward developing such understanding; a step that will hopefully complement other approaches by providing a way to analyze and theorize about SES as complex adaptive, intertwined systems of humans in nature.

Responses to this article can be read online at:
http://www.ecologyandsociety.org/issues/responses.php/11012

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APPENDIX 1

Collapse of the Newfoundland Cod fishery

In the early 1990s the Newfoundland cod fishery collapsed despite management measures that were targeted at controlling the access to the resource (Hutchings and Myers 1994, Milich 1999, Mason 2002, Mather 2013). Fishing of cod by foreign fleets was portrayed as the most important source of overfishing by Canadian media (Mason, 2002). However even after the declaration of a 200-mile Exclusive Economic Zone by Canada and bringing of cod management under Canadian control, the social and social ecological processes in the cod fishery developed in a way which led to overharvesting of the resource. We apply SE-AS to develop a hypothesis about a set of interlinked AS that have partially been set off by the ban of foreign fishing in Newfoundland and may have led to unsustainable harvesting and collapse of the resource.

The two key social-ecological ASs before the collapse were the interaction of the foreign and domestic fishers with the Atlantic cod population (Harvesting AS) which created competition between the two types of fishers. The two action situations were, however, affected differently by governance actions (Rule-making AS) that determined who gets to harvest the resource and receives subsidies. The cod population, apart from the fishing pressure, was also affected by environmental factors such as water temperature and to some extent – salinity and seal predation (Hutchings and Myers 1994). Nevertheless, the social factors are emphasized as the major cause in later research (Mather, 2013).

The left figure shows the state of the system before the foreign fishing ban was introduced. Cod was fished both by Canadian fleets and foreign trawlers. The two different types of fishermen competed for cod, and harvesting of the resource by one type of fisherman could lead to reduced availability of the resource for the other. The importance of the local fishing industry to the economy and employment in the region meant a strong domestic fishermen lobby, which increased the pressure on the government to adopt the Exclusive Economic Zone and ban foreign fishing of Newfoundland cod. The figure to the right shows the system after the ban was officially introduced in 1977. The cod was then harvested exclusively by domestic fishermen. The ban of the foreign fleets was interpreted as a sign of state support, as well as the continued subsidies. This has attracted more fishermen and encourage existing ones to invest in their activity – through financial as well as social (knowledge, social relations, building up trust, etc.) capital. After the fishing pressure on the stocks increased further, the catches declined, however it was difficult for the fishermen to stop the activity due to the investments mentioned above, which lead to overharvesting and collapse of the Newfoundland cod population.

This analysis reveals that explanations for the collapse of the Newfoundland cod stock have so far only been sought for in the social systems. It is unclear whether and to what extent changes in ecological interactions between cod and other species or cod and the biophysical environment may have contributed to the cod collapse.

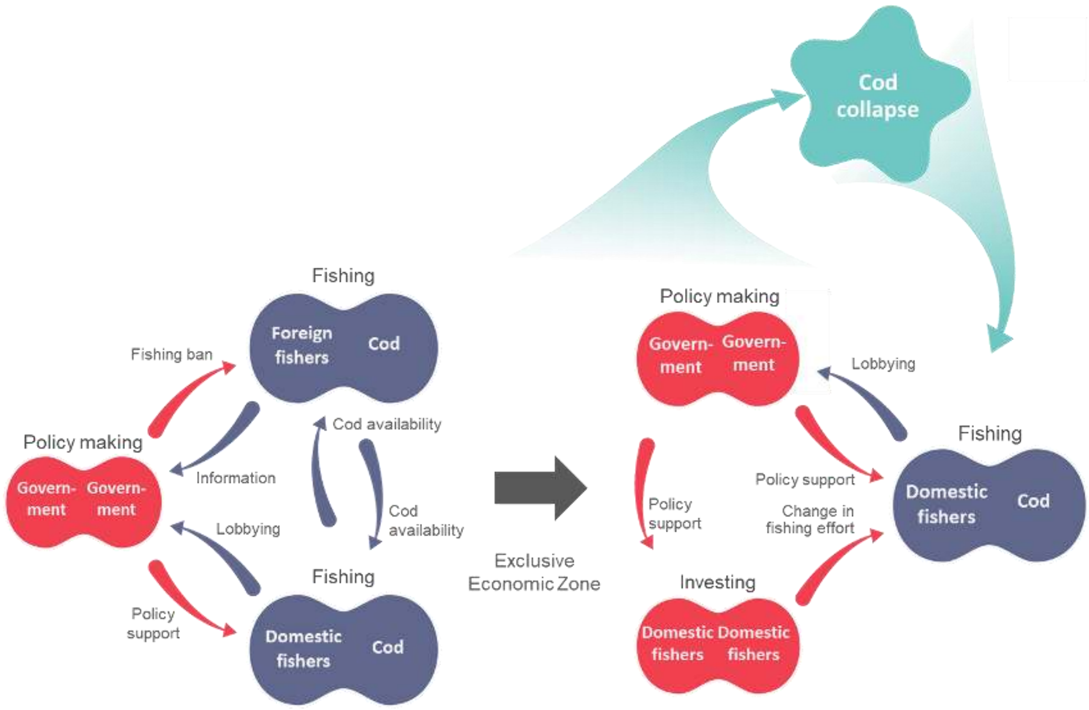

Figure A1: SE-AS representation of the configuration of social-ecological (dark blue) and social (red) action situations hypothesized to explain the collapse of the Newfoundland cod fishery

Regime shifts in lake Ringsjön

Shallow lakes that shift rapidly from a clear to a turbid state are a classic example for regime shifts. They are often caused by a slow accumulation of nutrients in the lake sediments from fertilizers used in nearby agriculture but also from insufficient sewage treatment in private houses along the lakeshore (Pers 2005, Jöborn et al. 2005). Turbid, highly eutrophied lakes pose a challenge for communities and lake managers who aim to restore the clear state of the lake to support lake-related ecosystem services such as recreational activities and drinking water supply. We apply the SE-AS framework to develop a hypothesis about key social-ecological interactions required to enable a successful lake restoration. The analysis is based on lake Ringsjön, a turbid lake in Southern Sweden where lake restauration activities have been under way for many years, including regulation of sewage treatment and bio-manipulation, however with varying success.

In this case there is no single key social-ecological AS, rather interactions between different actors and different aspects of the lake jointly influence the success of restoration. First, there is the social-ecological AS of nutrient pollution by private lakeshore house owners (Pollution AS) that causes harmful algae blooms and changes the food web towards a dominance of commercially low valued fish species such as bream and roach. Once an awareness of the problem reached policy making, algae abundance was monitored (Monitoring AS) and the municipality and the water council (an expert and stakeholder committee for lake use) agreed on policies for nutrient regulation (Policy making AS). The successful implementation of the regulation, i.e. the installment of new sewage treatment technology which is a high cost investment, however, depends on enforcement measures and how individual house owners were involved in the regulation process (Enforcement AS). In this case enforcement was carried out through visits of representatives of the municipality to house owners (Wallin et al. 2013). As the lake was already in a turbid state, the municipality engaged in bio-manipulation, i.e. a direct manipulation of the food web through the removal of white fish which is expected to decrease algae blooms and favor commercially higher valued fish (Restoration AS). Both enforcement and bio-manipulation are costly thus requiring repeated interactions within the policy making AS to allocated the required budgets. One future vision and motivation for the restoration of shallow lakes is that investments to restore a clear state facilitates more touristic lake use which will eventually provide revenues for municipalities (Recreation AS).

The AS configuration exemplifies that the overall success of lake restoration depends on three major outcomes to happen simultaneously. First, governing institutions need to deal with the legacy of past activities that affect the state of the lake today, for example through high nutrient levels in sediments, as well as ongoing pollution. They require measures to actively shift the lake back (bio-manipulation) as well as regulation and enforcement measures to reduce new inflow. Second, municipalities need to employ experts to conduct the practical restoration after evaluating carefully which methods are suitable in the local case. And third, the lake use through tourism (recreation) is both dependent on success of the first two activities while at the same time reinforcing their implementation. It may possibly accelerate the whole restoration process to include potential beneficiaries of the improved lake ecosystem from the beginning.

In summary, applying the SE-AS framework highlights that lake management needs to deal with three challenges at once: past practices of pollution in the catchment, present ecosystem manipulation and pollution and potential future income through touristic activities. These threefold challenge requires a sufficient investment in collaboration between different actors while it is uncertain when and how much of this investment will pay out. As a first step, we are investigating interacting time lags resulting from a subset of these linked action situations using a hybrid system-dynamics and agent-based model (Martin and Schlüter 2015).

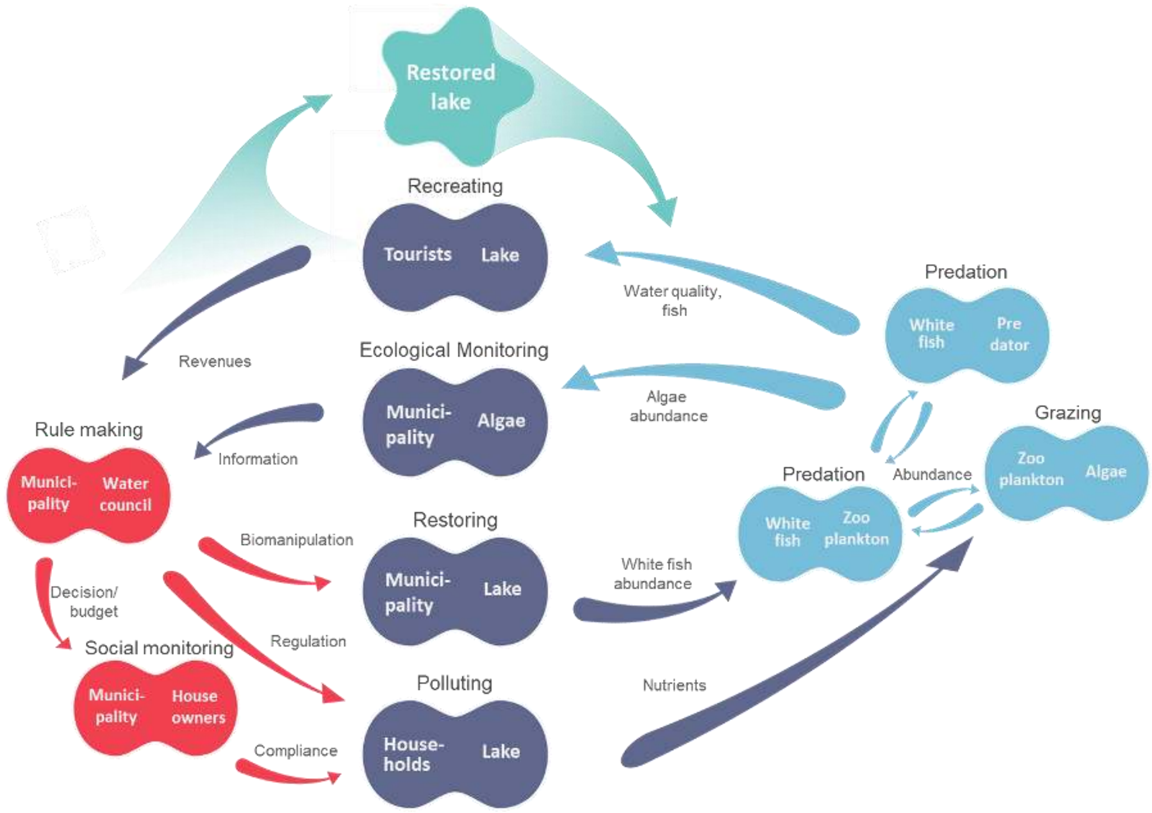

Figure A2: SE-AS representation of the configuration of social-ecological (dark blue), social (red), and ecological action situations (light blue) hypothesized to influence the success of restoration of the turbid lake Ringsjön.

The dominance of patron-client relationships in small-scale fisheries in Mexico

Small-scale fisheries in Mexico are to a large extent self-governed through fishing cooperatives (co-ops) that were promoted by the government since the 1930s (Young 2001). In recent years, however, patron-client relationships (PC) between fishers and fishbuyers seem to be rapidly on the rise (Leslie et al. 2015). The ecological and social consequences of an increase of patron-client relationships are unclear and will, most likely, depend on the specific social-ecological contexts in which they operate. Rather than examining the effect of the different organizational forms (co-ops and PCs), we were interested in understanding under which conditions one form or the other is more likely to establish and persist in the first place. Theoretical and empirical research has highlighted the importance of trust for the persistence of both self-governance forms. We apply the SE-AS framework to develop a hypothesis about the role of different dimensions of trust, such as reliability and loyalty for the persistence of each organizational form within a dynamic social-ecological environment.

The key social-ecological AS in this case is fishing (Fishing AS). Fishing pressure affects the competition for food and habitat between fish in the population affecting the growth of the fish population (Competition AS). The catch provided by fishing is then traded with the co-op or PC that provided the fisher with the fishing means or with another coop or PC that offers a better price (Selling catch AS). The outcomes of the Fishing and Selling catch AS influence the revenues of each organization. The outcome, however, also influence the building of trust within each organization as the trust between a fisher and his coop or PC will decrease after cheating or increase if the catch was landed in the organization providing the fishing means. The loyalty in an organization together with the revenues determine its functioning (PC or Coop Functioning). While coops cannot select their members, PCs engage in an interaction with free fishers to select those with highest reliability. Fishers' reliability and their loyalty to the coop or PC they are working with determines their level of cheating.

We implemented this set of action situations in an agent-based model to explore the conditions under which one organizational type dominates (Lindkvist et al. 2017). The model shows that PCs dominate when the initial loyalty within coops is low and the community is very heterogeneous, i.e. fishers' reliability varies greatly. Under these conditions only very few coops manage to develop a level of loyalty that lowers cheating to a level that enables them to persist and accumulate enough revenues when resource conditions are bad (because of competition between the different organizations). While coops have fixed members, PCs can select fishers with high reliability (depending on their availability) from the beginning thus reducing cheating. They can also dismiss fishers or engage more when needed. The latter, however, can also be detrimental as it causes PCs to increase their size when fish resources are low with the aim to increase their catch to meet the market demand. Overall, the persistence of an organization depends on the initial level of loyalty in an organization, its composition with respect to the reliability of its members, the competition with other coops are PCs for fishers and fish and the state of the fish population.

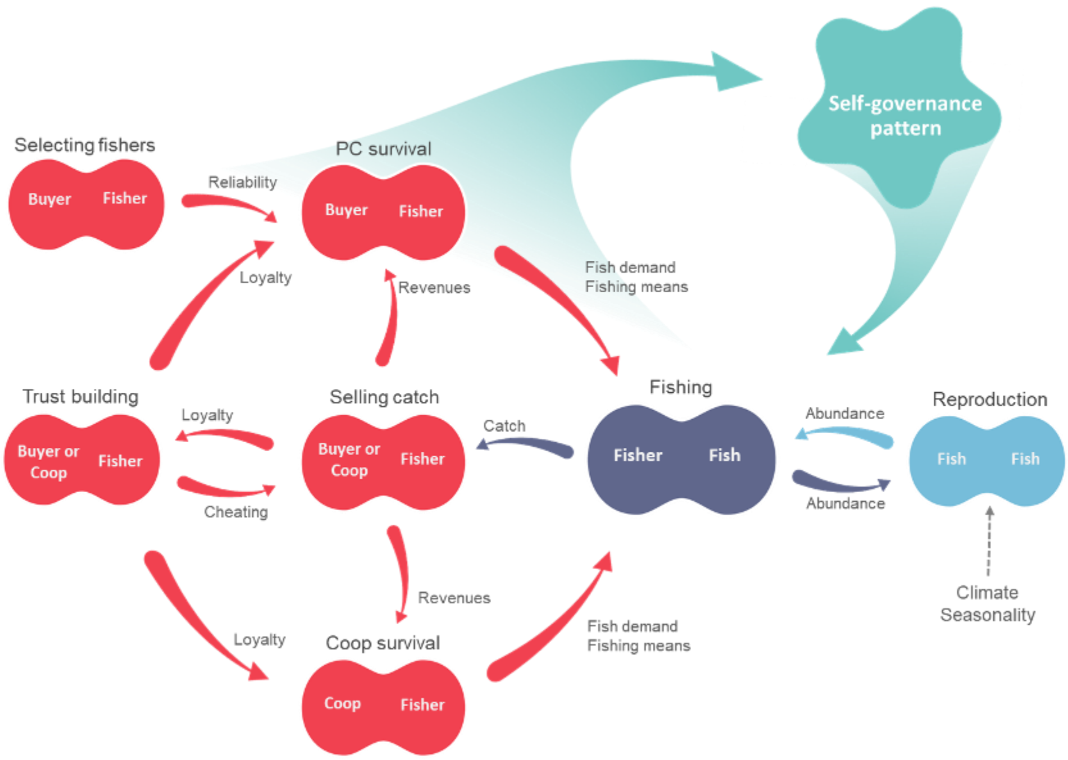

Figure A3: SE-AS representation of the configuration of social- ecological (dark blue) and social action situations (red) hypothesized to explain the dominance of patron-client relationships versus cooperatives in small-scale fisheries in Mexico.

Poverty traps in Tanzania

In contrast to the Pamir case above, in which a trap and attempted escape from it were analyzed, we now apply the framework to the descent into a poverty trap (Figure A4) in the Makanya region of Tanzania (Enfors 2013, Boonstra and de Boer 2014). Prior to the 1960s, families in the Makanya region of Tanzania engaged in low-intensity agriculture, growing maize for subsistence and vegetables for cash crops. Beginning in the 1960s, a number of drivers led to intensification of cultivation, our focal social-ecological interaction. Population growth led to increased pressure to produce food, and farmers responded by cropping twice per year. This intensification degraded soil quality and reduced the productivity of the cropland. In response, through a second social-ecological interaction, families relied more heavily on common resources from the rural landscape such as fodder, wood and vegetables, which also became degraded. Resource degradation was further exacerbated by a social and an ecological driver present at the time: 'villagization' policies that reshaped communities and their leadership led to decreased trust in community leadership and resource use rules and to degradation of the common pool resources; and increasing frequency of dry spells further degraded the productivity of the cropland.

Enfors (2013) analyzed how the causal interactions between these action situations led to the reinforcing feedbacks that are commonly understood to define a trap (Carter et al. 2007). Boonstra & de Boer (2014) analyzed how the historical sequence of these and other action situations led through a critical juncture to the appearance of the poverty trap.

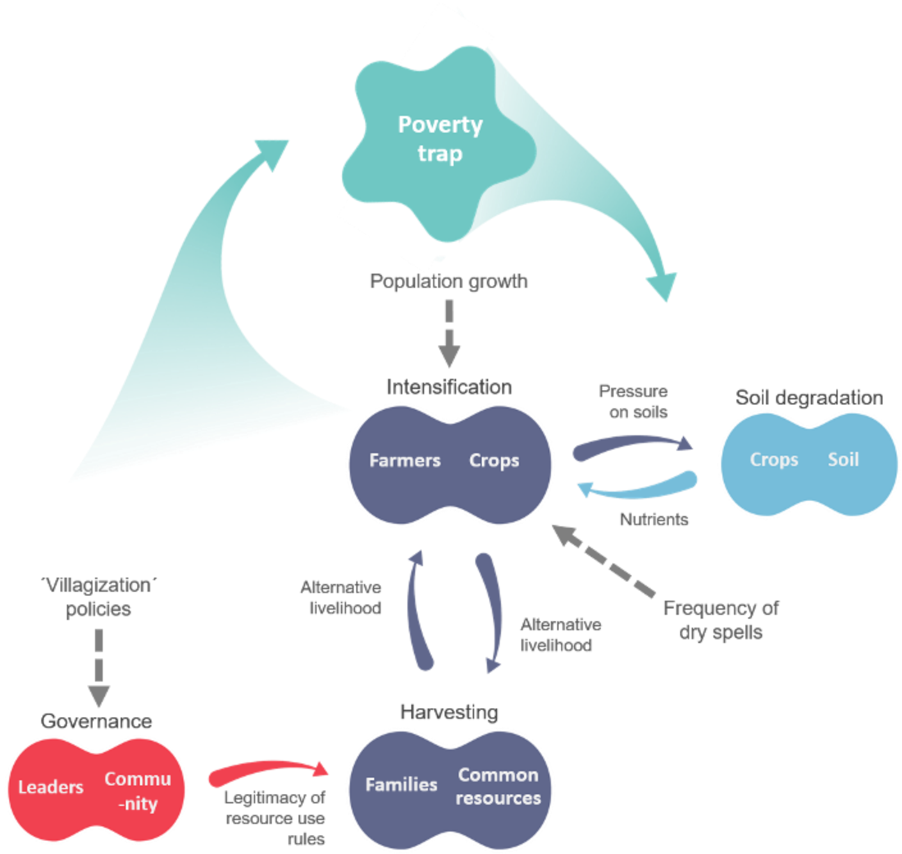

Figure A4: SE-AS representation of the configuration of social-ecological (dark blue), ecological (light blue) and social action situations (red) hypothesized to explain the emergence of a poverty trap in Tanzania.

Spread of Avian influenza

The local outbreaks of H5N1 subtype of avian influenza and its potential to spread from Asia poses a risk of an emergent global epidemic. The disease uses wild water birds as its natural reservoir. However various social-ecological processes have contributed to the spread of avian influenza to domestic birds and further to humans (Figure A5). Particularly, free-grazing domestic water birds (e.g. ducks) can interact with wild birds in their habitat (wetland), allowing for cross-species transmission (Kapan et al. 2006). Use of wetland for rice farming and conversion of wetland in general has decreased the habitat available for wild water birds, leading to increased contact between domestic and wild populations (Gilbert et al. 2008). The cross-species exposure via spill-over and spill-back, increasing human population density and poultry sector intensification have led to an emergence and local transmission of a pathogenic strain of avian influenza that could occur in humans (Kapan et al. 2006). The local spread of avian influenza has occurred mainly through interactions with poultry – particularly in crowded conditions, such as 'wet markets' or factory farms (Kapan et al. 2006). Both the spread of H5N1 and its ability to transcend the species barrier have been exacerbated by changes in precipitation, temperature and its further impact on wetlands (Kapan et al. 2006, Galaz et al. 2011).

However, avian influenza has had the potential to spread from its origin in South-East Asia to other countries due to both human and non-human factors. For example, through wild bird migration the virus can spread not only through regions of SE Asia, but to other continents (Gilbert et al. 2008). The migration behavior and distribution of wild birds are also greatly affected by climate change, potentially affecting the avian influenza epidemiology and global spread. Another link connecting local and global H5N1 spread is poultry trade. Changes in market price, trade conditions, modernized transportation also affect the spread of the virus via poultry products from its local origins to global market (Karesh et al. 2005, Kapan et al. 2006). The human-to-human spread of H5N1 has been suspected but not yet identified as an efficient source of transmission. However its evolution in this direction is possible, exacerbated by the population density and conditions for avian-human exposure on the local level (Kapan et al. 2006). The risks for potential global epidemic of avian influenza are thus maintained by the interconnected social-ecological processes on the global level (trade patterns, wild bird migration and climate change) and local level (land-use and wetland reduction, population increase) (Bahl et al. 2016).

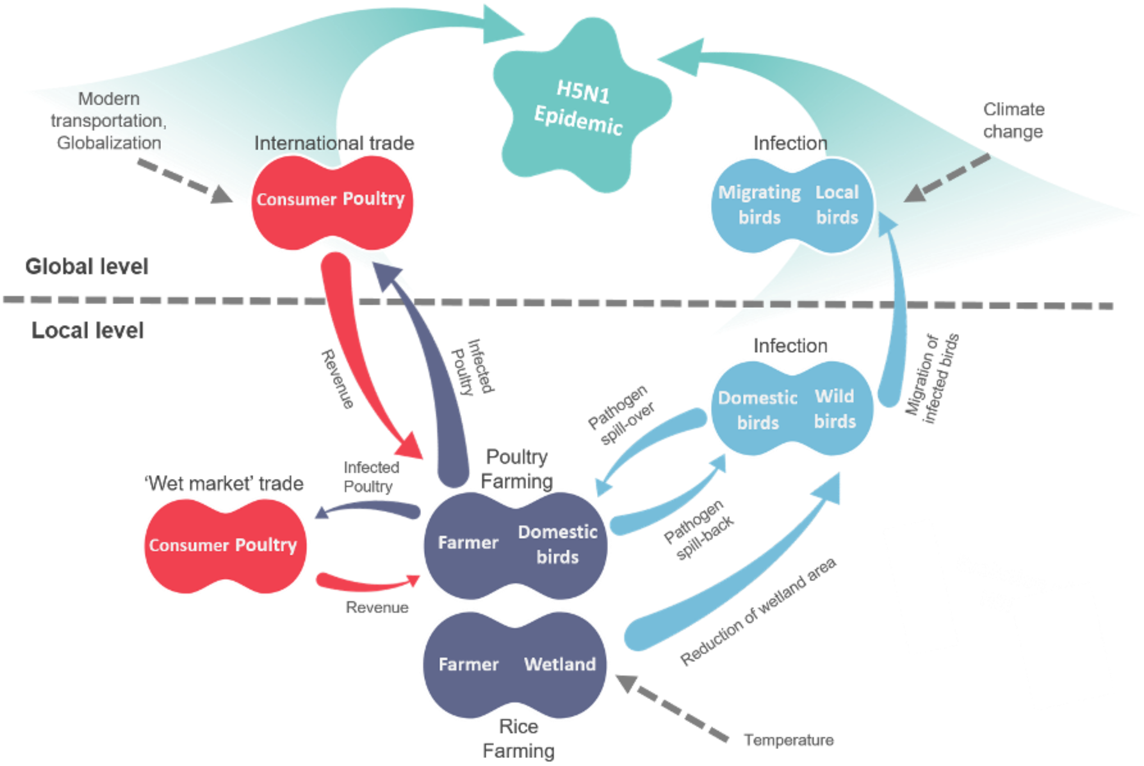

Figure A5: SE-AS representation of the configuration of the social-ecological (dark blue), ecological (light blue) and social action situations (red) hypothesized to influence the potential global outbreak of H5N1 avian influenza.

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APPENDIX 2

List of guiding questions for framework application

1. What is the emergent phenomenon that should be explained?
2. What social-ecological action situation or situations are at the core of the phenomenon, e.g. harvesting, cultivating, conserving, polluting, recreation, etc.? Which outcomes do they give rise to (e.g. catch, information, mortality, change in landscape structure).
3. For social-ecological AS: which actors (individuals, groups or collectives) and which ecological components constitute the social-ecological AS? Which roles do actors take in this interaction context, which actions can they take (e.g. harvesting, conserving), which ecological processes take place through the interaction (e.g. decrease in population size)? Through which structures are actors or ecological components connected, e.g. networks, spatial settings, etc.? What attributes of actors and non-human entities, such as preferences, motivations, skills or growth rates are important for explaining the emergent behavior of this AS?
4. Which drivers, structures or processes such as climate, regulations or food-web interactions or other social-ecological interactions enable or constrain the social-ecological action situation?
5. Are these external to the social-ecological system of interest, i.e. they cannot be influenced by actors or ecological processes within the SES, and can be represented as external drivers?
6. Or are they internal and directly influencing the social-ecological interactions and thus need to be represented as social or ecological AS? What are their emergent outcomes and how do they affect the social-ecological or other social or ecological AS?
7. For social AS: which actors (individuals, groups or collectives) participate in the social AS? How do actors relate to each other? Which roles do actors take in this interaction context, which actions can they take, which attributes of the actors are important for explaining the emergent behavior of this AS? How do the outcomes of social-ecological AS enable or constrain the social interaction? How are the social interactions in the social AS influenced by the social-ecological interactions?
8. For ecological AS: which ecosystem components (organisms, populations, geophysical entities) interact in the ecological AS? How do they relate to each other? Which processes or structural changes do they result in that are important for explaining the emergent behavior of this AS (e.g. change in food web structure, change in soil quality)? How are the ecological interactions in the ecological AS influenced by the social-ecological interactions?