DOI: 10.14512/gaia.26.S1.5

From Math to Metaphors and Back Again

Social-Ecological Resilience from a Multi-Agent-Environment Perspective

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Science and policy stand to benefit from reconnecting the many notions of social-ecological resilience to their roots in complexity sciences. We propose several ways of moving towards operationalization through the classification of modern concepts of resilience based on a multi-agent-environment perspective.

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GAIA 26/S1 (2017): 182–190

Abstract

Social-ecological resilience underlies popular sustainability concepts that have been influential in formulating the *United Nations Sustainable Development Goals (SDGs)*, such as the *Planetary Boundaries* and *Doughnut Economics*. Scientific investigation of these concepts is supported by mathematical models of planetary biophysical and societal dynamics, both of which call for operational measures of resilience. However, current quantitative descriptions tend to be restricted to the foundational form of the concept: persistence resilience. We propose a classification of modern notions of social-ecological resilience from a multi-agent-environment perspective. This aims at operationalization in a complex systems framework, including the persistence, adaptation and transformation aspects of resilience, normativity related to desirable system function, first- vs. second-order and specific vs. general resilience. For example, we discuss the use of the *Topology of Sustainable Management Framework*. Developing the mathematics of resilience along these lines would not only make social-ecological resilience more applicable to data and models, but could also conceptually advance resilience thinking.

Keywords

complex systems perspective, mathematical operationalization, multi-agent-environment systems, planetary boundaries, safe operating space for humanity, social-ecological resilience

Social-ecological system (SES) resilience is a popular concept now widely applied in many fields of science related to sustainable development as well as in science communication and education efforts (Folke et al. 2016, Folke 2016). Notably, the concept of resilience is at the heart of the *Planetary Boundaries Framework* (Rockström et al. 2009, Steffen et al. 2015), which, together with its extensions such as *Doughnut Economics* introducing the safe and just operating space for humanity (Raworth 2012), has been influential in formulating the *United Nations Sustainable Development Goals (SDGs)*[1]. However, as already Carpenter et al. (2001, p. 765) have pointed out: "Resilience has multiple levels of meaning: as a metaphor related to sustainability, as a property of dynamic models, and as a measurable quantity that can be assessed in field studies of SES". This multi-level nature of resilience can be seen as an intrinsic strength of the concept (e. g., Folke et al. 2016), but together with its often meandering use by various communities also has the potential to cause confusion and difficulties in operationalizing and practically applying the concept. The intention of this paper is to propose a classification of various modern concepts of social-ecological resilience from a multi-agent-environment perspective and, while not proposing a concrete operationalization, to discuss possible avenues to developing such a mathematical formalization reconnecting these notions to their theoretical foundations in complex systems theory.

SES resilience (Berkes and Folke 1998) originated from a complex systems perspective on ecological dynamics (Holling 1973) integrating at the time revolutionary mathematical insights into

1 *www.un.org/sustainabledevelopment/sustainable-development-goals*

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https://doi.org/10.14512/gaia.26.S1.5

the properties of even relatively simple dynamical systems including nonlinearity, multistability, bifurcations and chaos (Lorenz 1963). From these insights, the basal understanding of resilience can be summarized as "the magnitude of disturbance that can be tolerated before a socioecological system (SES) moves to a different region of state space controlled by a different set of processes" (Carpenter et al. 2001, p. 765).

This classical definition of resilience resonated well beyond the area of theoretical research and translated into a concept of practical value for policy makers and participatory research endeavours. Thus, "more liberal definition(s)" of resilience emerged in this context such as the "capacity of a system to absorb disturbance and reorganize while undergoing change so as to still retain essentially the same function, structure, identity, and feedbacks" (Scheffer 2009, p. 357). Eventually Folke et al. (2010) termed the integrated perspective of persistence, adaptation and transformation as "resilience thinking" based on Walker et al.'s (2004) seminal introduction of this triad of terms. This framework includes the spectrum from specific resilience of "what to what" (Carpenter et al. 2001) to general resilience (Carpenter et al. 2012). Additionally, Schneider and Vogt (2017, p. 179, in this issue) enrich this picture by distinguishing resilience of first-order associated to a specific system or actor from resilience of second-order that additionally encompasses the interactions of first-order resiliences of multiple systems or actors.

These extended definitions of SES resilience tend to use complex systems language metaphorically rather than focussing on operational measures and mathematical understanding. The purpose of this contribution is to argue for reconnecting these resilience metaphors to their foundations in complex systems theory. >

EXHIBIT *SURVIVING THE FUTURE – RESILIENCE & DESIGN* (2016)

MAGIC SEVEN: "HOW CAN DESIGNERS BE SUPPORTED IN DEVELOPING CONTEMPORARY, RESILIENT DESIGNS?"

Resilience factors account for our ability to react to unforeseeable developments. For the project Magic Seven, *these were transferred to design: a creative range of questions was devised to inspire designers to think outside the box, think for the long haul, and incorporate incalculable courses of action into their designs. In the exhibition, the seven principles (adaptiveness, fault tolerance, modularity, longevity, assumption of unpredictability, diversity, self-learning ability) were illustrated by seven forks. The three-headed fork in the front center of the picture symbolizes alternative courses of action and stands for the diversity principle.*

We believe that this agenda will serve to streamline communication on resilience across disciplines, help to avoid misunderstandings and improve the applicability of SES resilience concepts. In perspective, it will allow for devising useful quantitative measures capturing also more subtle aspects of SES resilience that are important for empirical measurements and applications to computer simulation models of SES across scales, for example, for use in advising policy makers. Beyond arguing for these more practical benefits of quantification and formalization, we follow the reasoning of Carpenter et al. (2001, p. 767) that a theory's "success is measured by the utility of the concepts in terms of their ability to influence the research topics chosen by scientists and stimulate productive hypotheses", and "progress in the definition of concepts is central to advancement of science".

Persistence Resilience: Rooted in a Complex Systems Perspective

The persistence aspect of SES resilience is the most formalized among the various other notions such as adaptation and transformation resilience. It corresponds to the foundational dynamical systems understanding of *ecological resilience* (Holling 1973): "the magnitude of disturbance a system can tolerate before it moves into a different (region of) state (space)" (Scheffer 2009, p. 357). In this view, the state of a system is formally described by a set of state variables (see dark green axes in figure 1), where the state at a particular time corresponds to a point or state vector in a potentially high-dimensional state space. The system state evolves in time along a trajectory following prescribed deterministic or stochastic rules.

In what are often called complex dynamical systems, multiple *attractors* can coexist in state space implying multistability, that is, the system can evolve towards alternative attractors depending on in which *basin of attraction* the initial system state lies. For example, in the domain of ecological resilience, turbid and clear attracting states of a lake can coexist in state space (Scheffer 2009). This property of multistability is central to formal definitions of persistence resilience and is captured visually by the so-called ball-and-cup diagram (figure 1a). The ball symbolizes the current system state. The minima of the stability landscape correspond to fixed point attractors. In analogy to a ball rolling along a hilly landscape, the cups or valleys depict the attractors' basins of attraction.

Generally, mathematical descriptions of persistence resilience build upon this picture of a dynamical system evolving in a state space with multiple attractors. A perturbation, shock or disturbance is then often seen as a sudden shift of the system state away from dynamical equilibrium (i. e., with the system residing on an attractor) induced by some external force. Measures of persistence resilience can then be related to various dynamical and geometrical properties of the attractor and its basin of attraction. Among others, operational measures of persistence resilience can be derived from the speed of return to the attractor after small perturbations (so-called *engineering resilience* related to linear stability concepts in dynamical systems theory, see Pimm 1984, Anderies et al. 2013), the attractors' distance to its basin boundary (Klinshov et al. 2015), the volume of the basin of attraction (Scheffer et al. 2001, Menck et al. 2013), or combinations thereof (Mitra et al. 2015, Hellmann et al. 2016). Recent work on early warning signals for critical transitions in SES (Scheffer et al. 2009) exemplifies a fruitful application of these and related mathematical formalizations of persistence resilience.

Resilience Thinking: Modern Concepts of Social-Ecological Resilience

While the formal study of persistence resilience is quite elaborate, it has been recognized that accounting for persistence aspects is not sufficient in a complex, nonlinear world. Walker et al. (2004) extended the persistence notion of resilience with the aspects of *adaptation* and *transformation*.

Adaptability usually refers to the capacity of a system to learn and adjust its responses to changing external processes within the current stability domain (Berkes et al. 2003); put in short "to manage (persistence) resilience" (Walker et al. 2004). An important extension in the mental model has been made at this point. Whereas persistence resilience can be defined in a dynamical systems model, the notion of adaptability requires thinking additionally of an agent, an entity capable of choosing among a certain set of actions. The distinction between the persistence and adaptation aspects of resilience has been reflected already through the *adaptive cycle* concept (Gunderson 2001) and in the seminal work by Holling (1973). A view going beyond this notion describes adaptability as the ability to maintain system functioning under a changing environment (Martin-Breen and Anderies 2011). This definition allows the system to modify its current attractor and the associated basin of attraction as long as the functioning of the system is ensured. What system function is considered as desirable here needs to be specified in addition. This is a normative notion that needs to be accounted for in advanced complex systems operationalizations of resilience to be outlined in the next section. Similarly, the resilience of "what to what" (Carpenter et al. 2001) has to be specified, for example, the resilience of a certain system property or function for a certain attractor with respect to a specific (fast) change of system state (shock) that may be either unforeseeable or anticipable. Also (slow) changes in the functioning and dynamics of the environment are possible influences a system can be resilient against (via adaptation).

Transformability recognizes that even an adaptation view of SES resilience is not sufficient and refers to the "capacity to create a fundamentally new system when ecological, economic, or social conditions make the existing system untenable" (Walker et al. 2004). Along these lines, the notion of *general resilience* acknowledges the fact that building *specific resilience* for one part of the system does not guarantee increasing specific resilience in other parts or the whole system, or may even undermine general resilience of the whole system. It therefore acknowledges the dangers of a too narrow perspective, for example, focussing only on the specific resilience of social or ecological subsystems of an SES (Carpenter et al. 2012). Both recognize SES as complex adaptive systems (Martin-Breen and Anderies 2011, Folke 2016). However, it remains unclear what makes a system *fundamentally* new and what is the exact difference between adaptation and transformation.

In summary, while persistence resilience is founded on deterministic concepts from the theory of dynamical systems (ultimately going back to Newton's classical mechanics), modern notions of SES resilience such as those related to adaptability and transformability, specific vs. general and first- vs. second-order resilience at their core require introducing agency into efforts towards much needed mathematical operationalizations. In the subsequent section, we contribute to this endeavour by classifying and discussing modern resilience notions from a multi-agent-environment perspective.

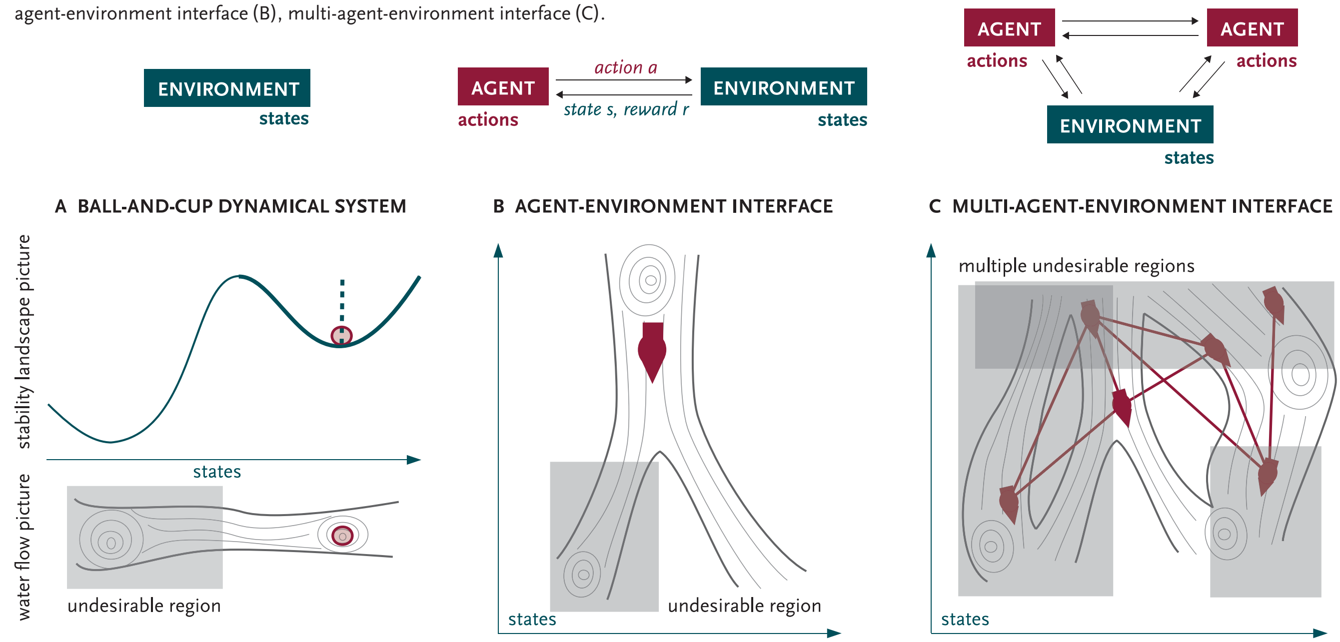
Notions of Social-Ecological Resilience from a Multi-Agent-Environment Perspective

In the following we outline how the resilience triad of persistence, adaptation and transformation (Folke et al. 2010) could be mathematically operationalized on the foundation of multi-agent environment systems that are well established in computer science (Busoniu et al. 2008) and that show parallels to Ostrom's conceptualization of SES (Ostrom 2009). We discuss normative notions related to the desirability of system states and classifications such as specific vs. general and first- vs. second-order resilience. However, we stress that it is beyond the scope of this article to fully develop the proposed agenda and that the following discussion outlines only one of potentially many possible operationalizations.

We propose three levels of SES resilience complexity (figure 1). The first level focuses on the persistence aspect described in the previous section (figure 1a). The term *environment* denotes the ecological, social and economic stochastic or deterministic system dynamics without any agent behavior. The system function notion of persistence resilience is connected to the desirability of system states: the gray area in figure 1a indicates states that are perceived as undesirable.

To describe the adaptation and transformation aspects of SES resilience, a "ball" representing the system state alone is not sufficient. Instead, moving to a second level of resilience complexity by introducing an agent equipped with the agency to choose among a set of actions is required (figure 1b). Schellnhuber (1998, 1999) already introduced related ideas in the Earth system context under the terms *geocybernetics* and *Earth system analysis* distinguishing the *ecosphere* and *anthroposphere* (together constituting the environment) from the *global subject* (the agent). Similarly, Anderies et al. (2007) – inspired by Ostrom's general framework to study SES (Ostrom 2009) – take a single-agent-environment perspective to study SES following a robustness approach. Introducing an agent extends the environment of the persistence resilience case to an agent-environment interface and simultaneously to a decision problem of what action to choose given a history of system observations. Any decision-making framework requires stating the choices or actions available to the decision maker and a criterion to evaluate the decisions, often called either rewards, utility or costs associated with the actions (Steele and Stefánsson 2016). With the agent's >

FIGURE 1: Three levels of increasing resilience complexity: dynamical system (environment) (A), agent-environment interface (B), multi-agent-environment interface (C).



strategy or policy we refer to the rule describing what action to apply given a history of observations. Fixing a (default) strategy, this system can be described equivalently to the dynamical systems case (first level of resilience complexity, figure 1a), that is, accounting for persistence resilience is also applicable here. This is visualized by the "default" flow in figure 1b. Hence, a change of strategy is equivalent to a change of the stability landscape in the ball-and-cup picture. To see the correspondence of the latter and the agent-environment view, imagine the agent climbing a hill (i.e., applying management deviating from the default strategy) in the stability landscape along a specific direction in state space. The agent's movement is equally well described by a different landscape in the ball-and-cup picture, in which the ball (now representing the agent) glides downhill in the same direction following the default flow.

Introducing an agent allows us to consider *meta-rules* or *algorithms* that govern how a strategy adjusts to the environment over time. These meta-rules may be inspired by modern artificial intelligence or machine learning algorithms (Sutton and Barto 1998) combined with *sustainability paradigms* as proposed by Schellnhuber (1998, 1999): optimization, pessimization, equitization, or standardization. For example, the equitization paradigm bears the maxim that the option space for future generations is kept as open as possible by actions of the current generation for building resilience (see also Vogt 2013). Practically this requires suitable meta-rules to govern multiple kinds of uncertainties and risks (Renn 2008).

In terms of desirability, at least two options seem plausible: 1. one can either fix the desirability of a state, or 2. the evaluation criterion of the decision context can be utilized. In the former case, a state's desirability is independent from the current strategy, whereas in the latter case the desirability of a state results from the reward the agents receive following that current strategy. The *Tolerable Windows Approach* (Petschel-Held et al. 1999) and the *Planetary Boundaries Framework* (Rockström et al. 2009, Steffen et al. 2015) are examples of a division of state space into desirable and undesirable states in the sustainability context. While the desirability of states depends on normative judgement, this does not necessarily hold for SES resilience, since an undesirable state may be resilient as well (Carpenter et al. 2001).

The third level of resilience complexity extends the agent-environment further to a multi-agent-environment system (figure 1c, Busoniu et al. 2008). While all characteristics of the agent-environment interface discussed above apply, the multi-agent aspect allows for the possibility of emergent phenomena (Sawyer 2005). It further emphasizes the potentially conflicting interests of the agents, visualized by the distinct individual desirability regions in state space.

In the following we discuss how some of the modern notions of social-ecological resilience integrate into the proposed three levels of resilience complexity (see table 1 for an overview).

TABLE 1: Applicability of resilience concepts (rows) to our proposed levels of resilience complexity (columns).

	ENVIRONMENT	AGENT-ENVIRONMENT	MULTI-AGENT-ENVIRONMENT
type	persistence	persistence adaptation transformation	persistence adaptation transformation
scale		first-order	first-order second-order
scope	specific general	specific general	specific general

Adaptation and transformation. Folke et al. (2010, p. 2) describe adaptability as the "capacity of a SES to learn, combine experience and knowledge, adjust its responses to changing external drivers and internal processes, and continue developing within the current stability domain or basin of attraction". Transformability is described as the "capacity to transform the stability landscape itself". In our view both aspects can only be treated either in the second or third level of resilience complexity: the agent-environment or the multi-agent-environment case, in which the agents use an internal meta-rule or algorithm to derive the actual rule (strategy) describing what action to apply given a history of observations. Typically these algorithms are constantly changing their internal variables, representing implicitly the agents' world model, as a reaction to the observations over time.

Interpreting these definitions of adaptation and transformation in their most narrow sense, any change of the internal variables of the meta-rule or learning algorithm is an adaptation, as long as it does not change the actual strategy. If the strategy changes one has to speak of a transformation, essentially because a change of strategy is equivalently describable by a change of the stability landscape.

As an alternative interpretation one may include into adaptations changes in the strategies altering the corresponding stability landscape smoothly, that is, those changes that vary the shape (e.g., height, extent) or location of the minimum without disrupting the structure of this landscape. In contrast, a transformation could be defined as strategy changes that alter the stability landscape qualitatively: destruction of old or creation of new attractors. Technically, these situations are commonly referred to as bifurcations, tipping points or critical transitions (Scheffer 2009). This interpretation focuses on the fact that a transformation is perceived as a "fundamental" change (Walker et al. 2004, Folke et al. 2010).

A further distinction between adaptation and transformation could build on the dialectic micro-macro relationship between an agent and the social structure connecting agents in the multi-agent-environment perspective. An adaptation would correspond to strategy changes of an individual that do not alter a suitable macroscopic description of the multi-agent system including the complex network structure of social-ecological interactions, whereas transformations are observable qualitatively on the macroscopic level (Lade et al. 2017). As a simple example, one microscopic variable could be the wealth of an agent, while the macroscopic observable is average wealth.

Specific and general resilience. Specific resilience refers to resilience of "what to what" (Carpenter et al. 2001) whereas general resilience is described as "the capacity of social-ecological systems to adapt or transform in response to unfamiliar or unknown shocks" (Carpenter et al. 2012, p. 3251). We here interpret specific resilience as the capacity to absorb shocks along a specific dimension of the state space (or a more general subset of dimensions) including fast (states) and slow variables (parameters). For example, while we illustrated the persistence aspect with only one dimension in state space (figure 1a), the agent-environment interfaces (figure 1b,c) are visualized with two dimensions. Depending on context, both projections may be radical simplifications of the actual high dimensional state space. Building resilience for a *specific* subset of these state space dimensions could correspond to increasing the basin of attraction only along these dimensions.

General resilience, however, acknowledges the importance of the total size of the basin of attraction, that is, where the direction of the shocks is not specified. Further it takes into account the interactions between different state space dimensions, that is, whether the increase of the basin of attraction in one dimension may change the basin's size in other dimensions. With this interpretation one can distinguish specific and general resilience in all levels of resilience complexity presented in figure 1 (see also table 1).

Resilience of first and second order. In analogy to the distinction of specific and general resilience, Schneider and Vogt (2017, p. 179, in this issue) discuss the notions of resilience of first and second order. They define resilience of first order for a specific system, entity, institution, or actor. Resilience of second order takes a perspective to include the relationships of a specific entity to further actors, structures, and contexts. We interpret the focus of the concept of resilience *order* to be the actor or agent. Thus we suggest formalizing resilience of first order as the resilience associated with one agent (figure 1b). Correspondingly, the resilience of second order asks how the resilience of one agent affects the resiliences of other agents in a multi-agent-environment system (see figure 1c). Thus, building resilience of second order demands building resilience of first order of individual agents in a mutually beneficial way. It is an interesting research question to ask what properties of the meta-rules or adaptation algorithms are required for this interpretation of second-order resilience.

Example: *Topology of Sustainable Management Framework*

To give a concrete example how our proposed classification of resilience complexities can bring new insights by a rigorous mathematical treatment, we briefly introduce the *Topology of Sustainable Management Framework* (Heitzig et al. 2016). Extending upon

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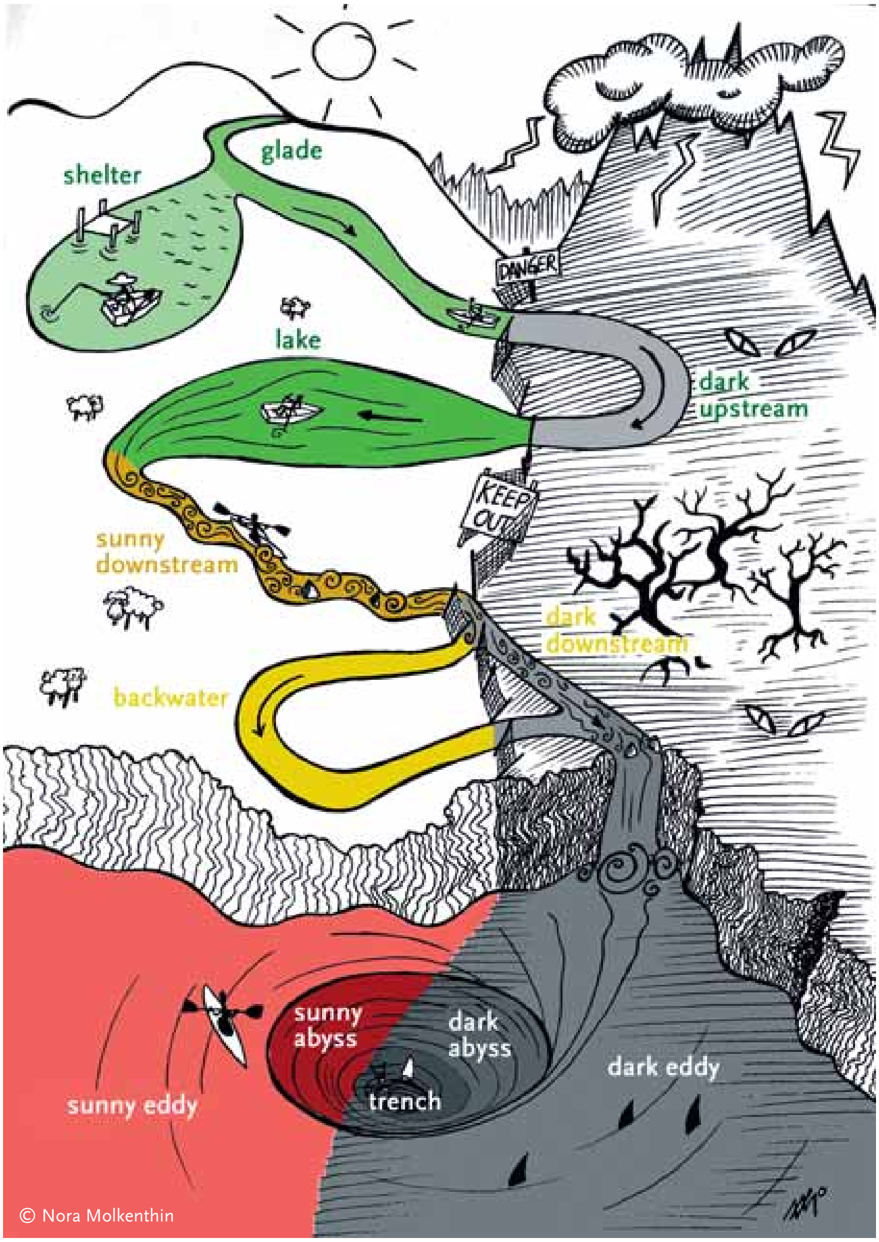

FIGURE 2: Illustration of the mathematical *Topology of Sustainable Management Framework* formalizing resilience based on an agent-environment perspective (modified from Heitzig et al. 2016).

related efforts to formalize resilience using viability theory (Deffuant and Gilbert 2011), Heitzig et al. (2016) show how a classification of qualitatively different regions in system state space emerges from the following three ingredients: 1. environmental dynamics under a default strategy, 2. available management options the agent can choose from, and 3. the division of state space into desirable ("sunny") and undesirable ("dark") regions. Hence, it uses an agent-environment interface perspective (second level of resilience complexity) with a default strategy and fixed state desirability (figure 2). The various elements of this picture metaphorically illustrate the underlying mathematical *Topology of Sustainable Management Framework* with the waterstream corresponding to the stability landscape under the default policy, similarly as in figure 1. The interested reader is referred to the original publication for the mathematical details.

For example, the *shelter* is the sunny set of states in which the agent can remain forever without any management. Both in the *glade* and the *lake* it is possible to reach the shelter but the agent has to apply management. From the lake it has to cross through the dark region, whereas from the glade it can reach the shelter without leaving the sunny region. In other regions, such as the *backwaters,* the shelter cannot be reached, but the agent can remain in the sunny region by constant or repeated management. These regions emerge from the allowed rule changes describing how the agent is able to adapt to and manage the environment.

In the *Topology of Sustainable Management Framework,* the default action is perceived as preferable to the other available management options. The rationale is that non-default actions are at risk of becoming inoperative, for example, due to external shocks. Hence, the default is considered as a safer option. Several dilemmas arise from this reasoning: for example, starting in the lake the agent can either remain in the sunny region under constant and potentially risky management or choose to cross the dark region to reach the shelter, where no management is needed. Note that while the mathematical framework serves to highlight these dilemmas, resolving them requires deep ethical considerations taking into account questions of justice, freedom and identity (Vogt 2013). See Heitzig et al. (2016) for a discussion of further dilemmas and various example systems to which the framework has been applied.

Generalizing from measures of persistence resilience discussed above, characteristics of these regions such as volume, depth, distance from the boundary or return rate could be interpreted as a sequence of operational measures capturing both persistence and adaptation aspects of SES resilience. For example, *shelter resilience* could correspond to the volume of the shelter region and indicate the size of a shock the system is capable to absorb to remain in the shelter without using management. Moreover, assuming the system continues to reside in the shelter or glade, *glade resilience* could correspond to the size of the glade plus the size of the shelter. This measure would indicate the magnitude of shock the system is capable to absorb under the potential need to apply management to return to the shelter without leaving the sunny region. Note that in this particular example all adaptation and transformation aspects of resilience have been incorporated into the classification of state space by emphasis on the default policy flow and possible management options deviating from the default action.

Reconnecting modern concepts of social-ecological resilience with their roots in complex systems theory, based on a multi-agent-environment perspective, is relevant for analytically addressing global change problems of the Anthropocene.

The point we would like to make with these examples is that even from fairly simple ingredients a rich and sometimes unintuitive picture of resilience may emerge under formal treatment with broad potential for applications. Future mathematical work could further extend the *Topology of Sustainable Management Framework* to accommodate more advanced resilience dimensions such as specific vs. general and first- vs. second-order resilience, for example, by including multiple agents with possibly distinct management options and desirability criteria.

Discussion: Earth System Resilience in the Anthropocene

Reconnecting modern concepts of social-ecological resilience with their roots in complex systems theory is relevant for analytically addressing global change problems of the Anthropocene (Haber et al. 2016). Viewed from a resilience angle, the *SDGs* can be interpreted as normative criteria defining desirable biophysical, social and economic Earth system states (Folke et al. 2016). The *Planetary Boundaries* (Rockström et al. 2009, Steffen et al. 2015) and related concepts such as *Doughnut Economics* (Raworth 2012) argue for biosphere stewardship to maintain a safe (and just) operating space (Vogt 2013, Ekardt 2016). This is where the planetary SES is seen as resilient and where development towards the *SDGs* is argued to be possible. Refined insights into principles for actively building resilience and their preconditions would be useful in this context. To this end, Biggs et al. (2015) summarize seven principles for building resilience including its persistence, adaptation, and transformation aspects: 1. maintain diversity and redundancy, 2. manage connectivity, 3. manage slow variables and feedbacks, 4. foster complex adaptive systems thinking, 5. encourage learning, 6. broaden participation, and 7. promote polycentric governance. These principles for building resilience can also be viewed in their inverse forms as principles for undermining resilience of undesirable system states and structures.

Operational measures of the various dimensions of resilience as outlined above including persistence, adaptation, transformation, first- vs. second-order and specific vs. general resilience could be employed for systematically evaluating these seven and more principles for building (or undermining) resilience and their detailed preconditions. Such an investigation would be supported by computer simulation models of SES of interest (Schlüter et al. 2012) but could also integrate various sources of empirical data. Using this approach, the validity of the principles for building resilience can be assessed in different situations, including possible unintended side effects induced by applying them.

Most analytical studies on the resilience of SES and the associated principles for building resilience have been conducted on local and regional scales. But a key characteristic of the Anthropocene and the inherent great social and environmental challenges are ever densifying global networks of teleconnected and tightly intertwined social-ecological processes. Therefore, computer simulation models as well as more stylized conceptual models are needed to operationally study resilience and principles for building resilience for the planetary SES that capture coevolving and networked biophysical, socio-economic and socio-cultural dynamics (Verburg et al. 2016, Donges et al. 2017). Applied in this setting, operational measures of resilience dimensions will serve as valuable tools for Earth system analysis (Schellnhuber et al. 2004).

As a recent example, it has been argued that to meet the Paris climate agreement (UNFCCC 2015) a controlled collapse of the planetary-scale fossil fuel sector must be induced for triggering a rapid global decarbonization transformation (Schellnhuber et al. 2016) as part of a concerted broader sustainability transformation (WBGU 2011). From a scientific perspective, this agenda calls for a deeper understanding of the apparently massive specific resilience of this part of the global SES, the associated general planetary SES resilience and principles for undermining this specific resilience without harmful and unwanted side effects such as economic crises. Reconnecting modern concepts from resilience thinking to their formal complex systems foundations through a multi-agent-environment perspective as proposed in this article could make a useful contribution to this endeavour by providing operational measures of various resilience dimensions and, more fundamentally, by shedding light on the underlying structure of modern resilience concepts and their interconnections.

This work was conducted in the framework of the project on *Coevolutionary Pathways in the Earth System (COPAN)* at the Potsdam Institute for Climate Impact Research (PIK). We thank *Boyan Beronov, Jobst Heitzig, Steven Lade, Wolfgang Lucht* and *Finn Müller-Hansen* for inspiring discussions on the concept of resilience. We are grateful for financial support by the Stordalen Foundation (via the *Planetary Boundary Research Network PB.net*), the *Earth League's EarthDoc Programme,* Leibniz Association (project *DOMINOES*) and the Heinrich Böll Foundation.

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Submitted December 1, 2016; revised version accepted June 19, 2017.

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GAIA ECOLOGICAL PERSPECTIVES FOR SCIENCE AND SOCIETY

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GRAPHIC DESIGN + TYPESET
Heike Tiller | Munich | E-Mail: h.tiller@freenet.de

PUBLISHER
oekom verlag – Gesellschaft für ökologische Kommunikation mbH | Waltherstr. 29 | 80337 Munich | Germany | *www.oekom.de* | Partners and shareholders: *Jacob Radloff,* Feldafing, 77 percent, and *Christoph von Braun,* Munich, 23 percent

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