LETTER • OPEN ACCESS

A modeler's guide to studying the resilience of social-technical-environmental systems

View the article online for updates and enhancements.

ENVIRONMENTAL RESEARCH
LETTERS

A modeler's guide to studying the resilience of social-technical-environmental systems

Lea A Tamberg[1,2,3,*] , Jobst Heitzig[4] and Jonathan F Donges[3,5,*]

1   Institute of Environmental Systems Research, University of Osnabrück, Barbarastraße 12, Osnabrück 49076, Germany
2   Institute of Mathematics, University of Osnabrück, Albrechtstraße 28a, Osnabrück 49076, Germany
3   FutureLab Earth Resilience in the Anthropocene, Earth System Analysis, Potsdam Institute for Climate Impact Research, Member of the Leibniz Association, Telegrafenberg A31, Potsdam 14473, Germany
4   FutureLab on Game Theory and Networks of Interacting Agents, Complexity Science, Potsdam Institute for Climate Impact Research, Member of the Leibniz Association, Telegrafenberg A31, Potsdam 14473, Germany
5   Stockholm Resilience Centre, Stockholm University, Kräftriket 2B, Stockholm 114 19, Sweden
*   Authors to whom any correspondence should be addressed.

E-mail: ltamberg@uos.de and donges@pik-potsdam.de

Abstract

The term 'resilience' is increasingly being used in Earth system science and other disciplines which study what could be called 'social-technical-environmental systems'—systems composed of closely interacting social (e.g. economic and political), technical (e.g. energy production infrastructure), and environmental components (e.g. climate and the biosphere). However, the diversity of resilience theories and a certain (intended) openness of proposed definitions can lead to misunderstandings and may impede their application to complex systems modelling. We propose a guideline that aims to ease communication as well as to support systematic development of research questions and models in the context of resilience. It can be applied independently of the modelling framework or underlying theory of choice. At the heart of this guideline is a checklist consisting of four questions to be answered: (1) Resilience of what? (2) Resilience regarding what? (3) Resilience against what? (4) Resilience how? We refer to the answers to these resilience questions as the 'system', the 'sustaint', the 'adverse influence', and the 'response options'. The term 'sustaint' is a neologism describing the feature of the system (state, structure, function, pathway, …) that should be maintained (or restored quickly enough) in order to call the system resilient. The use of this proposed guideline in the field of Earth system resilience is demonstrated for the application example of a potential climate tipping element: the Amazon rainforest. The example illustrates the diversity of possible answers to the checklist's questions as well as their benefits in structuring the modelling process. The guideline supports the modeler in communicating precisely what is actually meant by 'resilience' in a specific context. This combination of freedom and precision could help to advance the resilience discourse by building a bridge between those demanding unambiguous definitions and those stressing the benefits of generality and flexibility of the resilience concept.

1. Introduction

The concept of 'resilience', broadly describing the capacity of a system to absorb or recover from perturbations, has recently gained attention in Earth system science (Rockström *et al* 2009, 2021, Folke *et al* 2010, Steffen *et al* 2015, Gleeson *et al* 2020) with a particular emphasis on Earth systems that have the potential to display critical thresholds and tipping points (Lenton *et al* 2008, Dakos *et al* 2015, Wunderling *et al* 2020). This research implicitly or explicitly emphasizes the conceptualization, measurement and modelling of Earth system resilience within a 'safe operating space for humanity' defined by planetary boundaries (Rockström *et al* 2009, Steffen *et al* 2015). Acknowledging the central role of the

technosphere in shaping future trajectories of the World-Earth system in the Anthropocene (Donges *et al* 2017), resilience is furthermore increasingly being studied in diverse disciplines researching what could be called 'social-technical-environmental systems' (Donges *et al* 2021), 'social-ecological-technical systems' (Ahlborg *et al* 2019, Hamborg *et al* 2020) or 'coupled human-technology-environment systems' (Pahl-Wostl *et al* 2009)—systems composed of closely interacting social (e.g. economic and political), technical (e.g. energy production infrastructure), and environmental components (e.g. climate and the biosphere).

In this interdisciplinary context, a vast number of definitions, concepts and related terms has been proposed. Some of them are well-established in subfields, such as ecology (Holling 1973, Gunderson *et al* 2012) or engineering sciences (Woods and Hollnagel 2006, Woods 2015, Yu *et al* 2020), some have explicitly been proposed for systems that encompass these disciplinary boundaries. For instance, the relation between terms such as 'stability', 'adaptability' and 'transformability' of social-ecological systems is intensely debated in the context of 'resilience thinking' (Folke *et al* 2010, 2016, Cote and Nightingale 2012, Walker and Salt 2012, Curtin and Parker 2014, Donges and Barfuss 2017, Lade *et al* 2017).

Part of the theoretical discussion is whether a narrow or a broad definition of the term 'resilience' is preferable. In ecology, a narrower scope appears to be emphasized (Holling 1973, Brand and Jax 2007, Hodgson *et al* 2015, Kéfi *et al* 2019), often seeing 'stability' as the more general and 'resilience' as the narrower term (Van Meerbeek *et al* 2021). Other authors, especially from the domain of social-ecological systems, explicitly advocate for a broader understanding of the term (Anderies *et al* 2006, Folke *et al* 2010, Walker and Salt 2012), valuing its role as a boundary object or bridging concept between different academic and non-academic fields (Turner 2010, Baggio *et al* 2015).

At the same time, different resilience theories may be hard to apply, operationalize or quantify when it comes to the analysis and modelling of specific realworld complex systems, particularly beyond wellquantified scientific fields such as physics or materials science. This has several reasons including the mentioned openness of definitions, lacking formalization, and missing estimation methods (Brand and Jax 2007, Strunz 2012, Hodgson *et al* 2015). Also, experience shows that research questions based on abstract theoretical concepts often cannot easily be answered with pre-existing models that were not specifically developed for this purpose. Often, central aspects of resilience theory are simply not represented in the model. For instance, a model in which the possibility of structural changes is not included does

not fit to a research question addressing the adaptation or transformation capacity of a system.

These considerations imply at least two complementary challenges for the modeler. First, the large variety of previously proposed definitions and theoretical frameworks in different fields makes it necessary to communicate very precisely what is actually meant by 'resilience' in a particular study to avoid confusion. Second, research questions and the model(s) to answer them should be developed simultaneously in the same structured process in order to ensure their compatibility.
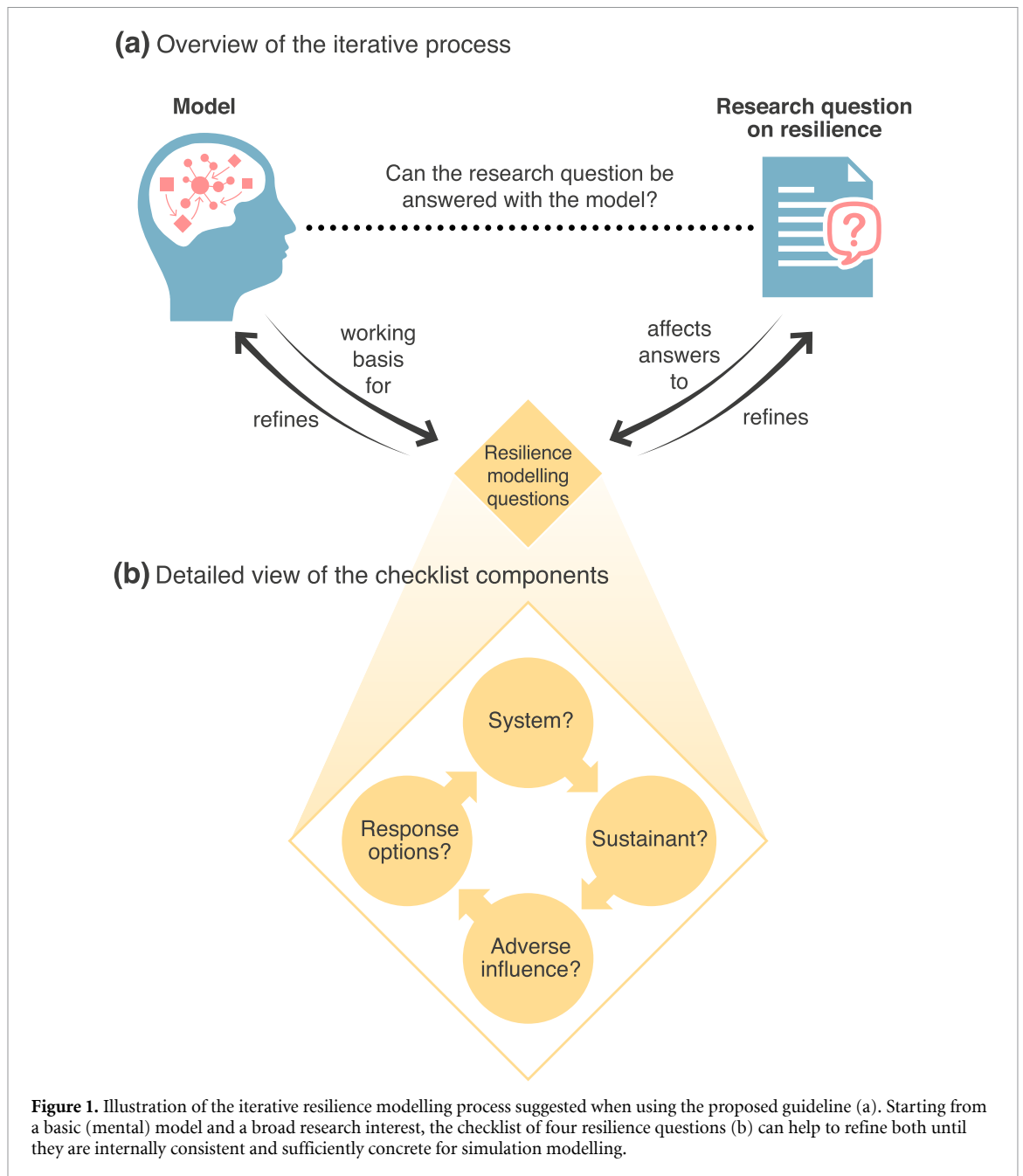
In this paper, we argue that these two concerns—precise communication and compatible modelling—can be addressed together in the modelling process. For this, we propose a guideline for an iterative approach to modelling systems[6] for studying their resilience. Our approach is based on a checklist that helps narrowing down on the precise form of resilience to be studied, the respective research question to be answered, and how a model should be designed in order to address that question. We exemplify our approach at the hand of three illustrative example applications.

In view of the ongoing theoretical debate, we take a neutral position regarding the definition of debated terms such as 'resilience', 'adaptability', 'stability', 'transformability', etc. Operating more on a meta level, our guideline does not adhere to one theoretical framework but is designed to be compatible with those frameworks currently discussed in the literature. The answers to our checklist can even inform the selection/definition of a suitable one for a particular study.

The style of the questions of the checklist is inspired by Carpenter *et al* (2001), who demand to answer the question 'Resilience *of what to what*?'. However, our guideline extends and differentiates this question considerably, while putting less conceptual restrictions on the possible answers. Checklists related to ours have also been proposed for 'politics of urban resilience' (Meerow and Newell 2019) and for 'stability' in ecology (Grimm and Wissel 1997). Our guideline differs from these in its clear focus on the modelling process, its theoretical flexibility, and its applicability to any system.

The paper is structured as follows: In section 2, we present a proposed methodology for resilience modeling. By way of results, we then exemplarily apply this methodology to the Amazon rainforest in section 3, which is complemented by two more application examples in the appendix. The discussion in section 4 concludes the paper.

---

[6] These systems could be of any kind, from purely physical to social-technical-ecological. The resilience perspective is particularly promising for the latter; However, the guideline should be applicable to all domains of systems modelling.

(a) Overview of the iterative process

Model

Research question
on resilience

Can the research question be
answered with the model?

working
basis
for

affects
answers
to

refines   refines

Resilience
modelling
questions

(b) Detailed view of the checklist components

System?

Response
options?

Sustainant?

Adverse
influence?

Figure 1. Illustration of the iterative resilience modelling process suggested when using the proposed guideline (a). Starting from a basic (mental) model and a broad research interest, the checklist of four resilience questions (b) can help to refine both until they are internally consistent and sufficiently concrete for simulation modelling.

2. A methodology for resilience modeling and research question refinement

In this section, we introduce and justify our proposed framework for developing simulation models of large social-technical-environmental system, such as complex Earth systems, to be used to answer different kinds of research questions relating to the system's resilience, such as quantifying it, assessing its evolution over time, determining factors that influence it, or identifying ways to increase (or decrease) it. The approach we put forward can be seen as an iterative process, summarized in figure 1.

We start from the assumption that in any particular research study, at least a basic, possibly only

mental, initial 'model' of the system exists, as well as an initial, possibly only broadly defined, research interest. They serve as a working basis for the further process. While working through a checklist of guiding questions, more precise characterizations for an improved model and a more specific formulation of the research question will arise. Whenever the answer to one guiding question is modified, it may become necessary to reconsider certain other guiding questions iteratively until the system model and research question are consistent.

In the following, the different questions of the checklist are presented and explained with the help of examples. Each of these questions includes a set of subquestions helping to be as precise as possible.
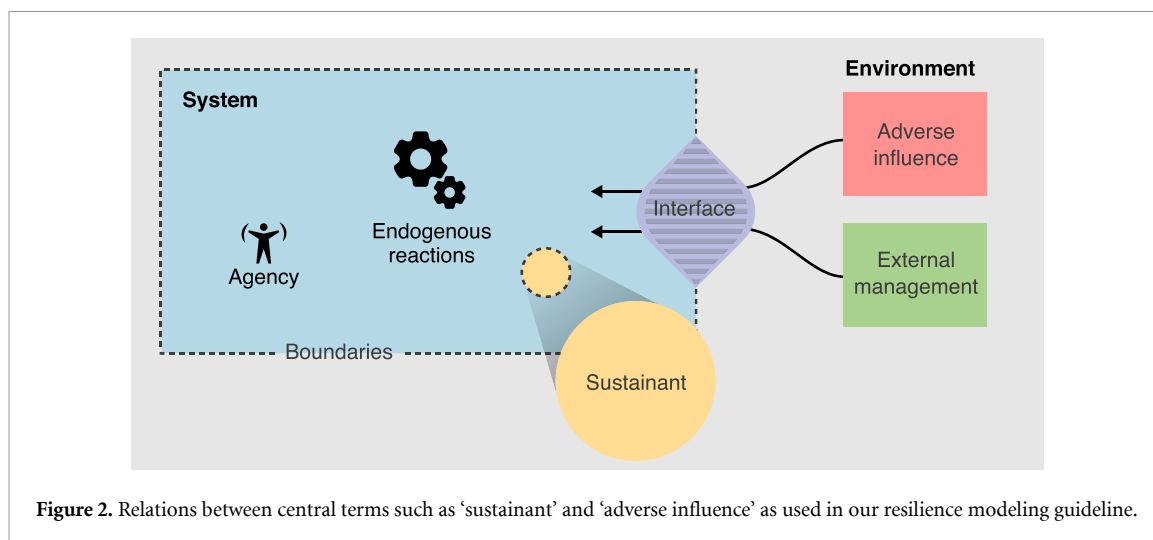
Figure 2. Relations between central terms such as 'sustainant' and 'adverse influence' as used in our resilience modeling guideline.

In figure 2, some important terms used in the checklist are presented graphically. The general idea is to specify four different aspects of resilience in the context of a specific system: *Resilience of what, resilience regarding what, resilience against what and resilience how?*

2.1. Resilience of what: what is the system?
What are the system *boundaries* and how sharp are they? What are the system's *parts* and their *interactions* that appear relevant for answering the research question? With what aspects of its *environment* does the system interact, through which kind of *interfaces?* Is there *agency*[7] in the system, meaning that parts of the system may exhibit targeted, intentional action?

Following the usual linguistic convention, the question 'Resilience *of* what?' refers to the whole system of interest, not a specific system state as in Carpenter *et al* (2001). The latter is covered in the next question of the checklist. Working out the mentioned aspects of the system is of course not a step only taken in the resilience context but in systems modelling in general (Bossel 2007, Voinov 2010). Particularly, the choice of boundaries is a typical challenge and often needs to be modified with a changing research interest (see the application examples in section 3 and the appendix for typical choices). The following questions are more focused on the modelling of resilience itself and build on the results of the first one, often making it necessary to reconsider those in further iterations.

2.2. Resilience regarding what: what is the 'sustainant'?
Which feature or property of the system would have to be *sustained* in order to call the system resilient? Its state or structure, its pathway? Some long-term equilibrium? Its function, purpose, or utility for some stakeholder? Some quantitative or qualitative aspect of the system?

This 'sustainant' is not an objective feature of a system but is chosen by the modeller, which should be clearly communicated. Especially what the 'function' or 'purpose' of a system is can be seen differently from different perspectives (Cutter 2016, Meerow and Newell 2019). For instance, for different observers, the function of a forest could (among others) be to produce wood, to enhance biodiversity, to provide a habitat, to serve for recreation, or to be beautiful. The model analyzing the resilience of the forest regarding wood production would differ substantially from a model with biodiversity as the sustainant.

Note that the neologism 'sustainant' is conceptually distinct from the broader concept of 'sustainability' (Anderies *et al* 2013). Instead, it is intended to cover different ideas from the literature about which system property the resilience of a system is related to. For instance, Carpenter *et al* (2001) demand the specification of a certain system state as an answer to the question 'Resilience *of* what?' (while their '*to* what' refers to our '*against* what'). In contrast, Folke *et al* (2010) define that a system is resilient if it essentially retains 'the same function, structure and feedbacks'. The term 'sustainant' is not restricted to one of these (or other) perspectives but leaves it to the modeller to clearly specify which system property is of interest.

The sustainant does not necessarily have to be a desirable property (although it is most often used that way). This decision is up to the modeler. One could for instance study the resilience of a farming community regarding their too high level of manure

---

[7] Agency is originally a concept from sociology (Barker 2002), meaning the capacity of individuals to act independently and to make their own free choices. It is increasingly used in the context of resilience in social-ecological systems (Larsen *et al* 2011, Armitage *et al* 2012, Westley *et al* 2013, Otto *et al* 2020).

application, or a 'neutral' sustainant, as in a purely physical context.[8]

The choice of the sustainant can be subject to power relations, inequality, and competing interests. Many authors therefore demand to consider the question 'Resilience for whom?'[9] to account for these aspects (Cretney 2014, Cutter 2016, Meerow and Newell 2019). This question is located on a meta level above that of the checklist. It can help to both choose the sustainant and to criticise this choice, for example from an inequality perspective.

Part of the task of selecting the sustainant is to ask whether there are any kinds of *threshold* values for certain indicators that shall either not be exceeded ever or may only be exceeded temporarily. For example, when modelling the development of the oxygen concentration in an aquarium and choosing this system property as the sustainant, its restoration after a drop may be irrelevant if it was zero in between so that all fish have died. One could argue that in this example, a better sustainant would be the fish being alive. However, this is a question of model boundaries. If the fish is not explicitly modelled but is only described as a consumption factor in the water-oxygen system, the potential interest of the modeler in the fish staying alive leads to the definition of an acceptable range for the oxygen level (possibly even different ranges for different species). If the modeler does not care about fish survival but the general capacity of the system to restore oxygen level, the sustainant can be defined without any threshold values.

Such thresholds depend, as the choice of the sustainant itself, on the perspective and interests of the observer who has to define an *acceptable range* for the sustainant. Correspondingly, an *acceptable recovery time* should be defined.

For instance, a fish stock may recover 50 years after a collapse; however, this is not relevant for someone aiming to evaluate the risks of investments into the fishery industry that is dependent on this resource on much shorter time scales. Again, the boundary choice (here only to model the fish population and describe the fishery as an external factor) leads to the population size being the chosen sustainant, specified by an acceptable recovery time motivated by the concern for the fishery industry.

As another example, consider a social network. A possible sustainant could be that every individual has at least one connection to another individual.

This sustainant would be a property of the system's structure. An appropriate recovery time could for instance consider how long an individual can endure social isolation without developing mental illness. Of course, this could also differ from individual to individual.

2.3. Resilience against what: what is the adverse influence?

What is the concrete influence *affecting the sustainant* that shall be considered for this specific resilience analysis? Is it an abrupt but temporary disturbance (pulse), a shock, a constant pressure, noisy fluctuations, a perturbation, an abrupt but permanent shift in some feature, or a slow change? Does it originate in the system or in its environment? Does it affect the structure, a parameter, or the state of parts of the system?

In some cases, the influence that is supposed to be studied does not have a direct effect on modelled aspects of the system, but through an intermediate linked to the boundary interface of the system, making it important to be precise about the actually modelled influence. Note that the term 'adverse' in 'adverse influence' is not necessarily meant as something undesirable. It only reflects that this influence affects the system in a way that weakens the sustainant. If the observer views the sustainant as undesirable, the adverse influence on it can be seen a positive process (Donges and Barfuss 2017, Dornelles *et al* 2020).

Remark to the 2nd and 3rd question of the checklist (sustainant and adverse influence): Of course, a sustainant could be composed of several aspects and resilience could be required against different (internal or external) influences at the same time. Often, such a 'multi-resilience' is of higher interest than a 'single-aspect-resilience' regarding only one parameter. However, the required analysis is more complex, not only because more aspects have to be modelled and studied but also because possible interdependencies between different sustainants and/or influences must be considered and the design of a suitable aggregate quantitative indicator may be more difficult and risks to appear arbitrary[10].

For instance, one may be interested in the resilience of the climate system against a rise of CO_2 concentration in the atmosphere (=single-influence)

---

[8] This is also one difference to the notion of 'desired configuration' used in Walker *et al* (2002), which implies a normative understanding of resilience. A second difference is again the higher flexibility of the term 'sustainant', which can for instance also be chosen to be a specific function (or malfunction), which goes beyond the meaning of the term 'configuration'.

[9] This question makes of course only sense in a setting where the sustainant is considered to be something positive. However, the issue of normativity will also play a role in the other case, one might then simply ask 'Resilience against whom?'.

[10] Folke *et al* distinguish between *specified resilience* ('resilience of some particular part of a system, related to a particular control variable, to one or more identified kinds of shocks') and *general resilience* ('resilience of any and all parts of a system to all kinds of shocks, including novel ones') and argue to concentrate on the latter one in order to cope with uncertainty and trade-offs (Folke *et al* 2010). However, in a modelling context, specificity is crucial. It is inherent to the modelling process that decisions on what to represent in the model and what not have to be taken. Therefore, our guideline asks to *specify* which sustainants and influences are considered. By choosing a multi-sustainant and a multi-influence, the risk of overlooked trade-offs can at least be reduced.

regarding the global mean temperature (=single-sustainant) or regarding the ensemble of temperature, precipitation, and wind maxima over the course of the year in each region (=multi-sustainant).

Another example of interest may be the resilience of a society against increasing abundance of misinformation and the shock of a pandemic (multi-influence) regarding trust in the government (single sustainant) (Bak-Coleman *et al* 2021).

2.4. Resilience how: what are the response options?

At which levels can or does a system react to adverse influences? Which types of reactions can be observed? What is the range of possible reactions? Which reactions are endogenous as a consequence of the system's structure and rules? Which response options require external management or internal management/agency?

One type of reaction could be the inherent stability behaviour of a system, bringing it back to a state compatible with the sustainant, for instance in a fish population with logistic growth. Another response could be a change of structure or rules, for instance the creation of new links in a communication network or the switch to another set of rules in a transport system. Rather abstract sustainants also allow for more profound response options. For instance, it is argued that the decarbonization of the global economy would transform it so much that it would look completely different—while ensuring the resilience of the economic system regarding its ability to provide for humanity. This goes beyond simple 'bounce-back' resilience and more in the direction of 'bounce-forward', or transformability as envisioned in resilience thinking (Folke *et al* 2010). However, such a response option is also much more of a challenge to model.

2.5. Refining the research question on resilience

With the help of the checklist and the notion of 'sustainant', the research question on system resilience can be specified more precisely. Some possible types of such research questions are:

- *Is the system 'in general' resilient regarding the sustainant?* This might be a rather qualitative question: Is the sustainant easily affected and does it recover in an acceptable time range?
- *How much adverse influence can the system bear without a change of the sustainant or with a recovery on a relevant time scale?* This corresponds to a quantified measure of the specific form of resilience analysed, e.g. using metrics such as 'basin stability' or 'survivability' or variants thereof (Menck *et al* 2013, Mitra *et al* 2015, Hellmann *et al* 2016, Kan *et al* 2016).
- *How can the system be designed to be more resilient through its structure and internal dynamical rules?* Often, this is a question for general rules about

how to build or fix certain kinds of systems so that they show the desired resilience (Biggs *et al* 2015). To answer this question, the system model(s) must have a certain level of genericity that allows for the comparison of different structural or dynamical changes.

- *What are resilience-promoting management strategies?* In this case, the model should reflect the possibility to change structure, states, parameters and rules/cause-effect relationships easily.

2.6. Choosing appropriate modelling techniques

Answering the above guiding questions does not produce a complete model but a collection of requirements that should be met by a more technical description. For this, our guideline does not specify a single approach. In general, any mathematical or simulation technique from differential equations over agent-based modelling to game-theoretical modelling may be used. Of course, the description resulting from answering the guiding questions will influence this choice. For instance, if an important feature of a system is the social structure connecting people, choosing a network model appears natural.

3. Application example: Amazon rainforest

To show how the proposed guideline can be applied in modelling and communication of Earth system resilience, let us consider the Amazon rainforest: its hyperdiverse ecosystem and the human societies interacting with it.

We start with the broad research interest of whether climate impacts may cause a large-scale dieback of the forest via possible tipping dynamics (Lenton *et al* 2008, Lovejoy and Nobre 2018). To highlight the flexibility of the guideline, we formulate several related research questions and discuss respective modeling options. Each version is meant to be a potential result of one or more iterations of the above process.

3.1. First version: aggregate tree-cover reacting to overall aridity

From the broad research interest, one may derive the straightforward binary *sustainant* that Amazonia remains a predominantly forested area. A possible quantitative indicator of this sustainant may be that the overall share of area that is covered by forest, $0 \leq C \leq 1$, is above 1/2. A related *system* model could have as its sole variable the rainforest cover, influenced by climate conditions. If water availability is seen as the limiting factor for vegetation growth which is most affected by climate, the relevant *adverse influence* is a potentially increasing aridity A, which could hence serve as the sole parameter of the model. A rather simplistic example of such a model was given in Menck *et al* (2013) as:

$$dC/dt = -\delta\, C + 1_{C > C_0(A)}\, \gamma\, C(1 - C), \qquad (1)$$

where δ is a decay rate due to respiration and degradation and γ and C are the parameters of a logistic growth happening when C exceeds some minimal value $C_0(A)$ that depends on A in a strictly monotonic fashion. This model has a stable fixed point of $C^* = 1 - \delta/\gamma$ (largely forest) as long as $C_0(A) < C^*$, and another stable fixed point of $C = 0$ (pure savannah) as long as $C_0(A) > 0$. If it is in the forest equilibrium, it is unaffected by changes in A that keep $C_0(A) < C^*$, since its responses to those changes are not detailed in the model. Once $C_0(A)$ exceeds C^*, the model goes to the savannah equilibrium.

Here, the only modelled *response option* of the system to the slow parameter change of A is its inherent relaxation to equilibrium. Therefore, such a model may be used to answer *research questions* such as: If there were no other influences than an increase in aridity, would the Amazon rainforest be resilient enough to survive predicted levels of global warming? How much can aridity increase without a die-back?[11]

3.2. Second version: adding abrupt reductions of forest cover

In the above type of model, the only human impact on the system is increasing aridity. To get a more realistic picture of the risk humans put on the sustainant, one may consider other, often abrupt mechanisms on the system, such as droughts (Potter *et al* 2011), deforestation (Staal *et al* 2020), fire (Faria *et al* 2017), storms (Negrón-Juárez *et al* 2018) or soil poisoning by mining activities (Asner and Tupayachi 2016). Formally, a *multi-influence* could be defined, composed of increasing aridity and sudden forest loss. This would help formulating various *research questions*, e.g. about the interplay between the two different influences: How does an increase in aridity shrink the basin of attraction of the forest state so that sudden forest losses get more likely to push the system to the savannah state (e.g. Menck *et al* 2013)? How much do these shocks have to be reduced by external management for any given level of climate change to avoid a collapse of the sustainant?

3.3. Third version: Adaptation of species composition

Only considering the aggregate tree cover ignores crucial ecological adaptations of species composition (Jones *et al* 2014) and forest structure (Rödig *et al* 2018). Related *research questions* are: How much do these additional *response options* help sustaining or recovering the forest cover for any given level of

---

[11] As the described model is extremely stylized and its quality mostly dependent on the quality of the function $C_0(A)$, it should not be interpreted as a recommendation for answering the research questions but as an easily understandable example for the kind of models more suitable for this purpose.

the identified adverse influences (Sakschewski *et al* 2016)? At what rapidity of climate change will such adaptation get too slow to prevent collapse? Studying these requires significant changes in the model, tracking stocks of different phyla, genera, species, etc e.g. via coupled differential population equations or more sophisticated dynamic vegetation models (Shugart *et al* 1984, Köhler *et al* 2003, Botkin *et al* 2007, Fischer *et al* 2016).

3.4. Further directions

As the Amazon rainforest interacts with both the climate system (Shukla *et al* 1990, Cowling *et al* 2008) and with socio-economic systems (Müller-Hansen *et al* 2019) via various, sometimes rather regional feedback mechanisms, examples of further *research questions* may be: How does the resilience of the whole Amazon rainforest, its regional parts, and these coupled systems interact? How should rules ensuring a sufficiently low level of deforestation despite economic shocks be designed?

Addressing these research questions may require seeing the relevant *system* as including the moisture-recycling atmosphere (Zemp *et al* 2017) and/or certain land use systems, adding economic shocks as another adverse influence, regionally disaggregating both *adverse influences* and *response options,* and adding the corresponding spatial resolution to the model.

4. Discussion and conclusions

The example above helps to understand how our guideline supports different potential perspectives that could be taken on formulating the focus of a study on the resilience of the Amazon rainforest. As it shows, the presented checklist is not a strict recipe but rather a guideline that can be used to structure the modelling process, ensuring that all important aspects are taken into account. Still more importantly, it helps to communicate clearly about the specific research question of interest and the meaning of the term 'resilience' in the context of a specific system. All these aspects help the modeler to meet their responsibility for research quality, transparency, and replicability.

Since one could question the need for more terms in an already convoluted theory space, we would like to discuss in the following how the terms used in our guideline actually help navigate that theory space.

Let us first note that the term 'sustainant' allows to communicate about the system property of interest without predefining its nature (e.g. function, state, structure, …). This enables the modeler to analyze resilience 'anchored in the situation in question' as it has been demanded by Grimm and Wissel (1997) for the term 'stability'. Following the checklist, one can avoid getting lost in discussions about relationships between terms like 'persistence', 'adaptability',

'resistance', etc in the modelling process. Still, it is possible to reconnect a model developed following our checklist to different theoretical terms. Depending on the choice of sustainant, adverse influence, and response options, one can examine different definitions of resilience.

For instance, according to Hodgson *et al* (2015), resilience is the resistance and/or recovery of a system's state, where resistance is the 'instantaneous impact of exogenous disturbance on system state' and recovery 'captures the endogenous processes that pull the disturbed system back towards an equilibrium' (Hodgson *et al* 2015). This interpretation can be the result of a specific set of answers to our checklist's questions: the sustainant is the system's state, the adverse influence is some exogenous disturbance aiming at changing this state and the response options are both the capacity of the system to stay unchanged in state (or only change slightly) despite this disturbance (=resistance) and the capacity to develop back to the original state after the state has been perturbed (=recovery).

As a second example, consider the forms of resilience used in 'resilience thinking': persistence, adaptability and transformability (Folke *et al* 2010). A model with a specific system state as the sustainant can be used to study persistence, while adaptability requires the model to include the possibility to change the system's structure or rules. If one would like to examine the transformability of a system, it is obvious that the chosen sustainant would have to be a more abstract property, such as system function, since a system undergoing a general transformation of structure and feedbacks (e.g. according to (Folke *et al* 2010) a change of its stability landscape) can by definition not be resilient regarding for instance its pathway.

These examples from resilience theory show how different answers to our checklist can be used to cover different abstraction levels of resilience, reaching from a simple 'bounce-back' conception to the broader perspective of transformation. By this, our approach could help to build a bridge between two different views on the concept of resilience: as already mentioned in the introduction, some authors stress the importance of a clearly specified concept in order to facilitate formalization and measurement while others value resilience as a transdisciplinary bridging concept. Our guideline connects elements from both views. A modeler *can* examine the system for its adaptability or resistance by choosing appropriate answers to the checklist's questions. However, in contrast to merely naming these terms, a conscientious application of the guideline will clarify and define their meaning in a specific context. Therefore, the proposed approach may help to contribute to the development of a unified theoretical framework on resilience of complex systems.

The current version of our framework, as presented in this article, is still limited in several ways, which opens up respective avenues for future extensions and research. For example, we do not define any type of quantitative 'resilience metrics' or study their consistency. However, our questions may help defining such metrics, which might take different mathematical forms to deal with these various dimensions, e.g. in a way similar to basin volume-based metrics proposed by Menck *et al* (2013), Mitra *et al* (2015), Hellmann *et al* (2016), Kan *et al* (2016)or the quantifiers following Hodgson *et al* (2015). One example of this is the work of Bien *et al* (2021) in the context of power grids. A more sophisticated type of novel resilience metric might be a real-valued function f that maps a combination of four indicators—one for the current state x of the system, one for the acceptable threshold θ of the sustainant, one for the strength σ of potential adverse influences, and one for the allowable recovery time T—to the probability $p = f(x, \theta, \sigma, T)$ that the system will return to acceptable levels of the sustainant within the allowable time after suffering in the specified state an adverse influence of the given strength. This approach and other quantifiers would make an important contribution to the study of resilience in complex systems.

Another limitation is that our avoidance to choose a specific theoretical resilience framework could be understood as a capitulation to the exhausting but important process of concept formation. Still, the application of a similar pragmatic approach such as ours to a series of concrete systems could eventually reveal general insights that might feed back into the more theoretical discussions about the concept of resilience. For instance, conceptualizations along the dimensions of system, sustainant, adverse influence, and response options may be used in some kind of 'resilience study intercomparison project' in the spirit of the inter-sectoral impact model intercomparison project (ISI–MIP) (Warszawski *et al* 2014) or similar activities. Such an endeavor would be particularly helpful for choosing from the large group of existing Earth system models those that help best assessing the resilience of the Earth system regarding the sustainant of a 'safe operating space'—defined by planetary boundaries—against the adverse influence given by human pressures such as greenhouse gas emissions and degradation of biosphere integrity.

Data availability statement

No new data were created or analyzed in this study.

Acknowledgments

Appendix A. Additional example: a fishery

As an additional application of much smaller extent than the Amazon rainforest, let us study the paradigmatic and well-studied example from environmental economics of a fishery (Perman *et al* 2003). The most elementary description of this system is a fish stock that is harvested by a fisher community (= basic mental model). Traditionally, one would like to analyze the ability of this system to maintain its harvested yield (= broad research interest).

A.1. First version: constant harvesting effort

What is the system? A very simple way to model a fishery system is by a single differential equation describing the change of fish population size via logistic growth and harvesting. In this case, the system description only has one variable, the fish stock. There are two interfaces to the system's environment. First, the fish population, x, is influenced by ecosystem factors such as food supply, competition with other species and climatic conditions. All these aspects are aggregated in the two parameters, the intrinsic growth rate r and the carrying capacity K. The second interface is the harvest of fish by human fishers, modeled as a subtractive harvesting term, e.g. a concave term controlled by an effort parameter h and elasticity $\alpha < 1$:

$$\frac{dx}{dt} = rx\left(1 - \frac{x}{K}\right) - hx^{\alpha}. \tag{A1}$$

In this scope, the model does not reflect any agency—the harvest effort is a given for this choice of boundaries.

What is the sustainant? So far one can imagine different sustainants. An environmental organization could consider the system resilient if $x > x_{\min}$ for some threshold $x_{\min}$. In environmental economics, more importance is given to yield, $y = hx^{\alpha}$, which

is what we choose here as well. One could define a minimal yield $y_{\min}$ and a maximal time $t_{\max}$ that y may stay below $y_{\min}$ because fishers have limited financial reserves.

What is the adverse influence? The sustainant can be challenged by an abrupt reduction of x due to, e.g. a fish pest or an invasion by an external fishing fleet. Since a reduced x means less yield, this affects the sustainant.

What are the response options? The only response 'option' of the system is the built-in basic dynamic stability that lets the stock converge to its unique stable equilibrium value x^* from whatever initial condition $x(0)$. Depending on parameters and perturbation size, x may recover fast enough to ensure that the drop in y does not last too long.

Research question: First of all, one can ask whether, given some value of h, equilibrium yield $y^* = h(x^*)^{\alpha}$ is above $y_{\min}$. If so, the model can be used to find out by how much x may be reduced without exceeding the acceptable recovery time for y. With knowledge of the probability distribution of such reduction events, one may also calculate the risk and expected first occurrence time of a fishery breakdown depending on the value of h.

A.2. Second version: adaptation of harvesting effort

In a more realistic model version, one could argue that fishers could adapt their effort h to a changing y. This extension of the *response options* makes it necessary to modify the model. Instead of treating h as an exogenous parameter, we need a new component representing the harvest decisions of the fishing community. This could be done by specifying h (or the change dh/dt) as a function f of current and past yield, $y(\leq t)$. The modified model now includes agency since it models the fishers' reaction to changing yield. A *research question* could be: What is the optimal effort function f that minimizes the risk of collapse?

A.3. Third version: public good problem

The 2nd model would certainly lead to the insight that under certain conditions, h has to be reduced temporarily or permanently to ensure a long term sustainable y. However, a fishing community is typically not a single entity but a heterogeneous group of fishers with individual interests. The model could thus reflect the resulting public good problem by including several agents i. This extension results in changes on all levels of the checklist. In contrast to the first and second model, we now need to model agents' decisions on individual efforts h_i. This could be done by assuming the same strategy for all fishers, e.g. individual short-term profit maximization. However, a large diversity of other approaches is possible, usually introducing more heterogeneity. Since our original *sustainant*, overall yield, is indifferent to yield inequality between fishers, an alternative sustainant could be that for a

specific percentage of fishers, individual yield y_i does not collapse below some $y_{i,\min}$ for longer than some time $\Delta t_{i,\max}$. Or some welfare function $W(y_1, \ldots, y_N)$ from welfare economics may be used to define a quantitative sustainant. The *adverse influence* would be the same as before but there would be several layers of *response options*: The stock's inherent convergence to equilibrium, the effort change of the agents due to their existing strategies, the change of these individual strategies, e.g. due to social or individual learning, and the collective setting of rules by the community. One may then have a suitable model to answer—amongst others—the following *research question*: What rules should the community implement to maintain the sustainant?

A *4th version* might be necessary if fishers generate profit $y_i p - g(h_i)$ (the new sustainant, with $y_i p$ being the sales and $g(h_i)$ the costs given by some function $g(.)$) by selling their yield to a market (an additional model component) whose price p may drop (adverse influence), to which they may react by jointly reducing their efforts h_i to maintain a higher p or by redistributing income through taxation (response options).

Appendix B. Additional example: an electricity transmission system

Power grids have often been studied regarding various forms of stability, robustness, and performance (e.g. Menck *et al* 2014, Hellmann *et al* 2016, Plietzsch *et al* 2016, Nitzbon *et al* 2017, Wienand *et al* 2019), many of which can naturally be seen as specific forms of resilience (e.g. Anderies *et al* 2013). Therefore, this kind of system is a good example to illustrate the proposed framework, even though it is only interacting with the environment but has no major environmental component itself. A basic starting model description for a power grid could be that electricity producers and consumers are connected by power transmission lines. The broad research question is to analyze if the grid is easily disturbed by changing conditions.

B.1. First version: static consumption patterns
What is the system? The historically earliest and also most simple model of a power grid is a graph with edges representing high-voltage transmission lines and nodes representing transformers to lower voltage levels, aggregating consuming and producing subsystems not further defined. The interface to the environment of the system is the production/consumption of every node. Each transmission line has a certain capacity. It is assumed that production and consumption are always balanced. This reflects the fact that the model does not include mechanisms to match electricity offer and demand, such as a market. The model is non-dynamic, the electricity transport is calculated with static power flow equations basically

representing Kirchhoff's laws. This can be used as a base model to address the next questions of our framework.

What is the sustainant? From the perspective of a society maintaining a power grid, the function and sustainant of such a system can be seen as enabling all power transmission desired by producers and consumers. This is a binary sustainant: Either everyone's transmission demand is met or not.

What is the adverse influence? In this model, the sustainant can be challenged by a new (but still balanced) production and consumption pattern that may lead to line overload. Since our base model treats production/consumption as part of the environment rather than as part of the system, this influence is seen as an external influence on the system at this point, affecting the system by the input or consumption status of nodes.

What are the response options? Since the model does not include any agency, the only response option is that the power flow adjusts automatically to shift load from overloaded lines to others as a consequence of Kirchhoff's laws.

The model is suitable for answering the very specific *research question*: 'Can the grid transmit all desired production/consumption or not?' for a specific state, as well as deriving from that: 'Which production/consumption patterns' transmission demands can be served?' or 'How must the grid be designed to serve the transmission demands of a specific production/consumption pattern?'.

B.2. Second version: adding rules for reducing production or consumption
Answering the questions mentioned above will not be very satisfying since production/consumption of nodes usually changes often over time and there may occur situations in which it can be necessary to reduce production/consumption of some nodes for some time to avoid line overload. Therefore, another *research question* could be: 'If a reduction is necessary, which reduction pattern should be applied?' For this question, the sustainant must be refined.

The new *sustainant* could be the fulfillment of each consumer node's demand. In order to call the overall system resilient, for each node, the delivered power needs to be within an acceptable range after the reduction.

To study the resilience of the power grid regarding this new sustainant, the current system model is insufficient. It has to be extended with the critical demand of each consumer node. The *adverse influence* is then a continually changing production/consumption pattern on the nodes.

Additionally, the system model is equipped with a first *response option* to these pattern changes: an algorithm that specifies which nodes' production or consumption gets reduced how and under which conditions.

The new research interest can then be addressed by varying the reduction algorithm.

B.3. Third version: regarding multi-influences

In reality, of course, rules exist that deal with adverse influences which exceed the reaction capacity of the reduction algorithm or influence the sustainant in another way than only a changed infeed/consumption pattern. It may therefore be helpful to define an extended *influence*, a multi-influence that consists of the well-known pattern changes as well as line tripping and generator failures. As a consequence, the system model has to be extended with the information whether a node or edge is active or not. A new interface to the environment is their activation/deactivation (Plietzsch *et al* 2016).

The new *research question* could then be: Is the system's reaction resilient (regarding the sustainant defined in the last version) in cases where the chosen reduction algorithm fails? To study this reaction, it is necessary to model the decisions taken in system operation (by engineers and software) in certain contingencies (*response options*).

B.4. Fourth version: adding management options

If the research interest is not to determine whether the reaction of a specific system is resilient but rather which kind of management decisions make it resilient (exploration instead of prediction/evaluation), the model has to be extended by a set of additional *response options* that can be chosen in certain contingencies. For example, the network operator could build additional lines, the government could introducing network fees, taxes or subsidies to incentivize changes in production or consumption, and electricity companies could change their pricing schemes and production locations.

This system model would not be purely deterministic or stochastic since the agents' decisions are not modelled, only their decision options. Therefore, the model would have game-theoretical traits.

B.5. Fifth version: frequency stability

In more recent considerations on the resilience of power grids, frequency stability has become an important aspect due to an increasing producer volatility caused by larger shares of renewable

energy sources. Therefore, a suitable extension of the *sustainant* is the following: At every node, the frequency must not leave an acceptable range for longer than some (very short) acceptable time spam so that devices do not get damaged (Hellmann *et al* 2016). Adding this aspect to the already considered sustainant, we obtain a 'multi-sustainant'. To answer any research question regarding this new sustainant, the electricity transport on the network has to be modelled representing dynamics of frequencies and phases on short time scales. Technically, this could be done by replacing power flow equations by so-called 'swing equations,' the power flow would then be a result of these new equations. The *adverse influence* would then be extended by the change of frequency at a specific node due to fluctuations in consumption and renewable energy production, and *response options* would include the programming of fast-reacting power electronics devices that switch lines and redirect flows.

B.6. Outlook on further modelling approaches

The presented ways of how to answer the checklist when studying the resilience of a power grid are by far not complete. In order to get an idea of the vast number of other possibilities, consider these further aspects:

- The net operator could define the purpose of the network (and, in their perspective, the sustainant) as generating profit. A corresponding model would have to include a power market which could produce internal fluctuations as an adverse influence inside of the system boundaries (Heitzig *et al* 2017).
- From the perspective of the government of a country having a power grid, an interesting question could be: What policy-instruments give resilience-promoting incentives to grid-operators? Such a question builds upon the answers of many of the other research questions (in order to know which management decisions of a grid operator would be resilience-promoting) but adds a model layer reflecting the mechanisms leading from policy-instruments to such decisions.

All three application examples dicussed in the article are summarised in table B1.

Table B1. Possible answers to the guiding questions from our checklist for the three application examples. A '+' symbol implies 'additional to the items directly above'.

Application	Version	System	Sustainant	Adverse influence	Response options
Amazon rainforest	1	tree-covered area C	$C > 1/2$	slowly rising aridity	convergence to stable equil. C
	2			+ abrupt reduction in C	
	3	+ species composition			+ adaptation in species mix
	4	+ regional deforestation		+ econ. drivers of deforestation	+ regulation against deforestation
Fishery	1	fish stock, total harvest	total yield	population decline	convergence to stable equil. stock
	2	+ total fishing effort	total yield		+ lowering of effort
	3	+ individual fishers	fishers' minimal yield		+ fishers' strategic interaction
	4	+ external market	income-based welfare metric	+ price drop	+ output reduction, taxation
Electricity transmission system	1	network of transmission lines	every node's transmission demand is met	shifting consumption / production patterns	shifts in power flow due to Kirchhoff's laws
	2	+ production / consumption adjustment mechanisms	minimal level of consumption		automatic production / consumption reduction
	3	+ possibility that lines or generators are down		+ line tripping, generator failure	+ certain measures taken by system operators
	4	+ system operators			+ pricing, regulation, building new lines
	5		+ frequency stays within acceptable range	+ fast fluctuations in renewable energy production	+ power electronics

ORCID iDs

Lea A Tamberg ⓘ https://orcid.org/0000-0001-6601-5633
Jobst Heitzig ⓘ https://orcid.org/0000-0002-0442-8077
Jonathan F Donges ⓘ https://orcid.org/0000-0001-5233-7703

References

Ahlborg H, Ruiz-Mercado I, Molander S and Masera O 2019 Bringing technology into social-ecological systems research-motivations for a socio-technical-ecological systems approach *Sustainability* **11** 2009

Anderies J M, Folke C, Walker B and Ostrom E 2013 Aligning key concepts for global change policy: robustness, resilience and sustainability *Ecol. Soc.* **18** 8

Anderies J M, Walker B H and Kinzig A P 2006 Fifteen weddings and a funeral: case studies and resilience-based management *Ecol. Soc.* **11** 21

Armitage D, Béné C, Charles A T, Johnson D and Allison E H 2012 The interplay of well-being and resilience in applying a social-ecological perspective *Ecol. Soc.* **17** 15

Asner G P and Tupayachi R 2016 Accelerated losses of protected forests from gold mining in the Peruvian Amazon *Environ. Res. Lett.* **12** 094004

Baggio J A, Brown K and Hellebrandt D 2015 Boundary object or bridging concept? A citation network analysis of resilience *Ecol. Soc.* **20** 2

Bak-Coleman J B *et al* 2021 Stewardship of global collective behavior *Proc. Natl Acad. Sci.* **118** e2025764118

Barker C 2002 *Making Sense of Cultural Studies: Central Problems And Critical Debates* (London: Sage)

Bien S, Schultz P, Heitzig J and Donges J F 2021 Resilience basins of complex systems: an application to prosumer impacts on power grids (arXiv:2108.09474)

Biggs R, Schlüter M and Schoon M L 2015 *Principles for Building Resilience: Sustaining Ecosystem Services in Social-Ecological Systems* (Cambridge: Cambridge University Press)

Bossel H 2007 *Systems and Models: Complexity, Dynamics, Evolution, Sustainability* (Norderstedt: Books on Demand)

Botkin D B *et al* 2007 Forecasting the effects of global warming on biodiversity *Bioscience* **57** 227–36

Brand F S and Jax K 2007 Focusing the meaning (s) of resilience: resilience as a descriptive concept and a boundary object *Ecol. Soc.* **12** 23

Carpenter S, Walker B, Marty Anderies J and Abel N 2001 From metaphor to measurement: resilience of what to what? *Ecosystems* **4** 765–81

Cote M and Nightingale A J 2012 Resilience thinking meets social theory: situating social change in socio-ecological systems (SES) research *Prog. Hum. Geogr.* **36** 475–89

Cowling S A, Shin Y, Pinto E and Jones C D 2008 Water recycling by Amazonian vegetation: coupled versus uncoupled

vegetation–climate interactions *Philos. Trans. R. Soc.* B **363** 1865–71

Cretney R 2014 Resilience for whom? Emerging critical geographies of socio-ecological resilience *Geogr. Compass* **8** 627–40

Curtin C G and Parker J P 2014 Foundations of resilience thinking *Conserv. Biol.* **28** 912–23

Cutter S L 2016 Resilience to what? Resilience for whom? *Geogr. J.* **182** 110–13

Dakos V, Carpenter S R, van Nes E H and Scheffer M 2015 Resilience indicators: prospects and limitations for early warnings of regime shifts *Philos. Trans. R. Soc.* B **370** 20130263

de Faria B L, Brando P M, Macedo M N, Panday P K, Soares-Filho B S and Coe M T 2017 Current and future patterns of fire-induced forest degradation in Amazonia *Environ. Res. Lett.* **12** 095005

Donges J F and Barfuss W 2017 From math to metaphors and back again: social-ecological resilience from a multi-agent-environment perspective *GAIA-Ecol. Perspect. Sci. Soc.* **26** 182–90

Donges J F, Lucht W, Cornell S E, Heitzig J, Barfuss W, Lade S J and Schlüter M 2021 Taxonomies for structuring models for world–earth systems analysis of the anthropocene: subsystems, their interactions and social–ecological feedback loops *Earth Sys. Dyn.* **12** 1115–37

Donges J F, Lucht W, Müller-Hansen F and Steffen W 2017 The technosphere in earth system analysis: a coevolutionary perspective *Anthr. Rev.* **4** 23–33

Dornelles A Z *et al* 2020 Towards a bridging concept for undesirable resilience in social-ecological systems *Glob. Sustain.* **3** e20

Fischer R *et al* 2016 Lessons learned from applying a forest gap model to understand ecosystem and carbon dynamics of complex tropical forests *Ecol. Modell.* **326** 124–33

Folke C, Biggs R, Norström A V, Reyers B and Rockström J 2016 Social-ecological resilience and biosphere-based sustainability science *Ecol. Soc.* **21** 41

Folke C, Carpenter S R, Walker B, Scheffer M, Chapin T and Rockström J 2010 Resilience thinking: integrating resilience adaptability and transformability *Eco. Soc.* **15** 20

Gleeson T *et al* 2020 Illuminating water cycle modifications and Earth system resilience in the anthropocene *Water Resour. Res.* **56** e2019WR024957

Grimm V and Wissel C 1997 Babel, or the ecological stability discussions: an inventory and analysis of terminology and a guide for avoiding confusion *Oecologia* **109** 323–34

Gunderson L H, Allen C R and Holling C S 2012 *Foundations of Ecological Resilience* (Island Press)

Hamborg S, Meya J N, Eisenack K and Raabe T 2020 Rethinking resilience: a cross-epistemic resilience framework for interdisciplinary energy research *Energy Res. Soc. Sci.* **59** 101285

Heitzig J, Meyer-Ortmanns H and Auer S 2017 Comparison of electricity market designs for stable decentralized power grids (arXiv:1704.04644)

Hellmann F, Schultz P, Grabow C, Heitzig J and Kurths Jurgen 2016 Survivability of deterministic dynamical systems *Sci. Rep.* **6** 29654

Hodgson D, McDonald J L and Hosken D J 2015 What do you mean, 'resilient'? *Trends Ecol. Evol.* **30** 503–6

Holling C S 1973 Resilience and stability of ecological systems *Annu. Rev. Ecol. Evol. Syst.* **4** 1–23

Jones M O, Kimball J S and Nemani R R 2014 Asynchronous Amazon forest canopy phenology indicates adaptation to both water and light availability *Environ. Res. Lett.* **9** 124021

Kéfi S, Domínguez-García V, Donohue I, Fontaine C, Thébault E and Dakos V 2019 Advancing our understanding of ecological stability *Ecol. Lett.* **22** 1349–56

Köhler P, Chave Jerôme, Riéra B and Huth A 2003 Simulating the long-term response of tropical wet forests to fragmentation *Ecosystems* **6** 0114–28

Lade S J, Bodin Orjan, Donges J F, Kautsky E E, Galafassi D, Olsson P and Schlüter M 2017 Modelling social-ecological transformations: an adaptive network proposal (arXiv:1704.06135)

Larsen R K, Calgaro E and Thomalla F 2011 Governing resilience building in thailand's tourism-dependent coastal communities: conceptualising stakeholder agency in social–ecological systems *Glob. Environ. Change* **21** 481–91

Lenton T M, Held H, Kriegler E, Hall J W, Lucht W, Rahmstorf S and Schellnhuber H J 2008 Tipping elements in the earth's climate system *Proc. Natl Acad. Sci.* **105** 1786–93

Lovejoy T E and Nobre C 2018 Amazon tipping point *Sci. Adv.* **4** eaat2340

Meerow S and Newell J P 2019 Urban resilience for whom, what, when, where and why? *Urban Geogr.* **40** 309–29

Menck P J, Heitzig J, Kurths Jurgen and Schellnhuber H J 2014 How dead ends undermine power grid stability *Nat. Commun.* **5** 3969

Menck P J, Heitzig J, Marwan N and Kurths Jurgen 2013 How basin stability complements the linear-stability paradigm *Nat. Phys.* **9** 89–92

Mitra C, Kurths Jurgen and Donner R V 2015 An integrative quantifier of multistability in complex systems based on ecological resilience *Sci. Rep.* **5** 16196

Müller-Hansen F, Heitzig J, Donges J F, Cardoso M F, Dalla-Nora E L, Andrade P, Kurths Jurgen and Thonicke K 2019 Can intensification of cattle ranching reduce deforestation in the Amazon? Insights from an agent-based social-ecological model *Ecol. Econ.* **159** 198–211

Negrón-Juárez R I *et al* 2018 Vulnerability of Amazon forests to storm-driven tree mortality *Environ. Res. Lett.* **13** 054021

Nitzbon J, Schultz P, Heitzig J, Kurths J and Hellmann F 2017 Deciphering the imprint of topology on nonlinear dynamical network stability *New J. Phys.* **19** 033029

Otto I M, Wiedermann M, Cremades R, Donges J F, Auer C and Lucht W 2020 Human agency in the anthropocene *Ecol. Econ.* **167** 106463

Pahl-Wostl C, Sendzimir J and Jeffrey P 2009 Resources management in transition *Ecol. Soc.* **14** 46

Perman R, Yue M, McGilvray J and Common M 2003 *Natural Resource and Environmental Economics* 3rd edn (Harlow, Essex: Pearson Education Ltd.)

Plietzsch A, Schultz P, Heitzig J and Kurths J 2016 Local vs. global redundancy—trade-offs between resilience against cascading failures and frequency stability *Eur. Phys. J. Spec. Top.* **225** 551–68

Potter C, Klooster S, Hiatt C, Genovese V and Castilla-Rubio J C 2011 Changes in the carbon cycle of Amazon ecosystems during the 2010 drought *Environ. Res. Lett.* **6** 034024

Rockström J *et al* 2009 A safe operating space for humanity *Nature* **461** 472–5

Rockström J *et al* 2021 Identifying a safe and just corridor for people and the planet *Earth's Future* **9** e2020EF001866

Rödig E, Cuntz M, Rammig A, Fischer R, Taubert F and Huth A 2018 The importance of forest structure for carbon fluxes of the Amazon rainforest *Environ. Res. Lett.* **13** 054013

Sakschewski B, Werner V B, Boit A, Poorter L, Pe na-Claros M, Heinke J, Joshi J and Thonicke K 2016 Resilience of Amazon forests emerges from plant trait diversity *Nat. Clim. Change* **6** 1032–6

Shugart H H *et al* 1984 *A Theory of Forest Dynamics: The Ecological Implications of Forest Succession Models* vol 278 (Berlin: Springer)

Shukla J, Nobre C and Sellers P 1990 Amazon deforestation and climate change *Science* **247** 1322–5

Staal A, Flores B M, Aguiar A P D, Bosmans J H C, Fetzer I and Tuinenburg O A 2020 Feedback between drought and deforestation in the Amazon *Environ. Res. Lett.* **15** 044024

Steffen W *et al* 2015 Planetary boundaries: guiding human development on a changing planet *Science* **347** 1259855

Strunz S 2012 Is conceptual vagueness an asset? Arguments from philosophy of science applied to the concept of resilience *Ecol. Econ.* **76** 112–18

Turner B L 2010 Vulnerability and resilience: Coalescing or paralleling approaches for sustainability science? *Glob. Environ. Change* **20** 570–6

van Kan A, Jegminat J, Donges J F and Kurths Jurgen 2016 Constrained basin stability for studying transient phenomena in dynamical systems *Phys. Rev.* E **93** 1–7

Van Meerbeek K, Jucker T and Svenning J-C 2021 Unifying the concepts of stability and resilience in ecology *J. Ecol.* **109** 3114–32

Voinov A A 2010 *Systems Science and Modeling for Ecological Economics* (New York: Academic)

Walker B *et al* 2002 Resilience management in social-ecological systems: a working hypothesis for a participatory approach *Conserv. Ecol.* **6**

Walker B and Salt D 2012 *Resilience Thinking: Sustaining Ecosystems and People in a Changing World* (Washington, DC: Island Press)

Warszawski L, Frieler K, Huber V, Piontek F, Serdeczny O and Schewe J 2014 The inter-sectoral impact model intercomparison project (isi–mip): project framework *Proc. Natl Acad. Sci.* **111** 3228–32

Westley F R, Tjornbo O, Schultz L, Olsson P, Folke C, Crona B and Bodin Orjan 2013 A theory of transformative agency in linked social-ecological systems *Ecol. Soc.* **18** 27

Wienand J F, Eidmann D, Kremers J, Heitzig J, Hellmann F and Kurths J 2019 Impact of network topology on the stability of DC microgrids *Chaos* **29** 1–9

Woods D D 2015 Four concepts for resilience and the implications for the future of resilience engineering *Reliab. Eng. Syst. Saf.* **141** 5–9

Woods D and Hollnagel E 2006 *Resilience Engineering Concepts* 1st edn (Boca Raton, FL: CRC Press)

Wunderling N, Gelbrecht M, Winkelmann R, Kurths Jurgen and Donges J F 2020 Basin stability and limit cycles in a conceptual model for climate tipping cascades *New J. Phys.* **22** 123031

Yu D J, Schoon M L, Hawes J K, Lee S, Park J, Rao P S C, Siebeneck L K and Ukkusuri S V 2020 Toward general principles for resilience engineering *Risk Anal.* **40** 1509–37

Zemp D C, Schleussner C-F, Barbosa H M J, Hirota M, Montade V, Sampaio G, Staal A, Wang-Erlandsson L and Rammig A 2017 Self-amplified amazon forest loss due to vegetation-atmosphere feedbacks *Nat. Commun.* **8** 1–10