One Earth

CellPress
OPEN ACCESS

Perspective

Framing resilience to manage complex environmental systems

Ian Townend,[1,*] Jon French,[2] and Robert Nicholls[3]
[1]School of Ocean and Earth Science, University of Southampton, Southampton SO14 3ZH, UK
[2]UCL Department of Geography, University College London, Gower Street, London WC1E 6BT, UK
[3]Tyndall Centre for Climate Change Research, University of East Anglia, Norwich NR4 7TJ, UK
*Correspondence: i.townend@soton.ac.uk
https://doi.org/10.1016/j.oneear.2024.09.008

SUMMARY

The significant challenges of managing complex environmental systems in a changing world are widely acknowledged. There are widespread calls for transformation in our approach and for the adoption of more holistic perspectives. In this paper, we explore the concept of "resilience" within a system dynamics framework as an attractive and appropriate conceptual approach for this problem. We link this to the evaluation and selection of adaptation pathways and transitions within the constraints of a "safe operating space," recognizing planetary boundaries as well as operational and sectoral constraints. We discuss the relative merits of using quantitative modeling to explore the evolution of individual system state functions versus the use of suites of measures that aim to characterize and track the overall resilience of complex environmental systems. Using national and global examples, we demonstrate how such a resilience-based approach can be made operational, which is a fundamental requirement for wider adoption.

INTRODUCTION

There are widespread calls for transformation in our approach to the management of complex environmental systems in a changing world and for the adoption of more holistic perspectives capable of accommodating not only the "natural" but also the "human" components of such systems.[1,2] Systems that extend across environmental, social, and economic domains are, by their very nature, complex and dynamic. Concepts such as sustainability focus on securing human needs within the Earth's carrying capacity. Sustainability research examines the interaction of human and environmental systems to understand the role of ecosystem services and to evaluate the trade-offs needed to maintain specific services for future generations. Within this broad conceptual umbrella, vulnerability assessment examines the exposure of such systems to a range of threats. In contrast to sustainability, resilience focuses much more on the dynamics of a system, especially when it is disturbed. The response reveals the capacity of the system to self-organize and adapt and to either recover or evolve to a new state.[3] Understanding resilience allows decision-makers to consider whether to improve adaptive capacity or prepare for state transitions. Like sustainability, resilience is typically considered in qualitative terms. However, to support informed decision-making, particularly where trade-offs exist, some form of quantification is essential.[4]

In this perspective, we explore the concept of "resilience" within a system dynamics framework. We have chosen to explore resilience because it has the potential to provide a quantitative measure of these complex systems at multiple scales (local, national, and global) in a way that can directly contribute to policies aimed at their stewardship and management. Our focus is on ways to operationalize the concept as a policy-relevant measure by exploring the contributions that can be made by systems models and aggregated performance measures. We provide examples of the latter at national and global scales and highlight how quantification must necessarily incorporate value judgements. Although sometimes considered a drawback, the ability to incorporate some measure of what is or is not perceived to be important allows the differing values of a community, or society, to be captured. This helps to inform policy and decision-makers about the inherent trade-offs when dealing with systems that extend across social, environmental, and economic domains.

While the term "resilience" has been widely used in industrial,[5] academic,[6] and policy circles,[7] there have been only limited attempts to quantify it at a whole-system level within the realm of environmental management and policy formulation. Perhaps more importantly, the concept has not yet been framed in a wider context that embraces broader thinking, such as planetary boundaries[8] and social equity,[9] while also working in concert with more established approaches, such as adaptation pathways and transitions.[10,11] We start by summarizing this broader context before discussing how a quantitative conceptualization of resilience can be used to frame policy-making and the steps needed to make this operational. We examine the difference between the construction of detailed socio-ecological models (which have been reported extensively in the literature and are discussed below) and an alternative performance measure approach, which we illustrate for a national policy sector and the global ability to live within a safe operating space. We conclude by considering how quantitative metric-based resilience models might be further developed in practice and what further research is needed. The novelty of such a quantitative

Box 1. Concept definitions

Resilience: the ability of a system to be disturbed and then recover. For example, our ability to recover from illness reflects the resilience of the human body to disturbances such as physical damage or infectious disease.

Dynamic systems framework: a way of thinking about and understanding the nonlinear behavior of complex systems over time. In the cases we examine, this includes compound systems comprising multiple interacting physical, ecological, and socio-economic sub-systems that define the world in which we live.

System state: the configuration of a system at a given time, which can be defined by a set of attributes known as the state variables. In this perspective, we characterize this in terms of the capacity to absorb and recover from change or transition to a different state if the system is perturbed too much.

Planetary boundaries: a framework that describes nine components of the planetary system that are essential for human life, with the boundaries seeking to define one aspect of a safe operating space.

Social equity: the idea of an open and fair society that ensures justice and equal opportunities for all. This is seen as providing a necessary social foundation for humanity and, in conjunction with planetary boundaries, defines the other aspect of a safe operating space.

Adaptation: the actions we need to take in response to change. This can apply to any aspect of change in our lives but is commonly associated with the different pathways that we might need to follow, or implement, in response to existential threats such as climate change.

Transition: an idea that recognizes that a system can move between different states. Here, we consider managed transitions as a form of adaptation and forced transitions where external influences (such as extreme weather events) alter the system so that it is no longer possible to recover the original state. These types of changes are also commonly referred to as tipping points.

resilience-based framework is that it is embedded in broader systems concepts, drills down to the needs of specific policy sectors, and has the potential to be integrated into local, national, or global assessments (Box 1).

DYNAMIC SYSTEMS THINKING

Systems thinking and system dynamics have been the focus of scientists and engineers for many decades (e.g., von Bertalanffy[12] and Odum and Odum[13]) and have gained increasing recognition in policy and planning circles following the publication of *The Limits to Growth*,[14,15] which examined our use of resources in the context of a finite planet. Although both the economic assumptions and mathematical basis of these early global simulations have been heavily criticized,[16,17] this work marked a step change in that it focused attention on the global constraints within which human existence remains possible. This debate has subsequently shifted away from a predominantly resource-focused analysis to recognition of the growing and interacting pressures of pollution, intensified land use, and climate change. The emergence of the Anthropocene concept of contemporary human dominance over earth system processes[18] led Rockström et al.[8] to propose the concept of "planetary boundaries" that define a "safe operating space" for humanity (see Figure 1 in Rockström et al;[8]). This approach has been expanded by Raworth[9] to consider social equity. From this, she defined a safe space that also ensures that humanity has an adequate social foundation while remaining within sustainable ecological limits (see the figure on page 51 in Raworth[9]).

At a planetary scale, the maintenance of the safe operating space is necessarily a collaborative effort between nation states. International/intergovernmental bodies increasingly track a range of trend indicators to monitor encroachment upon the boundaries of specific sectors, inasmuch as these can be quantitatively estimated.[19] As we encroach on planetary boundaries, carrying capacity is reduced. Similarly, if we favor the few, embark on conflict, or suffer major disasters, so social equity diminishes. Importantly, as well as needing to integrate across sectors, the thresholds that define what is safe (the safe space) are also varying in time within the Earth system (Figure 1A). At a global scale, our collective societal choices will influence how the safe space evolves in the future. Given that society is a distributed network of actors, both understanding and achieving desirable collective actions and outcomes are major challenges.

Encroachment upon planetary boundaries has been well documented both before and since Rockström et al.'s seminal paper.[8,20,21] There is now compelling evidence for a progressive loss of carrying capacity, especially with respect to biodiversity, growing levels of pollution, and climate change (e.g., Baste et al.[22]), among others. It is important to note that not all trends in the safe space are negative. For example, damaging depletion of stratospheric ozone caused by industrial chlorofluorocarbons has been halted and is now slowly being reversed because of the Montreal Protocol.[23] There has also been progress in human development, such as a reduction in levels of infant mortality and in absolute poverty[24] and the promotion of equality.[25] Looking to the future, global efforts to tackle the loss of critical habitats, pollution, and to both mitigate and adapt to climate change suggest that, with the necessary commitment and shift from recognition to delivery, some recovery of safe space may be possible.[26] The transition to a more circular economy will be vital to underpin the move away from unsustainable exploitation and build a more inclusive society that maintains and even improves the social foundation that we all share.[9]

At a national level, policy is developed across a range of sectors, and the concept of safe space needs to be cascaded to each of these while maintaining an overview of the interactions and potential conflicts between them. This is illustrated schematically in Figure 1B. While a single sector is potentially tractable, as explained in more detail below, the challenge of integrating across all sectors at a global or even national scale is

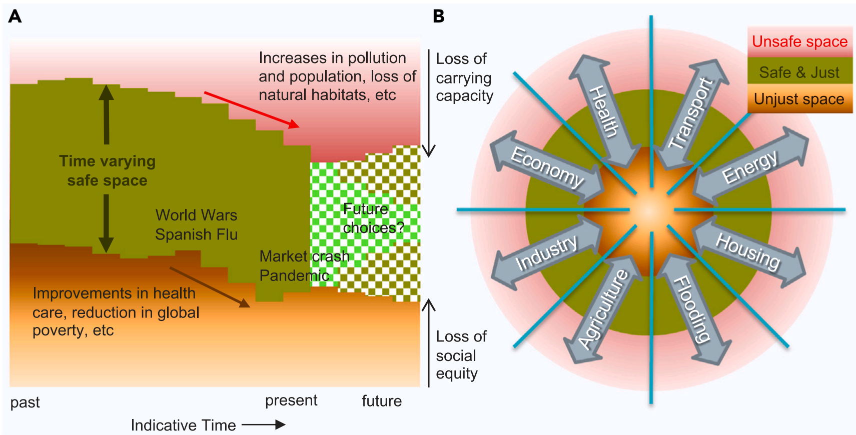


Figure 1. Two views of safe space
(A) A schematic of how safe, unsafe, and unjust space evolves over time with some indicative "events" that have significantly moved the boundaries.
(B) Typical policy sector partitions that must collectively aim to maintain society's safe space, a challenge made more difficult by conflicting interests.
The vertical (A) and radial (B) axes represent some measure of overall system state performance relative to some lower threshold ("just space") and upper threshold ("safe space").

much more demanding and may indeed be intractable. As Berlin's[27] analysis of the writings of Tolstoy carefully articulates, Tolstoy's view that history is the integration of *all* human activity and so cannot be rationalized may equally apply to global endeavors to maintain a collective safe space. One need only think of the changes brought about by the internet and social media, financial crashes, pandemics, and large-scale natural catastrophes to see how quickly forecasts and plans can be knocked off track locally, nationally, and globally. By focusing on the emergent or characteristic properties of the systems, some form of synthesis may be possible, although the potential for complex interactions and feedback means that any form of simulation or prediction is challenging.

One of the most difficult aspects of the problem is that it involves compound systems that include both natural and human components. In this context, "natural" can include physical, chemical, biological, and, hence, ecological sub-systems, while "human" encompasses social, economic, technological, and infrastructural sub-systems. The scope of these compound systems makes succinct naming difficult. For example, there is a growing literature on environmental "socio-ecological systems" (SESs). However, the inclusion of technological sub-systems, to consider social, ecological, and technological systems (SETSs),[28,29] provides a broader definition of coupled systems that embrace a variety of natural and human components.

Several studies have explored how the environmental form of SESs can be kept within their safe operating space so that tipping points, or transitions to a new system state, are avoided.[30,31] These have mostly examined well-defined case study problems, such as the fishing economy of a coastal lagoon,[32] the implications of agricultural intensification in two rural regions of China,[33] and a range of interacting pressures, including climate change, land use change, water scarcity, floods, salinity rise, and urbanization on coastal Bangladesh.[34] Such studies illustrate the application of a system dynamics modeling approach to assess increasingly complex issues, much as envisaged over 50 years ago by Forrester.[35] Typically, these endeavors remain problem focused on a specific issue, as the above examples illustrate, and, hence, only represent a sub-set of the complete system. The use of histories based on past human societies and their interactions with their environments has been suggested as one way of extending our understanding of the system dynamics.[36] This is supported by arguments put forward by Wallerstein[37] in his broader agenda for world systems analysis, seeking to re-integrate the disparate range of social sciences with natural sciences to achieve greater insight when interpreting historical events. Such transdisciplinary thinking is a key requirement when seeking to characterize complex environmental systems.

The system models referred to above define boundaries or envelopes for selected state variables and use these to determine whether the system remains within a safe space. In some cases, system behavior can be linked to tipping points and state changes, but there is always an element of subjectivity in both the selection of variables to track and the definition of what constitutes "safe." An alternative is to focus on aggregate measures of overall system "health." For example, Anderies et al.[38] argue that robustness is a suitable measure when considering system interaction that involves institutions, whereas Mumby et al.[39] modeled the dynamics of coastal reef systems to identify the thresholds that distinguish net recovery from decline, as an expression of overall system resilience. The concept of vulnerability has also been widely used,[3,40] including within the Intergovernmental Panel on Climate Change assessments.

The distinction between the three terms was explored by Mumby et al.[41] They suggest that robustness measures the ability of a system to maintain itself within a narrow range of function and should be used to manage a defined state. Vulnerability has component properties of exposure, sensitivity, and adaptive capacity. It has been widely applied to the management of hazard risks, where intervention can either be through mitigation of the hazard or through increasing adaptive capacity. When the interest relates to the loss of recovery potential or the likelihood of switching to some new state, resilience neatly encapsulates the most relevant system dynamics and is often taken to encompass adaptive capacity, transformation, and learning. It should be noted that a resilient system can be vulnerable and robust to varying degrees (see Figure 2 in Mumby et al[41]).

As already noted, resilience can be analyzed for well-defined problems by tracking the behavior of a set of key state variables (e.g., Levin et al.[31] and Dearing et al.[31,33]). Despite the difficulty in scaling such a mechanistic approach to more complex environmental systems that intersect with policy sectors at national and international scales, the concept of resilience has been widely adopted in policy circles. With this usage, policy-makers emphasize the need to cope with change at both the individual and institutional level, and their efforts reflect attempts to move away from central control, the elimination of redundancy, and a narrow focus on efficiency. There is, however, a gap between this conceptual use and an operational use that would allow policy-makers and implementers (planners, engineers, managers, etc.) to actively track progress toward enhanced system resilience; this is the focus of this perspective.

DEFINING RESILIENCE FOR THE POLICY SECTOR

Definitions of resilience abound, and, as documented by Alexander,[42] its etymology has a history dating back at least to the Roman philosophers. Modern usage in the context of environmental systems has tended to emphasize the maintenance of system stability. This stems largely from its introduction into ecology by Holling,[43] who drew directly on theoretical work by von Bertalanffy[44] on the stability of ecological systems. In this sense, the concept of resilience is directly linked to the realization that systems have operating limits, defined by thresholds that, once crossed, push the system into an alternative state. Crossing these boundaries has fundamental implications for resilience, and any assessment of resilience needs to acknowledge such tipping points. In the 1990s, resilience found application within the social sciences,[45,46] where it is now widely used as a framework for disaster management.[6] A general definition in this sphere can be found in the United Nations International Strategy for Disaster Reduction,[7] page 24:

> The ability of a system, community or society exposed to hazards to resist, absorb, accommodate to and recover from the effects of a hazard in a timely and efficient manner, including through the preservation and restoration of its essential basic structures and functions.

While the term "resilience" has been widely used in both academic[5] and policy circles,[7] quantitative determination of resilience as a system property has been hitherto largely confined to specialized applications. Quantitative methods emerged relatively early in disaster planning, notably for building safety and the provision of critical services at a community level.[47,48] Resilience is now also firmly established as a quantitative model for a variety of infrastructural and technological systems, including supply chains[49] and power distribution networks,[50] as well as generalized models of such systems.[51] The development of operational methods for quantifying the resilience of SESs has been more of a challenge, and initial assessments expressed pessimism.[52] Moreover, despite the wealth of ecological studies that refer to resilience, those that quantify it often resort to assumed proxies for resilience (such as diversity) that may not capture essential aspects of the system dynamics.[53] The importance of integrating assessment of resilience with system dynamics is also illustrated by studies of financial networks, which reveal that attributes that impart stability under some conditions can lead to instability (e.g., through propagation of shocks such as a financial crash or banking crisis) in other situations.[54,55]

Such broad definitions provide a shared understanding of the concept, but to move to application, context is important, and it is necessary to specify "resilience against what?" and "resilience for whom?" For example, in a coastal disaster risk reduction context, Linkov et al.[6] identify four slightly different phases, which have been formally encapsulated in the definition adopted by the US Army Corps of Engineers (USACE),[56] namely:

> Coastal resilience is defined as the ability of a system to prepare, resist, recover, and adapt to disturbances in order to achieve successful functioning through time.

SESs are, of course, more complex than typical engineered systems and the theoretical ecological systems envisaged by Holling.[43] They include a greater variety of components, not least human actors, whose diverse beliefs and priorities complicate the formulation of problems and preclude the identification of unique solutions; these reside in the classic "wicked problem" domain.[57] This makes elucidation of their most important functional dynamics as well as quantitative determination of the overall system state more difficult.[11] Our conceptualization has become more sophisticated, exemplified by the recognition of SETSs, but assessment of resilience in this domain remains almost entirely qualitative.[11,43,58] In the context of safe operating space, planetary boundaries and the social foundation provide measures of the state of the system, and resilience is an attribute of the system dynamics, reflecting how well the system can cope with disturbance.

CONCEPTUAL MODEL OF SYSTEM RESILIENCE

Considering the USACE definition of resilience, the first and last phases of preparation and adaptation are undertaken with reference to a certain system state. The dynamics of the system are encapsulated in the resist and recover phases, as shown in Figure 2, which illustrates system response to an event. An initial loss of capacity is followed by the recovery of some or all of the capacity that was lost, possibly even with some enhancement of that capacity. Capacity here could refer to a specific aspect of system functionality (as captured by one or more state variables). However, for complex systems that extend into the human domain, capacity might more usefully represent an aggregation of system function based upon a potentially large and diverse set of metrics. Each of these phases has a characteristic timescale, denoted here as the resistance and recovery times. The temporal variation in capacity reflects both how well the system resists some imposed stress and how well it subsequently recovers. We therefore reason that the area under the system response curve is a meaningful measure of the system resilience. This is slightly different from the conceptualization of Linkov et al.,[6] who suggest that the slope of the recovery phase reflects the system resilience. As explained below, when relating the concept of resilience to adaptation, the ability to better resist (e.g., by being better prepared) is an important aspect of resilience, and, hence, integration of the system response over time captures both the loss and recovery phases. Consideration of multiple events allows assessment of the influence of the frequency of events (or inter-arrival time) and leads to a time-dependent measure of resilience. The dynamic response is illustrated in Figure 2A, which shows a perturbation followed by complete recovery. However, many other types of system response can be represented using this schematic cartoon, as shown in Figure 2B. The total loss of a system following a perturbing event is depicted in Figure 2B(i). This typically results in the shift to a different system state, which we discuss below as

CellPress
OPEN ACCESS

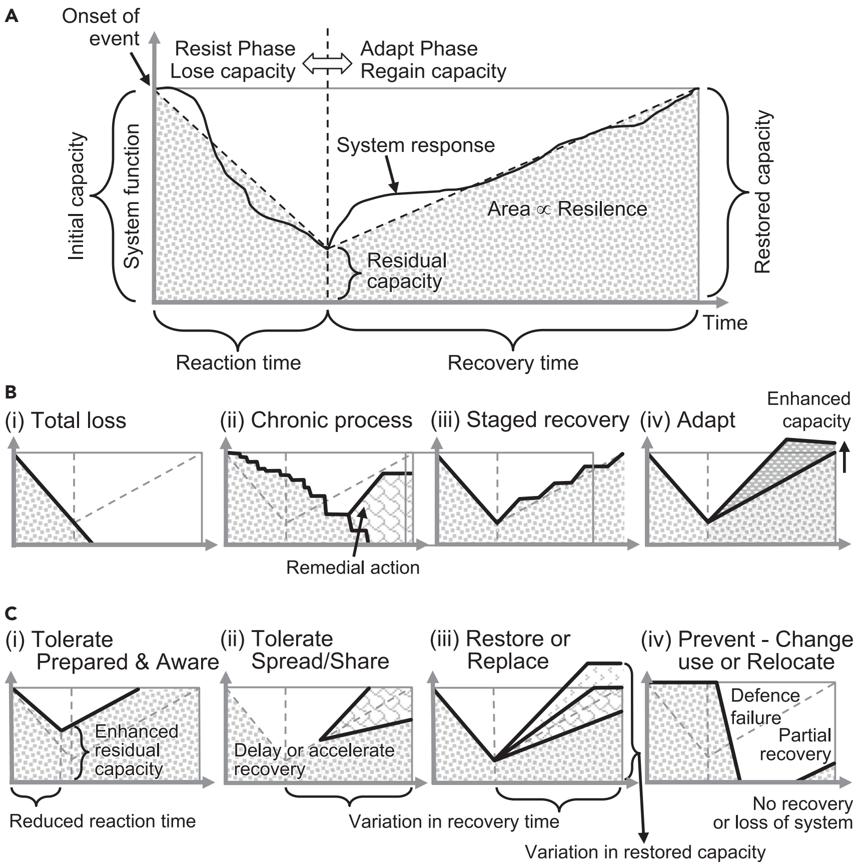


Figure 2. Schematics of different types of system responses

(A) System response to an event that diminishes its functional capacity, including the attributes that contribute to resilience.
(B) Different types (i–iv) of perturbing events.
(C) Response under different (i–iv) adaptation strategies. As discussed in the text, (i) shows adaptation option 2, (ii) shows options 2 and 3, (iii) shows option 6, and (iv) shows options 1 and 5.

one form of state transition. Extreme examples of this include the burial of Pompeii, the much debated flooding of the Black Sea due to the breaching of the sill in the Bosphorus,[59–61] and island abandonment by its community (e.g., Arenstam Gibbons and Nicholls[62]). Such loss of function may be the result of a single event or a progressive or cumulative loss due to successive events (Figure 2B(ii)). A classic example of this is chronic coastal erosion and the loss of entire coastal communities, which have occurred widely around the world.[63–65] Remedial actions, such as relocation or the construction of defenses, may defer or prevent total loss. Alternatively, the response to a major event may be followed by a staged recovery before full functionality can be restored (Figure 2B(iii)). Such a sequence of clean-up, repair, and system modification is often required in the aftermath of major flood events. Responses to events that occur against a background of progressive environmental change (e.g., climate) or changing expectations (e.g., desire to reduce economic damage costs) are often accompanied by attempts to increase the ability to cope with future events via some form of adaptation (Figure 2B(iv)). In the context of hazard risk management, this might include measures such as improved forecasts and warnings, construction of new or improved forms of community protection, or relocation of assets or activities.

Adaptation can modify the loss phase as well as enhance the recovery phase. Cimato and Mullan[66] draw on Burton[67,68] and Burton et al.[67] to identify six high-level adaptation strategies: (1) prevent loss, (2) tolerate loss, (3) spread or share loss, (4) change use or activity, (5) change location, and (6) restoration. Note that these adaptation strategies focus on human actions and interventions. When considering changes in resilience, this means that we are predominantly assessing the response of affected communities.

Different adaptation strategies can similarly be illustrated using schematic cartoons, as shown in Figure 2C. By introducing suitable warning systems or implementing community response plans, it may be possible to reduce the reaction time, and this may also limit the loss of capacity (Figure 2Ci). At a local level, this means developing a community that is both aware and prepared and can take actions to reduce the likely impact. Introducing measures that spread or share loss may enable a faster recovery in some parts of the system but a delayed recovery in other parts (Figure 2C(ii)). For example, having designated areas for flood water storage or providing cyclone evacuation shelters are a means of reducing damage or loss of life. Restoration and recovery (Figure 2C(iii)) will depend on the nature of the lost capacity and the ability of the system to recover naturally. Where interventions are needed, these will predominantly depend on the means available, with wealthy regions being more able to recover quickly, typically enhancing their resilience in the process; this may take longer in poorer regions, where recovery may, in some cases, still result in some loss of capacity. Finally, there is the option to change the exposure of at least those components of the system that can be moved (Figure 2C(iv)). Changing the use may entail limiting development in the hazard zone or moving those most at risk to safer locations. An example might be the case where protection against a hazard (fire, flood, tsunami, volcanic eruption, etc.) fails so that some, or all, of the protected area becomes uninhabitable, and the only options are to change the use of the area or to relocate out of the hazard zone.

The discussion has so far considered a single system (which may encapsulate the compound response of coupled sub-systems) to a single event. Moving to a more complete assessment, there is a need to consider how sub-systems combine and interact over multiple events. This is illustrated in Figure 3 for a system comprising two sub-systems that are exposed to multiple events. For each component, the resilience is plotted over time, and, for this simple example, the compound resilience of the system is

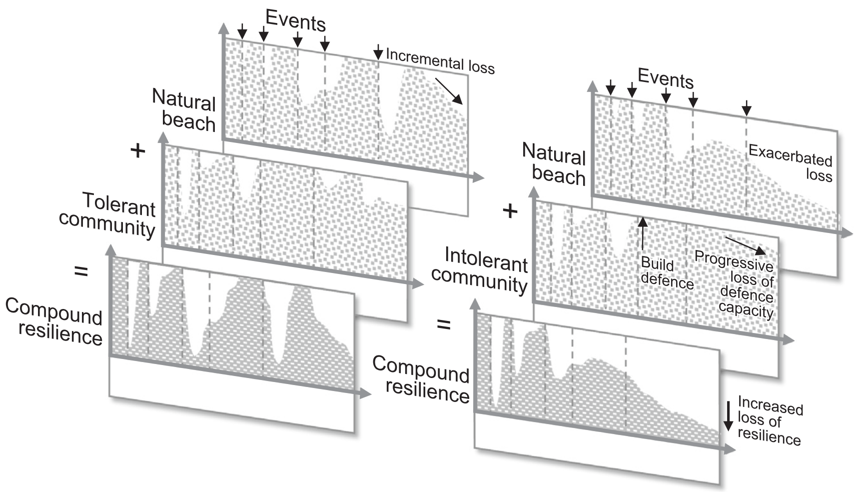


Figure 3. Compound resilience due to sub-system resilience and a series of events
On the left, a community living next to a natural beach suffers losses but can build back and recover from most events. This is contrasted, on the right, with a less tolerant community that decides to build some defenses, which have the knock-on effect of exacerbating the beach loss and so ultimately reducing the overall compound system resilience.

taken to be the summation of the contributions made by the two sub-systems. The example shows a coastal community living near a beach. In the set of plots on the left, the community and beach are affected by events, but they co-exist, so that the compound resilience recovers (although it has not yet done so for the last event, and this may reflect a permanent loss of capacity). By way of contrast, the set of plots on the right shows a less risk-tolerant community that decides to build a defense to limit the impact of flooding when the beach flattens during storm events. To begin with, this greatly enhances the community resilience while limiting the ability of the beach to recover from subsequent storm events. Depending on local factors, such as sediment supply, this may result in continued beach lowering, leading to the ultimate failure of the defense and an even greater loss of compound resilience.

Another aspect of adaptation over time is the likelihood of multiple possible interventions, the need to choose between them, and the likely need for subsequent interventions as conditions continue to change. This introduces the concept of adaptation pathways[10,69,70] and the definition of decision or trigger points[71,72] at which policy changes need to be made. Identification of these allows options to be kept open to await better information, potentially avoiding unnecessary lock-in.[28] This aspect can also be examined by considering the Pareto-optimal set of pathways that maintain future options using some form of real options analysis,[73] although such models need to be interpreted with a degree of care and even skepticism.[74]

The narrative so far has assumed that the essential structure of the system remains unchanged. However, total loss of system function (Figure 2Bi) typically results in the formation of a different system state, which we refer to as a state transition. We consider two types of state transition; namely, "forced" and "managed." The former occurs in response to some natural hazard, whereas the latter is the result of intentional human intervention. The time-varying resilience of a system with various adaptations and subject to both a forced and a managed transition is shown schematically in Figure 4. This brings together the dynamics of the individual system under consideration and the need for the changes for it to operate within its safe space with due account of how this safe space may be affected by other systems. Continuing with our coastal perspective, consider a community living behind a barrier beach and lagoon. A storm event may breach the barrier to form a tidal inlet—a forced transition. Subsequently, the community may decide that they are no longer safe and either relocate inland or implement some form of progressive realignment (or roll-back) of the barriers that entails a further change of state, both being managed transitions. Alternatively, the community might introduce jetties to manage and adapt the inlet sub-system created by the forced transition, this being an adaptation within a given state.

The timescale associated with transition may also vary, reflecting rapid forced or managed changes or the longer-term influence of chronic changes or staged transitions. For this reason, we consider two types of managed transition: (1) directed (and generally relatively rapid), where the changes needed are known and can be planned, and (2) progressive (slower and with greater uncertainty about the endpoint), where there is a need to explore options and work toward acceptance within local communities.[11]

In summary, key aspects of any analysis of resilience are the characteristics of the response to events (resist and recover phases), the frequency of events, the adaptation options available, the thresholds that can trigger forced transitions, and the potential for directed or progressive managed transitions. These all contribute to the system dynamics and must be encapsulated in any aggregate quantitative measure of system resilience.

OPERATIONALIZING A RESILIENCE-BASED APPROACH

As already noted, problem-focused quantitative modeling of system dynamics has been undertaken as one means of operationalizing resilience to inform management decision-making and move from concept to practice.[34,39,75] While predominantly focusing on SESs, this kind of analysis has recently been extended to embrace technological infrastructure systems.[28,58] This approach has the benefit of providing the ability to explore the parameter space and identify which changes may lead to desirable or undesirable outcomes.

In any modeling exercise, inherent uncertainties stem from limits to knowledge, model abstraction, adequacy and accuracy of the data, and user error. Interaction across scales, with the potential for feedback and emergent behavior, can be difficult to identify and/or capture within models.[76] Models of social systems try to capture the agency of the community, typically at a local

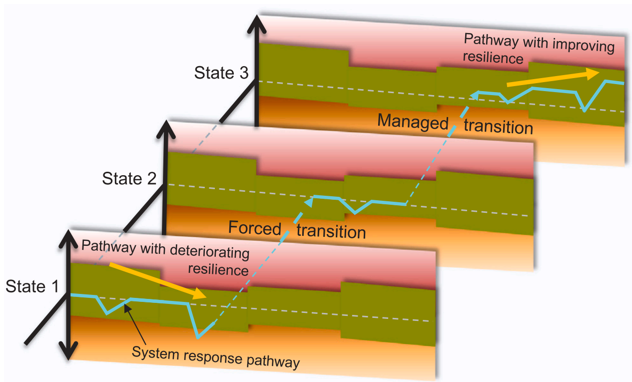


Figure 4. Changing states and the concept of transitions
The light blue line shows the variation of the system function (or capacity) over time, as schematized in Figure 2, superimposed on the time-varying safe space (green zone). As in Figure 1A, the vertical axis represents a measure of overall system state performance relative to some lower threshold (just space) and upper threshold (safe space). The time sequence starts with an initial state, state 1, at which the system is progressively losing capacity and, hence, resilience. The pathway is shown migrating to state 2 following some event that forces a change in state; i.e., a forced transition. This is followed by an intervention, which changes the state of the system to state 3, giving rise to a managed transition. Some examples of the two types of transition and the implications for managing the safe space are given in the text.

scale, and this needs to be linked into the simulation of the environmental and economic system dynamics.[77] However, the fact that these systems can co-evolve means that models also need to have the capacity to adapt or be adapted. As already noted, discipline segmentation has inhibited the development of trans-disciplinary knowledge, suggesting that theory developed to examine world history and social change[37] may offer a way forward. These limitations highlight the extensions needed to broaden the focus from SES, which primarily considers limits on the ecosystem, to one that looks at community resilience in the face of a mix of environmental, social, and economic pressures.

Much thought has been given to the requirements for complex environmental system modeling.[30,76,77] If these models can be used to identify important feedback, system state boundaries, instabilities, and emergent behavior, then this will contribute to a better understanding of how resilience changes and what is and is not resilient. This will necessarily need to capture social interactions between communities, administrations, and their environment (physical, ecological, and economic)[78] to assess unintended consequences and the influence of adaptive behavior.

This provides an extensive research agenda for model development over the coming decades. However, policy-makers are inevitably having to make decisions today with the information currently available. In this context, politics and policy have run ahead and adopted the term "resilience" to the extent that it currently enjoys widespread, albeit vague, use in many policy documents.[11,79] For operational use in policy sectors, resilience needs to be quantified so that, as a minimum, changes in system state can be tracked.[4] One further important requirement is that any metric must be able to capture the cultural traditions that influence perceptions and the value placed on the constituent components of the system, such as landscape, ecology, safety, prosperity, etc.[80]

The multiple dimensions of the systems that we seek to manage mean that there is no single resilience measure. There is also a need to define the context—who or what needs to be resilient in response to what? This sets the overall aim and allows the component systems to be identified. By considering what enhances resilience and what degrades resilience, a set of objectives can be defined and progress in delivering the objective tracked using a suite of performance measures. Policy interventions seek to improve progress toward enhancing resilience and may entail adaptations and transitions (Figure 5).

The performance measures aim to capture the various facets of the system dynamics and their interactions. However, different groups, within or affected by the system, will have differing views on the relative importance of the constituent attributes. This is a problem that is routinely faced by policy-makers, and tools such as multi-criterion analysis provide a means of integrating a complex set of performance measures or metrics. Stakeholder views on the weightings that should be applied can inform an overall index (in this case, a resilience index) and capture the influence of different stakeholder perceptions on the index. Such an approach then provides a quantitative measure of the system state or, with the use of suitable models to examine how the measures change over time, can be used to explore future adaptive pathways.

This type of analysis can be done at a variety of scales reflecting specific interests from local to global. This might be to consider the situation within a country's individual policy sectors. Equally, it might be for nations to establish a shared global measure.

An example of a national sector approach is given in Box 2. This study of the resilience of coastal communities used tools already familiar to policy-makers and illustrated the framework with policy options based on the existing regulatory framework. We believe that this provides an exemplar that can be used across multiple sectors. Integrating multi-sector analyses, identifying the links and feedback, will both improve the understanding of dependencies, which will aid adaptation, and progressively provide a national measure of resilience. The initial focus might be to simply capture the "state of the nation." Such an index, which measures a nation's ability to be able to withstand shocks, recover, and adapt, could then be used alongside other indices, such as the inclusive wealth index, which is an indicator based on stocks rather than flows,[81] to better understand progress toward developing society within a safe operating space. Importantly, the use of SETS models and resilience indices is not mutually exclusive, with the former providing a robust means of developing specific metrics within the framework of a set of metrics that determine the state of resilience in a broader decision-making context.

As already noted, "for what and for whom" is an important consideration when identifying the relevant system components to be considered. Hence, when seeking a regional, national, or global measure of resilience, a similar methodology can be applied but with a different focus. The aim is to ensure that actions, from local to global scale, do not compromise our ability to maintain a safe operating space. The "what" therefore relates to how human activity threatens to exceed the limits of safe space, and the "whom" is humanity. This may seem like a

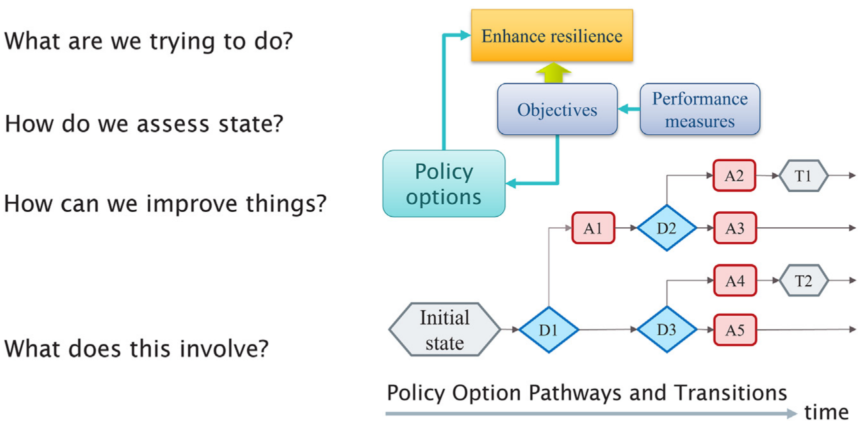


Figure 5. Framework to enhance resilience
Policy response will seek to define pathways that entail decision points (D), adaptations (A), and, in some cases, transitions (T).

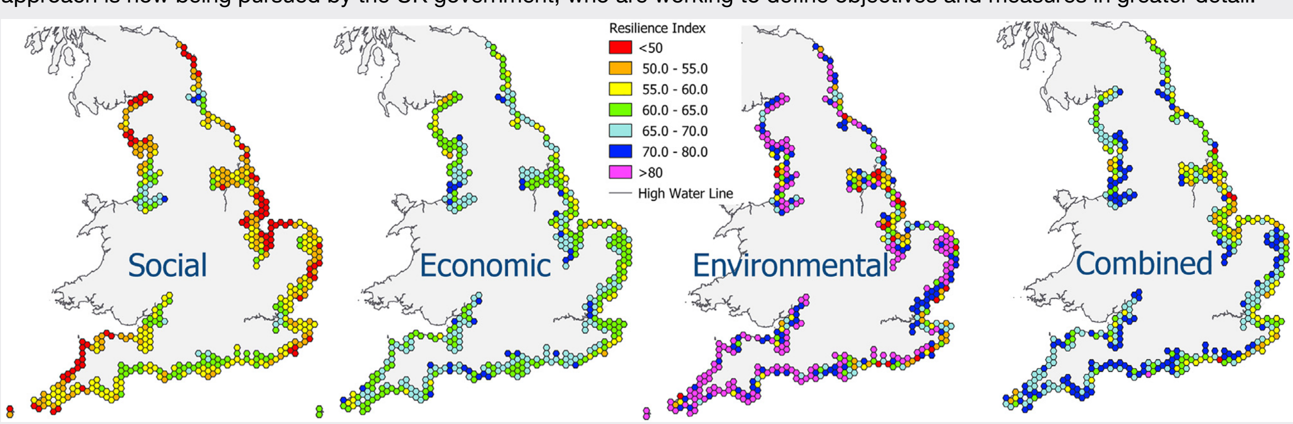
mammoth challenge, but much of what is needed is already in place. The work over the last decade on planetary boundaries provides clear objectives of the sectoral issues that need to be addressed, the evidence to define suitable boundaries, and the current state relative to those boundaries.[19,83] However, this is only part of what is required. The social foundation is the other important determinant of safe space. While, at a national scale, the social makeup that underpins concepts such as doughnut economics[9] are important, at an international scale, the broader objectives defined by the United Nations (UN) Sustainable Development Goals provide a good starting point. Again, following the definition of the goals set by the UN in 2015, much progress has been made, and measures are being developed to provide evidence of that progress.[19,84–89]

We therefore contend that these various measures can be assessed in relation to defined thresholds, or targets, to provide a set of metrics that users can weight and combine to give an overall index of resilience. Thus, the UN might weight the targets with a focus on security and well-being, whereas the World Bank might give greater emphasis to the sustainability of the global economy. To illustrate the concept, we make use of existing compiled datasets[19,88,90] to derive an illustrative resilience index (Box 3; Note S1).

We conclude that the construction of national and global measures of resilience is within our immediate grasp to inform policy,

Box 2. National (England) sectoral example

The agreed aim was to enhance the resilience of coastal communities to flooding and erosion. A set of objectives was developed in consultation with a range of stakeholders, and existing datasets were used to establish performance measures. These were used to define an index of overall coastal system resilience that could be scaled from local (district authority) to national (England) scales.[11] Within a policy context that advocates the enhancement of coastal resilience, the study demonstrated how a quantitative aggregate measure of resilience could be used in an operational CRM for management purposes. The CRM is based on well-established multi-criterion analysis techniques using a set of performance measures to indicate gain or loss of some aspect of resilience. Stakeholder and community agency is provided via the weightings used to combine the performance measures. This means that there is no absolute measure of resilience but, rather, a spectrum that reflects community and decision-maker values/preferences. This allows the trade-offs that are being made locally and nationally to be transparently recognized and explored in greater depth. The figure shows the resilience index (which varies from 0%–100%, where higher values indicate greater resilience) mapped onto 90 km^2 hexagonal units. Contrasting stakeholder perspectives, classified as social, economic, and environmental priorities, are shown reflecting different weightings, with the combined case being their average. The CRM portal allows local stakeholders to explore the influence of different weightings on coastal resilience (https://coastalresilience.uk/crm/), and the approach is now being pursued by the UK government, who are working to define objectives and measures in greater detail.[82]



Box 3. SOSR

Using existing global datasets[18,86,88] of the biophysical limits that contribute to planetary boundaries and the social limits that determine the social foundation, we apply a method similar to the one used to examine coastal resilience (Box 2). Details of the method are provided in Note S1. In brief, we map biophysical and social performance measures to scores on a scale of 0–1. These are then weighted and combined at a national level to give a weighted biophysical and social score. These plot onto a biophysical-social plane, and to obtain a global measure, we use a population-weighted mean for all countries included in the analysis. The figure below shows the weighted biophysical and social scores for 1992 (orange circles) and 2015 (blue circles).

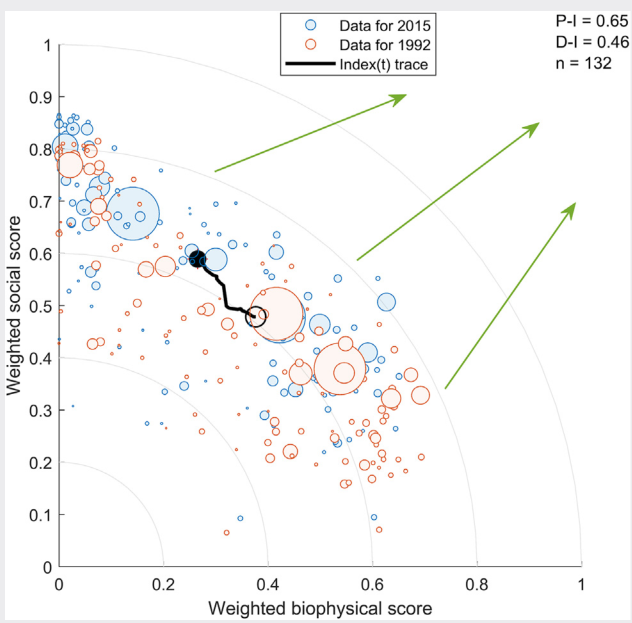
For any given year of analysis, the population-weighted mean for all countries defines an index point, which we take to be a measure of the overall system state; i.e., resilience. This is made up of two parts.

(1) The distance of this point from the origin, which we to refer to as a performance index (PI). A value of 1 or more implies good functional capacity to adapt to change, whereas a value close to 0 suggests limited capacity to adapt. The index has a range from 0 to 1.41 ($\sqrt{2}$).

(2) An angle (θ) about the 45° diagonal, normalized by 45° (i.e., disparity index [DI] = $(\theta - 45)/45$). Points on the 45° diagonal imply that social and biophysical performance are in balance so that one has parity. Hence, the index measures the anomaly from parity. The index has a range ± 1. A positive value indicates that social measures are being achieved to a greater extent than biophysical measures, and a negative value implies the opposite.

The track of the index over this period is shown in the figure, where the open black circle indicates the start position of the index in 1992, and the filled black circle indicates the value of the index in 2015. The size of the circles indicates relative size of the population, and *n* is the number of countries included in the analysis. The green arrows indicate the direction of response needed to improve global resilience.

We stress that this is an illustrative resilience index, as we have used a set of surrogate measures without explicitly determining their contribution to system resilience (see supplemental information). Given a time series of performance measures, the evolution of the index point over time clearly illustrates the progress made on social objectives at the expense of biophysical objectives, as noted by Fanning et al.[86]



including some measure of societal preference (Figure 5). Recent developments to formalize the identification of indicators that support the delivery of the UN Sustainable Development Goals suggest that a more robust framework is starting to emerge.[26] For now, the metrics used are necessarily a mix of direct and indirect measures of performance. However, these measures can be mapped onto established SES[33] and SETS[28] thinking. SETS models open the opportunity to explore a wide range of potential futures, including how sectors may change due to inter-sectoral effects, environmental changes, and sector-specific actions. The underlying models could be used to explore the dynamics associated with alternative development pathways rather than being constrained by having to articulate scenarios.[76] Hence, with suitable development, the outputs of such SETS models will complement and enhance traditional performance measures/indicators and potentially replace them.

Cast in terms of a resilience index, these effects can be integrated to national and supra-national levels and provide a means of "stress testing." This was the approach adopted during the Great Depression in the 1930s, where the need was economic growth, and gross domestic product (GDP) was adopted as the index to guide progress.[91] Since then, GDP has been one of the most influential policy indicators. However, GDP ignores the wider implications of development and provides no information on our resilience or our ability to live within the planet's safe operating space. A resilience index would be much more appropriate for the modern age.

Conclusions

Resilience is a powerful integrated concept with which to analyze and manage the complex SETSs in which we live. A resilience index provides a tool that is of immediate use to policy-makers and can help inform the public of progress while also establishing a clear research agenda to improve the basis on which resilience is measured. A consistent approach across policy sectors would enable integration to define a national index. The national data and indices might then feed into a global assessment, although, in the short term, it is more likely that global datasets will form the basis of a global index, as we have illustrated (Box 3). Such an index could then be used by supra-national institutions to explore pathways and monitor progress as they develop policies to sustain a healthy planet. As resilience is not absolute and depends on the evolving context, what constitutes resilience is likely to evolve, and what we measure may also need to change with time. Similarly, societal preferences and weights are also likely to evolve with time and understanding. Consequently, any resilience index must itself be viewed as an adaptive property of the systems it is used to monitor.

To implement the approach outlined, there is a need for research and policy action to

(1) define a set of measures that capture societal resilience within a global safe operating space,
(2) collate consistent national data to provide a global dataset,
(3) test the suitability of different scaling functions,
(4) capture the preferences of different stakeholder groups,
(5) use historical data to understand past performance and update the resilience indices (and possibly their component measures) on a regular (annual) basis, and
(6) promote understanding of the interpretation, meaning, and appropriate use of resilience indices.

The transformative change that we propose is for all levels of government to start measuring things more comprehensively. We seek a move away from the focus on GDP to measures that reflect the complexity of life on our planet—a measure that tracks the challenges we face to meet societal needs and recognizes that these are inextricably linked to the needs of all life on earth. While the approach we have outlined needs further development, we hope that our perspective contributes to an urgently needed conversation on how to mobilize a global change in outlook.

RESOURCE AVAILABILITY

Lead contact

The lead contact is Ian Townend (i.townend@soton.ac.uk).

Materials availability

This study did not generate new unique materials.

Data and code availability

Further information about the Coastal Resilience Model is available at https://coastalmonitoring.org/ccoresources/coastalres/. The national coastal resilience model (CRM) datasets can be accessed at https://coastalresilience.uk/crm/. The data for the safe operating space resilience (SOSR) model are available from the cited papers.[19,88,90] The MATLAB code used to read the files and generate the SOSR plots is available from https://github.com/CoastalSEA/Resilience.

ACKNOWLEDGMENTS

This work is a follow-on from a project supported by the Strategic Priorities Fund, UK Climate Resilience Programme, through a UK Research & Innovation award (NE/S016651/1).

AUTHOR CONTRIBUTIONS

All authors contributed to the conceptual thinking that underpins the paper. I.T. produced the initial draft, which was then developed by all authors.

DECLARATION OF INTERESTS

The authors declare no competing interests.

SUPPLEMENTAL INFORMATION

Supplemental information can be found online at https://doi.org/10.1016/j.oneear.2024.09.008.

REFERENCES

1. World Bank (2021). Toward a Holistic Approach to Sustainable Development: A Guide to Integrated Land-Use Initiatives (World Bank). http://hdl.handle.net/10986/36139.
2. Lü, Y., Lü, D., Gao, G., and Fu, B. (2021). A holistic framework for facilitating environmental and human health. Geography and Sustainability *2*, 298–303. https://doi.org/10.1016/j.geosus.2021.12.001.
3. Turner II, B.L. (2010). Vulnerability and resilience: Coalescing or paralleling approaches for sustainability science? Global Environ. Change *20*, 570–576. https://doi.org/10.1016/j.gloenvcha.2010.07.003.
4. Pimm, S.L., Donohue, I., Montoya, J.M., and Loreau, M. (2019). Measuring resilience is essential if we are to understand it. Nat. Sustain. *2*, 895–897. https://doi.org/10.1038/s41893-019-0399-7.
5. Hosseini, S., Barker, K., and Ramirez-Marquez, J.E. (2016). A review of definitions and measures of system resilience. Reliab. Eng. Syst. Saf. *145*, 47–61. https://doi.org/10.1016/j.ress.2015.08.006.
6. Linkov, I., Bridges, T., Creutzig, F., Decker, J., Fox-Lent, C., Kröger, W., Lambert, J.H., Levermann, A., Montreuil, B., Nathwani, J., et al. (2014). Changing the resilience paradigm. Nat. Clim. Change *4*, 407–409. https://doi.org/10.1038/nclimate2227.
7. UNISDR (2009). Terminology on Disaster Risk Reduction (United Nations Office for Disaster Risk Reduction (UNDRR)). https://www.undrr.org/publication/2009-unisdr-terminology-disaster-risk-reduction.
8. Rockström, J., Steffen, W., Noone, K., Persson, Å., Chapin, F.S., Lambin, E.F., Lenton, T.M., Scheffer, M., Folke, C., Schellnhuber, H.J., et al. (2009). A safe operating space for humanity. Nature *461*, 472–475. https://doi.org/10.1038/461472a.
9. Raworth, K. (2017). Doughnut Economics: Seven Ways to Think like a 21st Century Economist (Penguin Random House).
10. Haasnoot, M., Kwakkel, J.H., Walker, W.E., and ter Maat, J. (2013). Dynamic adaptive policy pathways: A method for crafting robust decisions for a deeply uncertain world. Global Environ. Change *23*, 485–498. https://doi.org/10.1016/j.gloenvcha.2012.12.006.
11. Townend, B.I.H., French, J.R., Nicholls, R.J., Brown, S., Carpenter, S., Haigh, I.D., Hill, C.T., Lazarus, E., Penning-Rowsell, E.C., Thompson, C.E.L., and Tompkins, E.L. (2021). Operationalising coastal resilience to flood and erosion hazard: A demonstration for England. Sci. Total Environ. *783*, 146880. https://doi.org/10.1016/j.scitotenv.2021.146880.
12. von Bertalanffy, L. (1968). General System Theory: foundations, Development, Applications (George Braziller).

13. Odum, H.T., and Odum, E.C. (2000). Modelling for All Scales: An Introduction to System Simulation (Academic Press).
14. Meadows, D., Randers, J., and Meadows, D. (2004). Limits to Growth: The 30 year Update (Earthscan).
15. Meadows, D., Meadows, D., Randers, J., and Behrens, I.I.I.,W. (1972). The Limits to Growth (University Books)).
16. Cole, H.S.D., Freeman, C.J.M., and Pavitt, K.L.R. (1973). Models of Doom : A Critique of the Limits to Growth, 1st Edition (Universe Publishing)).
17. Simon, J. (1981). The Ultimate Resource (Princeton University Press).
18. Crutzen, P.J. (2002). Geology of mankind. Nature *415*, 23. https://doi.org/10.1038/415023a.
19. O'Neill, D.W., Fanning, A.L., Lamb, W.F., and Steinberger, J.K. (2018). A good life for all within planetary boundaries. Nat. Sustain. *1*, 88–95. https://doi.org/10.1038/s41893-018-0021-4.
20. Steffen, W., Richardson, K., Rockström, J., Cornell, S.E., Fetzer, I., Bennett, E.M., Biggs, R., Carpenter, S.R., de Vries, W., de Wit, C.A., et al. (2015). Sustainability. Planetary boundaries: guiding human development on a changing planet. Science *347*, 1259855. https://doi.org/10.1126/science.1259855.
21. Steffen, W., Crutzen, J., and Mcneill, J.R. (2007). The Anthropocene: Are Humans Now Overwhelming the Great Forces of Nature. Ambio *36*, 614–621. https://doi.org/10.1579/0044-7447(2007)36[614:taahno]2.0.co;2.
22. Baste, I.A., Watson, R.T., Brauman, K.I., Samper, C., and Walzer, C. (2021). Making Peace with Nature: A Scientific Blueprint to Tackle the Climate, Biodiversity and Pollution Emergencies (United Nations Environment Programme).
23. Solomon, S., Ivy, D.J., Kinnison, D., Mills, M.J., Neely, R.R., and Schmidt, A. (2016). Emergence of healing in the Antarctic ozone layer. Science *353*, 269–274. https://doi.org/10.1126/science.aae0061.
24. Rosling, H., Rosling, O., and Rosling Rönnlund, A. (2018). Factfulness: Ten Reasons We're Wrong About the World–and Why Things Are Better Than You Think (Flatiron Books).
25. Gupta, J., Liverman, D., Prodani, K., Aldunce, P., Bai, X., Broadgate, W., Ciobanu, D., Gifford, L., Gordon, C., Hurlbert, M., et al. (2023). Earth system justice needed to identify and live within Earth system boundaries. Nat. Sustain. *6*, 630–638. https://doi.org/10.1038/s41893-023-01064-1.
26. Plag, H.-P., and Jules-Plag, S.-A. (2019). A goal-based approach to the identification of essential transformation variables in support of the implementation of the 2030 agenda for sustainable development. International Journal of Digital Earth *13*, 166–187. https://doi.org/10.1080/17538947.2018.1561761.
27. Berlin, I. (1951). The Hedgehog and the Fox (Weidenfeld & Nicolson).
28. Markolf, S.A., Chester, M.V., Eisenberg, D.A., Iwaniec, D.M., Davidson, C.I., Zimmerman, R., Miller, T.R., Ruddell, B.L., and Chang, H. (2018). Interdependent Infrastructure as Linked Social, Ecological, and Technological Systems (SETSs) to Address Lock-in and Enhance Resilience. Earth's Future *6*, 1638–1659. https://doi.org/10.1029/2018ef000926.
29. Sharifi, A. (2023). Resilience of urban social-ecological-technological systems (SETS): A review. Sustain. Cities Soc. *99*, 104910. https://doi.org/10.1016/j.scs.2023.104910.
30. Schlüter, M., Mcallister, R.R.J., Arlinghaus, R., Bunnefeld, N., Eisenack, K., Hölker, F., Milner-Gulland, E.J., Müller, B., Nicholson, E., Quaas, M., and Stöven, M. (2012). New horizons for managing the environment: a review of coupled social-ecological systems modelling. Nat. Resour. Model. *25*, 219–272. https://doi.org/10.1111/j.1939-7445.2011.00108.x.
31. Levin, S., Xepapadeas, T., Crépin, A.-S., Norberg, J., de Zeeuw, A., Folke, C., Hughes, T., Arrow, K., Barrett, S., Daily, G., et al. (2012). Social-ecological systems as complex adaptive systems: modeling and policy implications. Environ. Dev. Econ. *18*, 111–132. https://doi.org/10.1017/s1355770x12000460.
32. Cooper, G.S., and Dearing, J.A. (2019). Modelling future safe and just operating spaces in regional social-ecological systems. Sci. Total Environ. *651*, 2105–2117. https://doi.org/10.1016/j.scitotenv.2018.10.118.
33. Dearing, J.A., Wang, R., Zhang, K., Dyke, J.G., Haberl, H., Hossain, M.S., Langdon, P.G., Lenton, T.M., Raworth, K., Brown, S., et al. (2014). Safe and just operating spaces for regional social-ecological systems. Global Environ. Change *28*, 227–238. https://doi.org/10.1016/j.gloenvcha.2014.06.012.
34. Hossain, M.S., Dearing, J.A., Eigenbrod, F., and Johnson, F.A. (2017). Operationalizing safe operating space for regional social-ecological systems. Sci. Total Environ. *584–585*, 673–682. https://doi.org/10.1016/j.scitotenv.2017.01.095.
35. Forrester, J.W. (1968). Principles of Systems (Wright-Allen Press).
36. Van Der Leeuw, S., Costanza, R., Aulenbach, S., Brewer, S., Burek, M., Cornell, S., Crumley, C., Dearing, J.A., Downy, C., Graumlich, L.J., et al. (2011). Toward an Integrated History to Guide the Future. Ecol. Soc. *16*, art2. https://doi.org/10.5751/es-04341-160402.
37. Wallerstein, I. (2004). World Systems Analysis: An Introduction (Duke University Press).
38. Anderies, J.M., Janssen, M.A., and Ostrom, E. (2004). A framework to analyze the robustness of social-ecological systems from an institutional perspective. Ecol. Soc. *9*, 18. http://www.ecologyandsociety.org/vol9/iss1/art18/.
39. Mumby, P.J., Wolff, N.H., Bozec, Y.-M., Chollett, I., and Halloran, P. (2014). Operationalizing the Resilience of Coral Reefs in an Era of Climate Change. Conservation Letters *7*, 176–187. https://doi.org/10.1111/conl.12047.
40. Turner, B.L., 2nd, Kasperson, R.E., Matson, P.A., Mccarthy, J.J., Corell, R.W., Christensen, L., Eckley, N., Kasperson, J.X., Luers, A., Martello, M.L., et al. (2003). A framework for vulnerability analysis in sustainability science. Proc. Natl. Acad. Sci. USA *100*, 8074–8079. https://doi.org/10.1073/pnas.1231335100.
41. Mumby, P.J., Chollett, I., Bozec, Y.-M., and Wolff, N.H. (2014). Ecological resilience, robustness and vulnerability: how do these concepts benefit ecosystem management? Curr. Opin. Environ. Sustain. *7*, 22–27. https://doi.org/10.1016/j.cosust.2013.11.021.
42. Alexander, D.E. (2013). Resilience and disaster risk reduction: an etymological journey. Nat. Hazards Earth Syst. Sci. *13*, 2707–2716. https://doi.org/10.5194/nhess-13-2707-2013.
43. Holling, C.S. (1973). Resilience and Stability of Ecological Systems. Annu. Rev. Ecol. Systemat. *4*, 1–23.
44. von Bertalanffy, L. (1950). The theory of open systems in physics and biology. Science (New York, N.Y.) *111*, 23–29. https://doi.org/10.1126/science.111.2872.23.
45. Paton, D., Smith, L., and Violanti, J. (2000). Disaster response: risk, vulnerability and resilience. Disaster Prev. Manag. *9*, 173–180. https://doi.org/10.1108/09653560010335068.
46. Adger, W.N. (2000). Social and ecological resilience: are they related? Prog. Hum. Geogr. *24*, 347–364. https://doi.org/10.1191/030913200701540465.
47. Chang, S.E., and Shinozuka, M. (2004). Measuring Improvements in the Disaster Resilience of Communities. Earthq. Spectra *20*, 739–755. https://doi.org/10.1193/1.1775796.
48. Cimellaro, G.P., Reinhorn, A.M., and Bruneau, M. (2010). Framework for analytical quantification of disaster resilience. Eng. Struct. *32*, 3639–3649. https://doi.org/10.1016/j.engstruct.2010.08.008.
49. Munoz, A., and Dunbar, M. (2015). On the quantification of operational supply chain resilience. Int. J. Prod. Res. *53*, 6736–6751. https://doi.org/10.1080/00207543.2015.1057296.
50. Bie, Z., Lin, Y., Li, G., and Li, F. (2017). Battling the Extreme: A Study on the Power System Resilience. Proc. IEEE *105*, 1253–1266. https://doi.org/10.1109/jproc.2017.2679040.
51. Ganin, A.A., Massaro, E., Gutfraind, A., Steen, N., Keisler, J.M., Kott, A., Mangoubi, R., and Linkov, I. (2016). Operational resilience: concepts, design and analysis. Sci. Rep. *6*, 19540. https://doi.org/10.1038/srep19540.
52. Xu, L., Marinova, D., and Guo, X. (2014). Resilience thinking: a renewed system approach for sustainability science. Sustain. Sci. *10*, 123–138. https://doi.org/10.1007/s11625-014-0274-4.
53. Mori, A.S., Furukawa, T., and Sasaki, T. (2013). Response diversity determines the resilience of ecosystems to environmental change. Biol. Rev. *88*, 349–364. https://doi.org/10.1111/brv.12004.
54. Acemoglu, D., Ozdaglar, A., and Tahbaz-Salehi, A. (2015). Systemic Risk and Stability in Financial Networks. Am. Econ. Rev. *105*, 564–608. https://doi.org/10.1257/aer.20130456.
55. Haldane, A.G., and May, R.M. (2011). Systemic risk in banking ecosystems. Nature *469*, 351–355. https://doi.org/10.1038/nature09659.
56. Rosati, J.D., Touzinsky, K.F., and Lillycrop, W.J. (2015). Quantifying coastal system resilience for the US Army Corps of Engineers. Environ. Syst. Decis. *35*, 196–208. https://doi.org/10.1007/s10669-015-9548-3.
57. Rittel, H.W.J., and Webber, M.M. (1973). Dilemmas in general theory of planning. Pol. Sci. *4*, 155–169.
58. McPhearson, T., Cook, E.M., Berbés-Blázquez, M., Cheng, C., Grimm, N.B., Andersson, E., Barbosa, O., Chandler, D.G., Chang, H., Chester, M.V., et al. (2022). A social-ecological-technological systems framework for urban ecosystem services. One Earth *5*, 505–518. https://doi.org/10.1016/j.oneear.2022.04.007.

59. Ryan, W.B., Pitman, W.C., Major, C.O., Shimkus, K., Moskalenko, V., Jones, G.A., Dimitrov, P., Gorür, N., Sakinç, M., and Yüce, H. (1997). An abrupt drowning of the Black Sea shelf. Mar. Geol. *138*, 119–126. https://doi.org/10.1016/S0025-3227(97)00007-8.

60. Siddall, M., Pratt, L.J., Helfrich, K.R., and Giosan, L. (2004). Testing the physical oceanographic implications of the suggested sudden Black Sea infill 8400 years ago. Paleoceanography *19*, n/a-n/a. https://doi.org/10.1029/2003pa000903.

61. Yanchilina, A.G., Ryan, W.B., McManus, J.F., Dimitrov, P., Dimitrov, D., Slavova, K., and Filipova-Marinova, M. (2017). Compilation of geophysical, geochronological, and geochemical evidence indicates a rapid Mediterranean-derived submergence of the Black Sea's shelf and subsequent substantial salinification in the early Holocene. Mar. Geol. *383*, 14–34. https://doi.org/10.1016/j.margeo.2016.11.001.

62. Arenstam Gibbons, S.J., and Nicholls, R.J. (2006). Island abandonment and sea-level rise: An historical analog from the Chesapeake Bay, USA. Global Environ. Change *16*, 40–47. https://doi.org/10.1016/j.gloenvcha.2005.10.002.

63. Sear, D.A., Bacon, S.R., Murdock, A., Doneghan, G., Baggaley, P., Serra, C., and LeBas, T.P. (2011). Cartographic, Geophysical and Diver Surveys of the Medieval Town Site at Dunwich, Suffolk, England. Int. J. Naut. Archaeol. *40*, 113–132. https://doi.org/10.1111/j.1095-9270.2010.00275.x.

64. Ashton, W. (1920). The Evolution of a Coast-Line: Barrow to Aberyst-Wyth and the Isle of Man, with Notes on Lost Towns, Submarine Discoveries, Etc, Forgotten Books Edition (Edward Stanford Ltd).

65. Griggs, G.B. (2015). Lost Neighborhoods of the California Coast. J. Coast Res. *31*, 129. https://doi.org/10.2112/13a-00007.1.

66. Cimato, F., and Mullan, M. (2010). Adapting to Climate Change: Analysing the Role of Government. 2010. Paper 1. https://www.gov.uk/government/publications/adapting-to-climate-change-analysing-the-role-of-government.

67. Burton, I. (1996). The growth of adaptation capacity: practice and policy. In Adapting to Climate Change: An International Perspective, J. Smith, N. Bhatti, G. Menzhulin, R. Benioff, M.I. Budyko, M. Campos, B. Jallow, and F. Rijsberman, eds. (Springer- Verlag).

68. Burton, I., Challenger, B., Huq, S., Klein, R.J.T., and Yohe, G.W. (2001). Adaptation to Climate Change in the Context of Sustainable Development and Equity, pp. 877–912.

69. Ranger, N., Reeder, T., and Lowe, J. (2013). Addressing 'deep' uncertainty over long-term climate in major infrastructure projects: four innovations of the Thames Estuary 2100 Project. EURO Journal on Decision Processes *1*, 233–262. https://doi.org/10.1007/s40070-013-0014-5.

70. Schlumberger, J., Haasnoot, M., de Ruiter, M., and Aerts, J.C.J.H. (2022). Towards a Disaster Risk Management Pathways Framework for Complex and Dynamic Multi-Risk: DAPP-MR. SSRN Journal, 105219. https://doi.org/10.2139/ssrn.4164233.

71. Stephens, S.A., Bell, R.G., and Lawrence, J. (2018). Developing signals to trigger adaptation to sea-level rise. Environ. Res. Lett. *13*, 104004. https://doi.org/10.1088/1748-9326/aadf96.

72. Kingsborough, A., Borgomeo, E., and Hall, J.W. (2016). Adaptation pathways in practice: Mapping options and trade-offs for London's water resources. Sustain. Cities Soc. *27*, 386–397. https://doi.org/10.1016/j.scs.2016.08.013.

73. Woodward, M., Gouldby, B., Kapelan, Z., Khu, S.-T., and Townend, I. (2011). Real options in flood risk management decision making. J. Flood Risk Manag. *4*, 339–349. https://doi.org/10.1111/j.1753-318X.2011.01119.x.

74. Kay, J., and King, M. (2020). Radical Uncertainty: Decision making for an unknowable future (The Bridge Street Press).

75. Grafton, R.Q., Doyen, L., Béné, C., Borgomeo, E., Brooks, K., Chu, L., Cumming, G.S., Dixon, J., Dovers, S., Garrick, D., et al. (2019). Realizing resilience for decision-making. Nat. Sustain. *2*, 907–913. https://doi.org/10.1038/s41893-019-0376-1.

76. Verburg, P.H., Dearing, J.A., Dyke, J.G., Leeuw, S.v.d., Seitzinger, S., Steffen, W., and Syvitski, J. (2016). Methods and approaches to modelling the Anthropocene. Global Environ. Change *39*, 328–340. https://doi.org/10.1016/j.gloenvcha.2015.08.007.

77. Bai, X., van der Leeuw, S., O'Brien, K., Berkhout, F., Biermann, F., Brondizio, E.S., Cudennec, C., Dearing, J., Duraiappah, A., Glaser, M., et al. (2016). Plausible and desirable futures in the Anthropocene: A new research agenda. Global Environ. Change *39*, 351–362. https://doi.org/10.1016/j.gloenvcha.2015.09.017.

78. Harms, W. (2011). Evolutionary Games and the Modeling of Complex Systems. In Philosophy of Complex Systems, pp. 163–176. https://doi.org/10.1016/b978-0-444-52076-0.50005-5.

79. Brown, S., Tompkins, E.L., Suckall, N., French, J., Haigh, I.D., Lazarus, E., Nicholls, R.J., Penning-Rowsell, E.C., Thompson, C.E.L., Townend, I., and van der Plank, S. (2023). Transitions in modes of coastal adaptation: addressing blight, engagement and sustainability. Front. Mar. Sci. *10*, 1153134. https://doi.org/10.3389/fmars.2023.1153134.

80. Glaser, M., and Glaeser, B. (2014). Towards a framework for cross-scale and multi-level analysis of coastal and marine social-ecological systems dynamics. Reg. Environ. Change *14*, 2039–2052. https://doi.org/10.1007/s10113-014-0637-5.

81. UNEP (2012). Inclusive wealth report 2012 : measuring progress toward sustainability. UNU-IHDP and UNEP. 2012, 9781107032316 (hbk) *336*.

82. Ngai, R., E, B., High, H., Dale, A., Trewhella, S., and Nicholls, R. (2022). Measuring Reslience of Flooding and Coastal Erosion (Environment Agency). https://assets.publishing.service.gov.uk/media/636d2124e90e07618db6e570/FRS20288_Measuring_resilience_to_flooding_and_coastal_erosion_-_report_v2.pdf.

83. Persson, L., Carney Almroth, B.M., Collins, C.D., Cornell, S., de Wit, C.A., Diamond, M.L., Fantke, P., Hassellöv, M., MacLeod, M., Ryberg, M.W., et al. (2022). Outside the Safe Operating Space of the Planetary Boundary for Novel Entities. Environ. Sci. Technol. *56*, 1510–1521. https://doi.org/10.1021/acs.est.1c04158.

84. Avtar, R., Aggarwal, R., Kharrazi, A., Kumar, P., and Kurniawan, T.A. (2019). Utilizing geospatial information to implement SDGs and monitor their Progress. Environ. Monit. Assess. *192*, 35. https://doi.org/10.1007/s10661-019-7996-9.

85. Fuldauer, L.I., Thacker, S., Haggis, R.A., Fuso-Nerini, F., Nicholls, R.J., and Hall, J.W. (2022). Targeting climate adaptation to safeguard and advance the Sustainable Development Goals. Nat. Commun. *13*, 3579. https://doi.org/10.1038/s41467-022-31202-w.

86. O'Neill, D.W. (2015). The proximity of nations to a socially sustainable steady-state economy. J. Clean. Prod. *108*, 1213–1231. https://doi.org/10.1016/j.jclepro.2015.07.116.

87. Roser, M.; Our World in Data team (2023). SDG Tracker: Measuring progress towards the Sustainable Development Goals. Our World in Data. https://ourworldindata.org/sdgs.

88. Fanning, A.L., O'Neill, D.W., Hickel, J., and Roux, N. (2021). The social shortfall and ecological overshoot of nations. Nat. Sustain. *5*, 26–36. https://doi.org/10.1038/s41893-021-00799-z.

89. Jackson, J.C., and Medvedev, D. (2024). Worldwide divergence of values. Nat. Commun. *15*, 2650. https://doi.org/10.1038/s41467-024-46581-5.

90. Gapminder (2022). Gapminder - Population v7 and other sources – with major processing by Our World in Data. https://ourworldindata.org/grapher/population.

91. Kuznets, S. (1934). National Income, 1929–1932 (Natioin Bureau of Economic Research).