Trends in Ecology & Evolution

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Review

Unifying Research on Social–Ecological Resilience and Collapse

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Ecosystems influence human societies, leading people to manage ecosystems for human benefit. Poor environmental management can lead to reduced ecological resilience and social–ecological collapse. We review research on resilience and collapse across different systems and propose a unifying social–ecological framework based on (i) a clear definition of system identity; (ii) the use of quantitative thresholds to define collapse; (iii) relating collapse processes to system structure; and (iv) explicit comparison of alternative hypotheses and models of collapse. Analysis of 17 representative cases identified 14 mechanisms, in five classes, that explain social–ecological collapse. System structure influences the kind of collapse a system may experience. Mechanistic theories of collapse that unite structure and process can make fundamental contributions to solving global environmental problems.

Trends

As social–ecological systems enter a period of rapid global change, science must predict and explain 'unthinkable' social, ecological, and social–ecological collapses.

Existing theories of collapse are weakly integrated with resilience theory and ideas about vulnerability and sustainability.

Mechanisms of collapse are poorly understood and often heavily contested. Progress in understanding collapse requires greater clarity on system identity and alternative causes of collapse.

Archaeological theories have focused on a limited range of reasons for system collapse. In resilience theory, the adaptive cycle has been used to describe collapse but offers little insight into the mechanisms that cause it.

Theories of collapse should connect structure and process. Mechanistic, structure–process–function theories of collapse suggest new avenues for understanding and improving resilience.

Sustainability Science and Collapse

Ecology and human use of ecosystems meet in sustainability science, which seeks to understand the structure and function of social–ecological systems and to build a sustainable and equitable future [1]. Sustainability science has been built on three main streams of research. The first stream has focused on limits to growth and the actual or potential overshoot of environmental limits by societies [2–4]. The second has dealt with adaptation, innovation, and the ability of humanity to transform our environment [1,5,6]. The third has used complex systems theory, including the concepts of resilience, robustness, and vulnerability, to explore ideas of alternate pathways, regime shifts, and transformation [7–10]. These streams have, respectively, proposed to address environmental crises by aligning human civilization more effectively with ecological processes (e.g., greening cities, reducing consumption, setting aside more of the earth's surface for nature, and reducing agricultural impacts on biodiversity) [11–14]; geoengineering and ecological engineering of the Earth system to make or keep it suitable for human civilization [15,16]; and transforming society to create a more equitable, just world that has greater capacity for adaptation and environmental problem solving [17].

All three streams of sustainability research are interested in collapse. Most research disregards the potential for a single apocalyptic collapse and focuses instead on the smaller but potentially interacting collapses in different realms that have been observed throughout history [18,19]. Collapses have been identified in many types of complex system, including ecosystems as well as human-created systems such as markets, power grids, and agricultural systems. These collapses often have substantial negative consequences for people [20–22]. Analysis of collapse has generally focused on the properties of systems that collapse rather than the properties of the perturbations, which are often rare and difficult to predict.

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The exponential growth of the global economy is deepening humanity's use and modification of Earth's ecosystems [23]; globalization is creating ever-tighter connections between distant places [24]; and both cultural and ecological diversity are declining [25]. As the world moves deeper into the Anthropocene, new types of shock can be expected to challenge Earth's increasingly complex and interconnected social–ecological systems in new and surprising ways [19]. Finding ways of avoiding, anticipating, and reducing the negative impacts of collapses in social–ecological systems should therefore be central to both sustainability science and ecology [1,26,27].

Collapse and Resilience

Collapse and resilience are two sides of the same coin; collapse occurs when resilience is lost, and resilient systems are less likely to collapse. Resilience research has focused on thresholds, regime shifts, and abrupt changes in social–ecological systems [9,28]. In the past decade, an increasing variety of models and statistical techniques has been developed to warn of loss of resilience [29]. Some approaches, such as the measurement of changes in variance [28,29] or network properties [30], can be generalized beyond individual cases and may have relevance to societies as well as to ecosystems [31]. However, early warning signals may not be detected while collapse can still be avoided [32], and some types of collapse are fundamentally unpredictable [33]. With the exceptions of a few historical analyses [22,34–36] and some research on social–ecological traps and Holling's adaptive cycle [21,37–39], collapse has received relatively little attention in the sustainability literature; the focus of most researchers is on enhancing resilience rather than understanding collapse, a situation that has been termed an 'unnecessary dichotomy' [40]. Collapse remains a common feature of popular discussions of sustainability and in representations of the future in popular media [41], but the field lacks a cohesive analytical framework and its relationship to resilience is poorly defined. We propose that bringing together research on collapse and resilience requires four advances: a clearer definition of what is collapsing; the use of quantitative thresholds to define collapse; a shift in focus from 'how' systems collapse to 'why', through contrasting alternative mechanisms and hypotheses; and connecting collapse-related processes to system structure.

What Is 'Collapse'?

Before proposing a new framework for collapse, we (i) review how 'collapse' has been defined and used by others; (ii) define our own usage; and (iii) clarify how our working definition of collapse relates to other terms that address closely related phenomena.

Previous Definitions

A typical dictionary definition of collapse ('fall suddenly down or in; give way' [42]) has three elements: a change in structure, the implication that such a change has happened relatively fast, and the implication that something undesirable (or at least, destructive) has occurred. The same elements apply to definitions of collapse in societies, economies, and ecosystems, but there is considerable ambiguity on each point. For instance, the questions of how much and what kind of change constitutes a collapse, whether fast and slow changes both qualify as 'collapse', and whether collapse must have a normative dimension (and if so, then who decides on that dimension, since it may depend on perspective) are all contested [36].

Collapse has been defined and used in a variety of ways. Tainter [22,43] defined societal collapse as 'rapid loss of an established level of social, political, and/or economic complexity'. Most subsequent definitions have retained 'complexity', while adding complementary variables. For instance, Diamond [34] defined collapse as 'a drastic decrease in human population numbers and/or in political, economic, or social complexity'. Renfrew [44] viewed collapse as including loss or near-loss of central administration, the elite, and a centralized economy;

settlement shift; and population decline. Weiss and Bradley [45] stated that past collapses 'frequently involved regional abandonment, replacement of one subsistence base by another (such as agriculture by pastoralism) or conversion to a lower energy sociopolitical organization (such as local state from interregional empire)'. Hanson [46] ignored societal structure and instead defined 'social collapse' as a postdisruption reduction in productivity that is out of proportion to the disruption. Others have argued that collapse is best understood as the fragmentation of a particular political apparatus [40]. Importantly, loss of complexity does not necessarily imply collapse; political systems may reorganize in ways that reduce complexity while maintaining their identity. It has been proposed, for example, that Byzantium successfully simplified to avoid collapse [47].

In ecology, collapse is used to describe situations in which losses of species (locally or globally) and related changes in ecosystem biomass, nutrient cycles, carrying capacity, and function occur [48–50]. It is also applied to long-term reductions in the size and productivity of a single population, for example, in marine fisheries [51–53]. Population collapses may be accompanied by changes in complexity, such as a reduction in the number of trophic levels in a food web or a decline in food chain length [54], but a reduction in system complexity is not inevitable following the collapse of one population, particularly if substitution occurs (e.g., another top predator fills the vacant niche). Ecosystem collapse is often equated with shifts between alternate regimes, such as between savanna and desert in the Sahel of West Africa [9,55] or from forest to non-forest [56]. As with population collapses, shifts between regimes are often linked with changes in complexity, but not inevitably so. For example, phosphorus-driven shifts in shallow lakes from clear water to turbid regimes are likely to be accompanied by a decline in ecosystem service provision (e.g., water is no longer good for drinking or swimming; increases in undesirable fish populations) and might be viewed as collapses by human managers, but do not necessarily involve net losses of either biodiversity or complexity [57,58].

In economics, 'collapse' is used loosely, inconsistently, and often hyperbolically to describe breakdowns of economic processes or devices, particularly markets and currencies; a long-lasting period of economic contraction, reduced growth, or loss of financial capital; and/or the failure of multiple businesses or industries. While there has been substantial analysis of financial crises [59], there has been relatively little research on broader economic breakdowns, such as those in North Korea and Cuba following the halting of energy subsides from the Soviet Union.

In complexity theory and social–ecological systems theory, ideas about collapse are closely connected to resilience, vulnerability, and robustness [60]. 'Collapse' is a phase of Holling's influential adaptive cycle, which describes a common dynamic of resilience in social–ecological systems [21,61]. Resilience analyses often use 'collapse' interchangeably with 'reorganization', or in a mathematical sense to describe an abrupt shift from one regime to another. This definition, which is derived from catastrophe theory and nonlinear dynamics [62], does not necessarily fit criteria typically associated with 'collapse', such as the loss of wealth and well-being. One of the clearest definitions of social–ecological collapse in the resilience literature is that of Abel *et al.* [21], as ' . . . major losses of social, human, and natural capitals through the breakdown of social networks, deaths of individuals, loss of knowledge, depletion of flora and fauna for food and medicine, and loss of access to ceremonial sites and lands.'

Usages of 'collapse' across disciplines thus share important features, but the variation in definitions is *ad hoc* and makes systematic comparison across cases difficult. As the 2014 Intergovernmental Panel on Climate Change (IPCC) Impacts, Adaptation and Vulnerability Report [63] stated, while discussing negative consequences of ecosystem collapse for small islands, 'ecological collapse is not currently well defined or well understood'. The recent

International Union for Conservation of Nature (IUCN) initiative to identify endangered ecosystems [64] is a move in ecology toward tackling ecological collapse in a more systematic manner.

Defining Social–Ecological Collapse

It is impossible to measure change without a clear reference point. Such a reference point can be provided by the concept of identity [65,66]. Defining system identity does not require a detailed inventory of all system elements, because complex systems continually change. Instead, identity is defined by key components and relationships that must be maintained through time and space for the system to be considered the same system. Identity is subjectively defined according to the properties in which an observer, who may also be part of the system, is interested. Although subjective, it is not arbitrary; it requires establishment of (and agreement on) key criteria. For example, in law, different rules apply to children and adults, and you effectively become a different person once you reach the age of majority. However, you remain the same person to friends and family. Depending on the criteria applied to a person, they can thus either maintain or lose their identity as they age.

In practice, identity can be defined by determining thresholds for the quantities or properties of key components and interactions [66]. For example, a forested landscape might lose its identity if $<$45% of its area consists of forest. The value of 45%, which is derived from percolation theory [67], is the point at which a randomly deforesting landscape starts to become more disconnected than connected (and hence, at which forest-dependent processes and organisms start to be impacted). Identity is also scale dependent, and must be specified with clear spatial and temporal boundaries (i.e., extent and scope of the system under consideration). The identity approach has been used to define forest and savannah regimes in forested landscapes [68], to explore the potential impacts of disease on the resilience of protected areas [69], in the Kruger National Park in South Africa to define 'Thresholds of Potential Concern' to trigger management interventions [70], and more recently as the basis for identifying threatened ecosystems [64].

Specifying identity (by answering the question, 'What is the system?') is an essential first step in operationalizing ideas about collapse. It suggests four necessary conditions for a social–ecological system to qualify as collapsing or having collapsed (Box 1). Quantitative data are needed to support the case for collapse (Figure 1).

Relationship of Our Definition to Previous Definitions of Collapse

If all four conditions for collapse are met, it is extremely likely that there will be significant changes in both the structure and the functioning of the social–ecological system. Hence, although collapse almost inevitably entails a change in key processes, a functional or process-based definition of the system is not necessary to demonstrate collapse. Our focus on identity allows the same events to be considered a collapse or a success, depending on the identity criteria used, and can help clarify ongoing debates [36,40]. Our definition also has the operational virtue that it does not require the measurement of changes in system complexity, an often unmeasurable attribute that features in many existing definitions of collapse [22,34]. Excluding complexity from the definition of collapse avoids the operational and methodological problems associated with trying to quantify it, and escapes the one-dimensional definitions (e.g., as the depth of a hierarchical institutional arrangement) that have dominated the literature. Definitions of collapse should be universal, and order and complexity in human societies and ecosystems are not limited to systems that have a hierarchical architecture [71,72].

Collapse is usually, but not always, contrasted with growth. Growth occurs in most social–ecological systems, and its underlying mechanisms are well documented. Growth can be explained as different types of capital enabling more capital accumulation; growth's cumulative nature makes it relatively predictable. For instance, growth in plant and animal populations can

Box 1. The Four Criteria for Defining Collapse

1. The identity of the social–ecological system must be lost. Key actors, system components, and interactions must disappear. Many arguments have arisen because system identity prior to collapse has not been clearly specified or articulated. For example, discussions of the 4th century collapse of the Roman empire [22] implicitly assume that the Western Roman empire is the focus, not the Eastern Roman empire. A collapse from one perspective, such as hydrological infrastructure, may not be collapse from another, such as maintenance of social norms.

2. Loss of identity should happen fast relative to regeneration times and turnover rates of identity-defining components of the system. Loss of wealth, infrastructure, habitat, individuals, or other system elements is 'fast' if it occurs in less than one generation of the dominant actors (human or not). Otherwise, it may be experienced as gradual decline rather than collapse [98]. Since people shape social–ecological systems, social–ecological collapse will typically occur within time frames of <25 years (i.e., a human generation). By contrast, the ecological collapse of a redwood tree population might span a century.

3. Collapse involves substantial losses of social–ecological capital. 'Substantial' depends on the criteria used to define system identity. Events that have been labeled as 'collapses' illustrate the range of values that are used. For example, Detroit's population declined by 60% in 60 years, from ca. 2 million in 1950 to ca. 700 000 in 2013; the Lowland Maya population in Guatemala declined by over 90% ca. AD 790–890 [34]; and the Akkadian collapse led to a 40% reduction in numbers of settlements and a 70% decline in settled area [43]. In ecosystems, Newfoundland Cod spawner biomass declined to 99% below precollapse levels [99]; productivity reductions of >98% occurred in populations of forage fish (anchovies, capelin, herrings, mackerels, menhaden, sand eels, and sardines) [52]; and populations of 12 Hawai'ian bird species declined by >95% [91]. Keith *et al.* [64] proposed thresholds of 80–90% in a range of variables for 'critically endangered' ecosystems, while Lindenmayer *et al.* [56] considered collapse to be irreversible. In the economy, during the global financial crash of 2008, more than 90% of Organization for Economic Co-operation and Development (OECD) countries experienced a >10% decline in imports and exports [93]. While these figures give some indication of reasonable thresholds, the strongest criteria are determined quantitatively [91] and their exact values will vary with identity criteria and context. Identifying such thresholds can usefully focus attention on systemic trends [100].

4. The consequences of collapse must be lasting, persisting longer than a single generation or much longer than the typical dynamics of the system. Collapse alters system dynamics and increases recovery times, as in the loss of critical infrastructure (e.g., irrigation systems or slow-growing ecological structures, such as coral cover or forests) [56,101]. For people, the consequences of collapses may persist for centuries and are often irreversible.

be predicted from birth and mortality rates using growth curves and Leslie matrices [73], and changes in human population growth occur predictably due to changes in demographic structure [74].

Mechanisms of Collapse

Many theories of collapse have assumed, implicitly or explicitly, that there is a single type of collapse that routinely occurs in the same way. This assumption implies that a single theory, such as environmental degradation and overpopulation [34] or diminishing returns on increasing social complexity [22], can explain collapse (Figure 2). In practice, collapse may occur in many different ways and as the result of a variety of different causes. To synthesize the primary explanations and mechanisms that have been invoked in the literature, we reviewed 17 case studies (Table 1). Cases were selected to illustrate the diversity of perspectives, controversies, and disciplinary approaches, rather than to exhaustively cover the field. They include some of the most widely cited social–ecological examples (Cases 1–9), some recent ecological examples (Cases 10–15), and two economic cases (Cases 16 and 17).

Complex systems theory suggests that the vulnerability of a given system to collapse, and its resilience to different kinds of perturbation, will depend on the structure of the system as related to its processes and functions [72,75]. There is a large and fast-growing literature on the design of governance structures and monitoring approaches for the sustainable production of ecosystem services [76,77] but this literature has not yet been integrated with ideas about collapse.

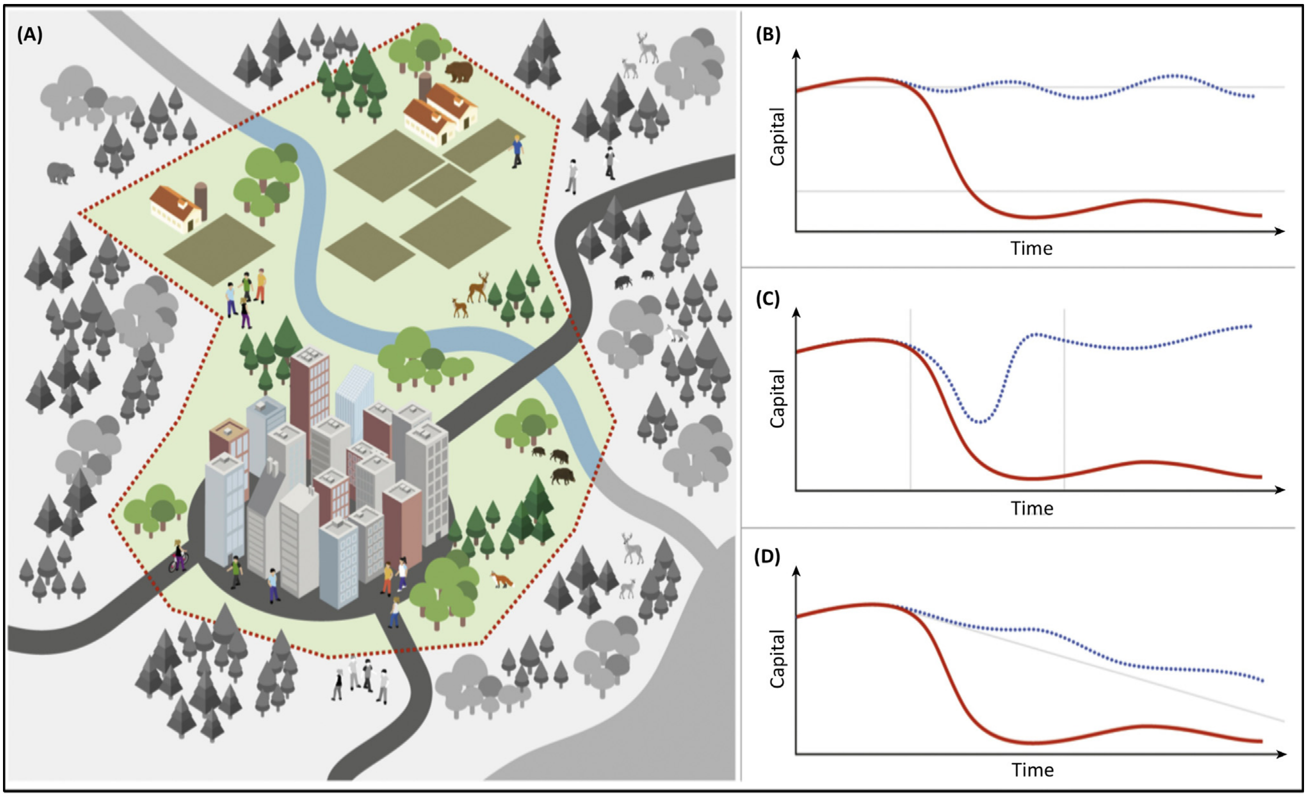

Figure 1. Specifying Collapse and Comparing It to Other Kinds of Change. (A) Defining identity requires specifying the core structure, dynamics, and boundaries of reality that are under analysis. (B–D) show cases of system collapse in red and alternative bifurcations into noncollapse trajectories in dashed blue. In each case, collapse has been subjectively defined as a change in one or more key capitals, which could encompass social, financial, natural, built, or other forms of capital. (B) Collapse must be substantial compared with previous system fluctuations, and can be quantified by specifying a relative decline, such as 80% (shown as the gray line). (C) Collapse must be persistent; if there is a quick recovery from a perturbation, there is no a collapse. The gray lines show how persistence can be specified by defining a period relative to the temporal dynamics of a system. (D) Collapse must be abrupt. A slow decline can be quantitatively differentiated from a collapse by specifying a rate that must be exceeded to qualify as collapse (gray line).

Our review of collapses (Table 1) identified 14 alternative mechanisms, or hypotheses, that may lead to collapse in social–ecological systems. The structure of any social–ecological system can be described as a heterarchy that is located within a continuum defined by axes of (i) flat versus hierarchical organization; and (ii) individual versus networked organization [72]. Mechanisms of collapse can be related to system structure using Cumming's [72] four-quadrat structural taxonomy of heterarchies (Figure 3). This framework suggests five major families of collapse explanations that correspond to the four basic system structural types plus the potential to shift between them: pyramidal systems are particularly vulnerable to 'top-heavy mechanisms' of collapse; polycentric systems, to 'mismatch mechanisms'; reticulated systems, to 'lateral flow mechanisms'; and individualistic systems, to 'obliteration mechanisms'. There is also a family of 'transition mechanisms' that apply to systems that occur on the boundaries of the basic structural types or may be in a process of shifting from one type to another. Within each family of mechanisms, a number of subcategories exist (Table 2).

As this analysis suggests, 12 kinds of collapse are most likely to be associated with particular heterarchical system structures; two additional kinds of collapse are more likely to occur in systems that are shifting between different structures. Most analyses of past civilization collapses (e.g., Table 1, Cases 1–9) have focused on hierarchical societies in which kingdoms

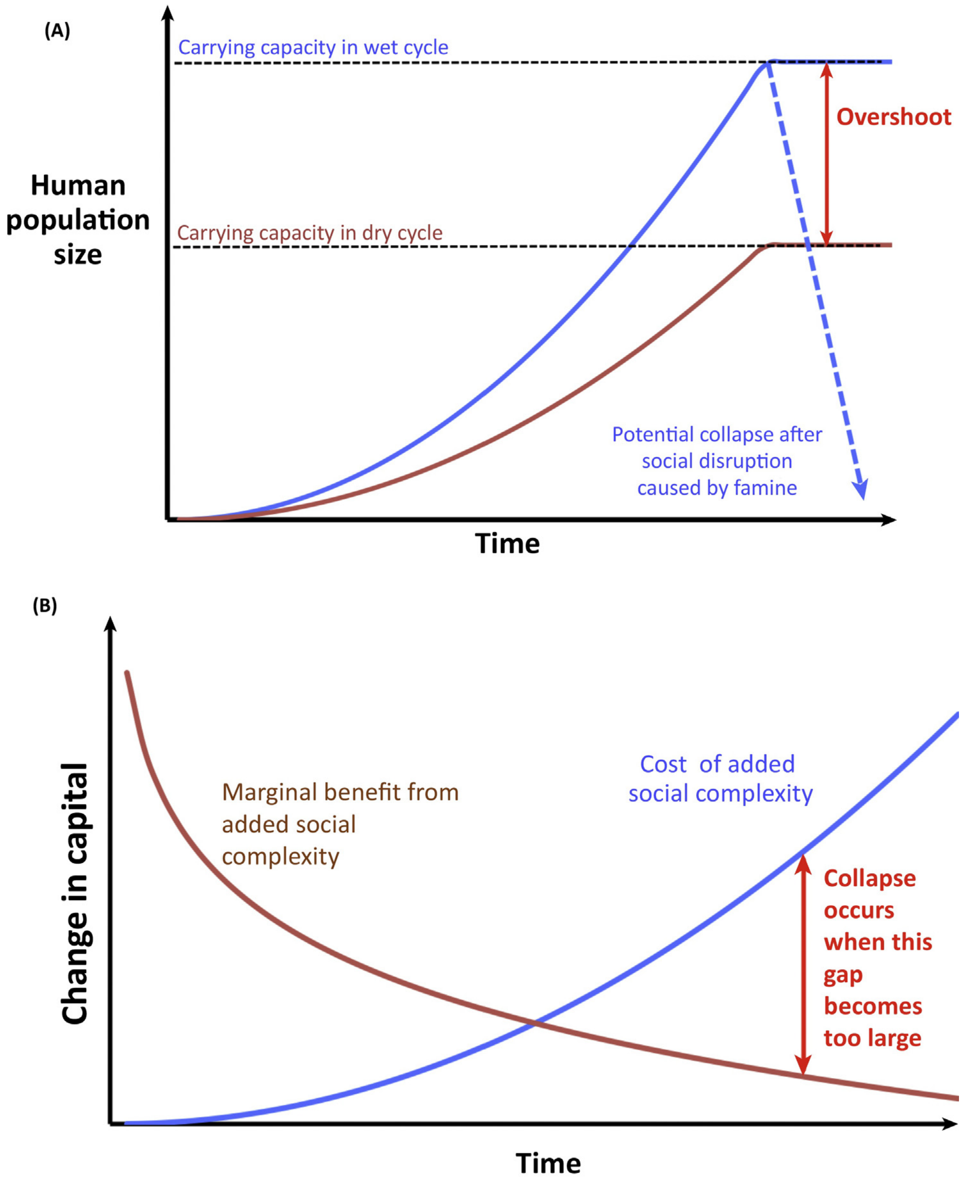

Figure 2. Examples of Specific System Dynamics That Can Lead to Collapse. (A) In overshoot [34], a society produces more food than it can consume during a favorable climatic period and the population grows. If the climate then shifts to less favorable conditions for a sufficiently long period, the population can no longer support itself and its size is reduced to carrying capacity by famine. Alternatively, if famine causes socioeconomic disruption and/or conflict, it may result in societal collapse. (B) The social complexity hypothesis [22] proposes that as societies become larger, they create new governance structures that consume an increasing proportion of resources while providing a diminishing return. Eventually, the burden of social complexity becomes too much for the society to support, and socioeconomic collapse results.

and empires collapsed. Our understanding of collapse might be different if the focus of archaeology had not been on 'perceived abandonment of palatial centers' [78]. Recent human developments, such as globalization and transport networks, mean that the analysis of historical cases may bear little relevance to contemporary society and yield few helpful insights [9,36]. In our opinion, the problem of uninformative comparison will continue until researchers more specifically consider system structure (Box 2). This framework provides a way of relating

Table 1. Case Studies of Collapse That Were Used to Develop Alternative Models of Collapse. These examples were selected to illustrate the full range of different collapse mechanisms, and related controversies, from an exhaustive search of the published literature

ID.	System	Time frame of data	Collapse metric(s) or evidence presented	Important system dynamics	Collapse explanation	Comments	Refs
1	Western Roman Empire	c. AD 200–476	Detailed historical records of conquests, budgets, and barbarian invasions available. Debasement of the denarius (Roman currency) from 91.8% silver under Nero (AD 54–68) to 58.3% under Septimius Severus (AD 193–211). Increasing pay rises to the army indicating inflation. Declining wealth of treasury in Rome. By c. AD 260, the Empire was essentially bankrupt.	From c. 400 BC to c. 20 BC, empire expanded by conquest; victories providing economic base for further expansion, creating a feedback loop. Heavy reliance on agriculture. Expansionism stopped under Augustus (27 BC to AD 14) and tax of Roman citizens introduced. Subsequent wars made state poorer rather than richer. Additional perturbations by plague (e.g., AD 165–150) and expensive wars with Germanic tribes. Rome gradually became unable to support its own government and infrastructure. As collapse set in, civil wars and incursions by barbarians further exacerbated problems.	As systems develop they begin to experience diminishing marginal returns to growth. As complexity increases, it creates problems whose solution requires more complexity; at some point the cost of added complexity is too much to cope with the problems and the system falls apart, reorganizing in a simplified state.	Presented as an economic explanation but also with many political and social elements. Tainter mentions but does not dwell upon the relevance of depopulation when comparing this case study to Britain: '. . . the later [Roman] Empire was substantially underpopulated' (p. 152).	[22]
2	Lowland Classic Maya (Peten, Guatemala)	AD 790–890	Style and iconography of monuments; spatial heterogeneity of homogeneity of monuments in different places. Number and spacing of population centers. Evidence of nutrition declines from skeletons. Evidence for deforestation and erosion on hillsides and for drought from pollen records in lake sediments. Population size claimed to have peaked around AD 600–700. Population stated to have declined from 3 000 000 to 450 000. Diamond (2005, p. 172) claims a disappearance of 90–99% of Mayan population after AD 800.	Development of increasingly more intensive agricultural systems, including hydraulic engineering, as population expanded. Competition and conflict between different groups. Warfare as a structuring influence. Burst of monumental construction and political decentralization prior to collapse.	Causality unclear. Several different interacting explanations have been offered: (i) escalating warfare triggered by overpopulation and food scarcity; (ii) overshoot and collapse following climate change (drought) that synchronously impacted all trading partners (i.e., scale mismatch); (iii) diminishing marginal returns from conquest; (iv) failures in leadership, particularly lack of long-term problem awareness; (v) changes in spheres of trade and influence.	Collapse is contested in this case, and there has been substantial debate about the exact timing of different events and whether chronology supports different hypotheses. Claims of overpopulation, increased warfare, and poor land husbandry also challenged.	[22,34,36,84]

Table 1. (continued)

ID.	System	Time frame of data	Collapse metric(s) or evidence presented	Important system dynamics	Collapse explanation	Comments	Refs
3	Greenland Norse	End of 14th century	Archaeological evidence showing decline and abandonment of Norse settlement. Some evidence in support of this claim that the last few families died of starvation.	Marginal environment, evidence of environmental degradation, arrival of little Ice Age (c. 1250–1300). Cultural factors: the Norse did not adopt successful practices of the Inuit who lived in the same environment.	Ecocide hypothesis proposed, based on evidence for land degradation, climate change, limited ability to adapt.	Collapse again contested. Middleton (2012) sees this simply as a case of outmigration from a harsh, isolated location gradually leading to an end of the settlement, not collapse of the entire society.	[34,36,84]
4	Rapa Nui (Easter Island)	c. AD 1300–1600	Archaeological evidence of changes in ecology, politics, and culture. Some support for deforestation, increased warfare, invasive species, and infectious diseases introduced by Europeans. Depopulation.	Tree felling to make rollers to move stone carvings (moai); overpopulation, deforestation, erosion, declining agricultural productivity. European colonization. Strong evidence for depopulation only comes much later (1800s).	Several different reasons have been proposed and remain hotly contested: (i) 'ecocide', collapse by overshoot, because of local degradation of the environment triggered by moai construction; (ii) impacts of introduced rats on palm regeneration; (iii) impacts of infectious diseases introduced by Europeans.	Proposed as the classic example of overshoot, or 'ecocide', this example instead highlights the difficulties of demonstrating collapse and understanding its causes.	[34,36,84,85]
5	Akkadian Empire (Northern Mesopotamia and Syria)	2000–1900 BC	Archaeological evidence indicating urban abandonment, including chronologies of ceramic artifacts. About 40% reduction in number of settlements and 77% reduction in settled area.	Some evidence suggests increased aridity following a volcanic eruption, especially in the Ḫābūr region, upon which the Akkadian economy depended. However, additional evidence questions the dating of collapse and suggests political causes as the primary driver.	'The Akkadian collapse seems best understood as a political collapse in which the attempt to create a unified state from competing independent polities was ultimately outweighed by their desire for independence'.	It is argued that collapse was fundamentally political, despite the potential for overshoot identified by others.	[84]
6	Several different societies: Natufians (SW Asia), Late Uruk (Mesopotamia), Akkadian (Mesopotamia), Moche (Peru)	Examples range from 13 000 years BC to AD 6.	Archaeological evidence for desettlement, abandonment of cities, famine, population declines.	Growing farming populations appear to have collapsed suddenly (<30 years).	Climate change made food production less viable. The broader theme is overshoot, whereby populations that expanded during productive periods exceeded the carrying capacity of the environment in less productive periods.	Prehistoric and early historic societies were vulnerable to climate change; climate forcing together with population overshoot proposed as primary agent of collapse.	[45]
7	Bronze Age civilizations in Mediterranean and near East areas (e.g., Troy, Mycenae, Petra)	c. 1400–1200 BC	Evidence for depopulation. Skeletons discovered under debris.	Period of high geological activity.	An 'earthquake storm' devastated major cities, leading (together with conflict) to a loss of cohesion and social change.	Highly contested but a good example of 'catastrophism', potential role of catastrophes in social collapse.	[86]

Table 1. (continued)

ID.	System	Time frame of data	Collapse metric(s) or evidence presented	Important system dynamics	Collapse explanation	Comments	Refs
8	Bronze Age civilization in Ireland	c. 800 BC	Depopulation, evidence for cultural changes. Regional pollen records identify a peak in farming activity in the late 11th century BC, followed by a decrease during the ninth to early eighth century BC. A major, rapid shift to much wetter conditions is registered in testate amoeba-based water table reconstructions and humification records from peatlands in Ireland, and has been precisely dated to ca. 750 cal. BC.	Although climate has been blamed for the decline in farming activity, the drop in population at the end of the Bronze Age began more than a century before the climatic downturn of the mid-eighth century BC.	Bronze manufacturing required extensive trade networks that were dominated by a wealthy elite. The adoption of technology around (more accessible) iron made these networks redundant. The more likely explanation for collapse is social destabilization.	Precise dating of climate change events can clarify whether climatic or overshoot explanations for collapse are viable – in this example, they are not.	[87]
9	'Anasazi', US Southwest, particularly the Chaco Canyon Pueblo society.	c. AD 1100–1200	Rainfall data from dendrochronology (tree rings) suggest drought beginning around 1130, during a period of dense population. Population decline and eventual depopulation, although controversy over numbers. Archaeological evidence for warfare. Reduction in number of outlying towns and an increase in mean travel distance between outliers from 17 to 26 km.	Marginal agricultural land, requiring sophisticated solutions to ensuring water supply and farming. The practice of shifting agriculture across the landscape may have created problems when too much available land was settled. Potential roles for deforestation and erosion. Strong dependence on trade, with Chacoans potentially reducing the cost of trade between groups in the San Juan Basin via administrative services.	Numerous explanations for collapse have been given, including (i) warfare and cannibalism; (ii) environmental degradation coupled with drought (overshoot); (iii) the sunk cost effect, whereby nonrecoverable investment in infrastructure made people unwilling to abandon sites or practices that became untenable in a changing environment; (iv) with densification, reduction in the efficiency of the system at resource averaging over suitable scales; (v) withdrawal of neighboring populations from a vital trade network because of costs of participating.	Another highly contested example. Diamond (2005) is convinced it reflects environmental degradation and overshoot; Tainter, that depopulation resulted from economic costs and diminishing marginal returns that demanded political reorganization. Wilcox (in McAnany & Yoffee) regards Diamond's narrative as a colonial construction that has little grounding in reality. He argues that there was no collapse but rather an ideological change that made Chaco's religious sites redundant.	[9,22,34,36]
10	Ecological collapse of Merrymeeting Bay	AD 1800–2000	Fish kills, loss of top predators, reductions in dissolved oxygen concentrations. 'Merrymeeting Bay is permanently shallower, its anadromous fish runs are vestiges of their former abundances, toxic substances remain in its biota and sediments, and it continues to receive excess nutrients from industrial and municipal sources'.	European settlement of New England; population growth and new technologies leading to gradual pollution of the environment via waterways.	Cumulative environmental degradation caused by human activities: overfishing, land clearance, and dam building in the 18th century and severe industrial and municipal pollution in the 20th century.	Gradual recovery since 1972 (DDT ban), but some components may never fully recover.	[50]

Table 1. (continued)

ID.	System	Time frame of data	Collapse metric(s) or evidence presented	Important system dynamics	Collapse explanation	Comments	Refs
11	Honeybee colonies	Contemporary	Numbers of bees in the hive become too small to maintain itself and the colony perishes.	Bee hives require sufficient foragers and defenders to survive. Recruitment is enhanced and mortality is reduced by the presence of more bees. In other words, per-individual rate of hive increases as a function of adult bee numbers.	Allee effects. Once these are in place, many causes (e.g., pesticides, mites, pathogens, and climate change), individually or interactively, can trigger hive collapse.	Demonstrates a collapse mechanism by which there is a critical threshold in population size. Runs counter to Tainter's argument of diminishing returns from larger societies.	[88]
12	Salt marshes in the USA	Contemporary	Die-off of salt marshes on the Western Atlantic coast of the USA.	Localized depletion of top predators at sites accessible to recreational anglers triggers increases in herbivorous crab populations, which overconsume marsh vegetation.	Trophic cascades. Overfishing may be a general mechanism underlying the consumer-driven die-off of salt marshes spreading throughout the Western Atlantic.	Relevance of trophic cascades (and knock-on effects through complex networks more generally) for collapse. Consumers play a dominant role in regulating marine plant communities and can lead to ecosystem collapse when their impacts are amplified by human activities, including recreational fishing.	[89]
13	Sea urchin fishery in Maine	Contemporary	Declines in sea urchin populations and viability of fishery.	'During the late 1980s and 1990s, the Maine sea urchin fishery was a classic gold rush fishery. In the beginning, the fishery was characterized by an abundant resource with little to no harvesting activity, followed by a period of rapid increase in landings and effort that led to a subsequent and persistent decline in the sea urchin population and a significant reduction in effort.'	Overexploitation blamed on a lack of fine-scale institutions regulating offtake.	Scale mismatch, where provincial legislation was inadequate for fine-scale management.	[90]
14	12 populations of Hawai'ian birds	One decade	Population size based on 50 years of bird counts. Declines occurred in <10 years and losses were >95% of the population.	Overexploitation, massive habitat loss and fragmentation, invasive species, and emerging infectious disease.	'Death by a thousand cuts'; no single event but rather a cumulative set of mortality-causing processes resulting from anthropogenic environmental degradation.	Ecosystem overwhelmed by external forces; too many pressures.	[91]
15	Forage fish fisheries: anchovies, capelin, herrings, mackerels, menhaden, sand eels, and sardines.	1960–2010	Population productivity of collapsed populations declined to −0.02/year of the average population biomass captured by the fishery. For uncollapsed	System shows high natural variance. Collapse preceded by high fishing pressure (50–200% greater than average) for several years and a sharp drop in	Lagged responses to fishing pressure amplify magnitude of population fluctuations. Overfishing becomes an additive effect that magnifies natural variation, leading to collapse.	Proposed solution is to reduce fishing when populations are low. More generally, indicates the importance of understanding natural variation and reducing impacts	[52]

Table 1. (continued)

ID.	System	Time frame of data	Collapse metric(s) or evidence presented	Important system dynamics	Collapse explanation	Comments	Refs
			populations, the minimum biomass was >0.3/year.	natural population productivity. Stocks take time to recover.		on ecosystems when they are themselves at vulnerable points.	
16	Low-income contemporary nation states: Cameroon, Cambodia, Ethiopia, Mozambique, Nicaragua, Rwanda, Uganda, and Zambia	1960s–1990s, decadal, exact period depending on individual country	Prolonged decline in per capita income (and/or GDP)	The author argues that recovery from economic collapse in poor countries may be rapid if the causes of collapse are removed. Demand-side stimulus plays a strategic role in swift recovery, alongside the removal of supply-side constraints.	Economic collapse is often associated with the collapse of political and social institutions, and the breakdown of civil peace and order (state collapse). This is not always the case. Economies also collapse because harmful policies are pursued over long periods, and/or because rigorous economic sanctions are applied by trading partners and capital markets.	Rapid economic recovery was associated with strong demand-side stimuli and underutilized capacity on the supply side, plus rapid removal of supply-side bottlenecks. Recovery was retarded in cases where macroeconomic circumstances, such as a legacy of high inflation and debt, made it impossible to finance demand-side stimulus domestically, where export growth was insufficient, and where external financing was inadequate to overcome supply-side constraints. More generally shows importance of balance between internal and external factors relating to economic production and trade.	[92]
17	Global financial crisis of 2008	Starting in 2008, repercussions still present in 2016	Synchronous declines in trade, currency values, etc. across a large number of nations.	During a boom period, high market confidence led to unreasonable expectations about return on investments. The housing market in the USA, for example, developed in such a way that low-interest loans were easy to obtain with little security. This created further speculation on house prices. When the housing market declined, lenders were unable to get their money back, creating a loan crisis that made the situation worse.	In economies with top–down regulation and lateral information exchange, speculative bubbles may develop in addition to actual growth. Success leads to a decreasing investment in regulation, because regulation slows growth. Returns to speculation exceed returns on investments in productive capacity. Combined with borrowing to fund speculation, this makes collapse likely if expectations about future growth are threatened, leading to abrupt collapse of speculation and general economic activity due to borrowing.	Underlines the importance of perceptions and regulation in economic contexts; the GFC was essentially a collapse created by and within the monetary system, but it had severe impacts on real people.	[93]

DDT, dichlorodiphenyltrichloroethane; GDP, gross domestic product.

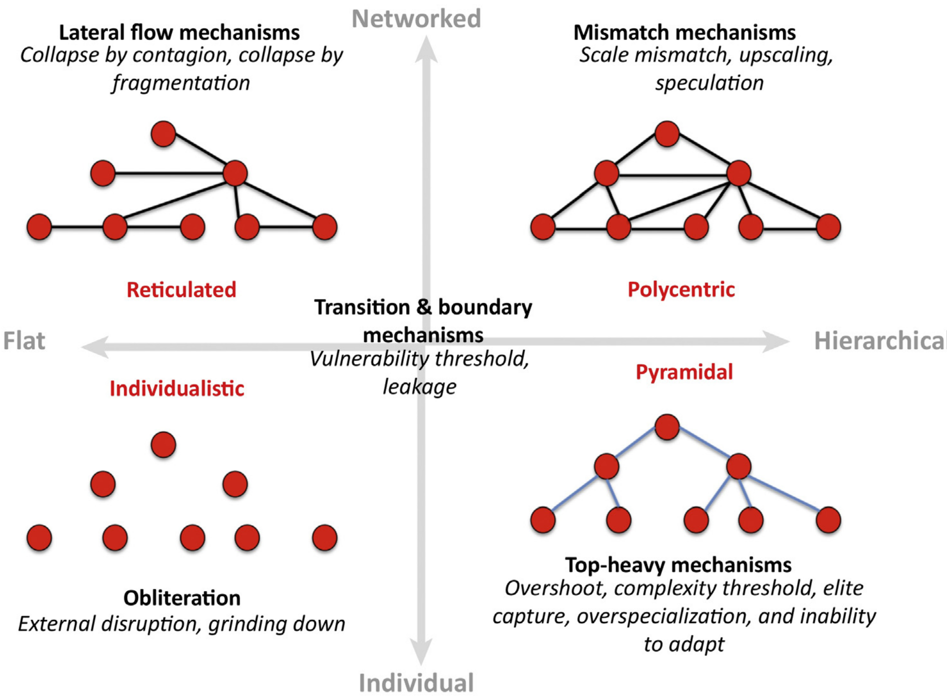

Figure 3. Summary of Proposed Relationships between the Governance Structure of a Social–Ecological System [72] and the Kind(s) of Collapse That the System Is Likely to Experience (Indicated in Italics). Further details in text.

collapse mechanisms to system structure, and offers an initial step toward system diagnosis for management and policy, by suggesting which type(s) of collapse are likely in a given context.

Discussion

A General Theory of Collapse

We began by arguing that if the study of social–ecological collapse is to become a rigorous scientific undertaking in its own right, it requires a cohesive body of theory that can be used to both classify and understand the nature of a particular situation and allow researchers to draw general inferences from multiple case studies. The foundations for a theory of collapse are (i) general, empirically viable, quantifiable definitions of identity and collapse; (ii) understanding the relationships between structure and process in social–ecological systems, because system structure – specifically, location on axes of heterarchical organization – influences the nature and likelihood of collapse; and (iii) explicit recognition and consideration of alternative mechanisms, here described as 14 archetypal system dynamics, that can explain why (and not merely how) collapse occurs.

A rigorous, quantitative theory of collapse based on these foundations has the potential to be an important element in the growing discipline of sustainability science. It promises to ground ideas about collapse in scientific principles and to move debates around collapse forward from arguments over whether or not an event qualifies as a collapse [34,36] to rigorous comparison across case studies to test alternative hypotheses about how, why, and when collapse occurs. A science of collapse will also contribute to new comparative approaches to history [79], and could be used to improve global environmental assessments and forecasts [27,75].

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Table 2. Summary of 14 Mechanisms, or Hypotheses, That May Lead to Collapse in Social–Ecological Systems. Examples of cases for which researchers have invoked many of these mechanisms are presented in Table 1

Family of mechanism	Specific mechanism	Summary of mechanism
Top-heavy mechanisms	Overshoot	Ecological degradation and excessive resource consumption; collapse caused by climate change or other impact on productivity [4,34,94].
	Complexity threshold	Complexity creates problems that only more complexity can solve; diminishing marginal returns mean burden becomes too great for society to support, and collapse occurs [22,43].
	Elite capture	Wealthy become parasitic on the poor. Resentment, revolution, or technological change can cause collapse [87].
	Overspecialization and inability to adapt	Specialization on a particular resource, sunk cost effects [20], and/or a lack of diversity create other vulnerabilities that lead to collapse [8,95].
Mismatch mechanisms	Scale mismatch	Scales of environmental variation and governance, or production and regulation, become misaligned. This can cause system dysfunction and collapse [22,90,96].
	Upscaling	Getting resources remotely can detach people from environmental degradation, creating an overconsumption feedback and potential for collapse [80].
	Speculation	Success leads to a decreasing investment in regulation; returns to speculation exceed those on investments in productive capacity. If expectations about future growth are threatened, abrupt collapse of speculation and general economic activity due to borrowing can occur [93].
Lateral flow mechanisms	Collapse by contagion	Perturbation or negative impact is transmitted through lateral connections [75].
	Collapse by fragmentation	Loss of modularity and reliance on connections result in collapse if connections are broken [22].
Obliteration	External disruption	A force from outside the system destroys or undermines it [86].
	Grinding down	Gradual depletion of key resources, such as biodiversity or soil fertility, eventually leads to collapse [91].
Transition and boundary mechanisms	Vulnerability threshold	Systems (or individual components) grow from less vulnerable sizes through more vulnerable sizes and may collapse during a vulnerable stage [97].
	Leakage	Semipermeable boundaries that are important for sustainability become permeable, leading to loss of key resources and/or influx of problem-causing agents [69].

Key Challenges for a Theory of Collapse

A key challenge in building the necessary body of theory is to connect structure, process, and system change over time. Some kinds of system change appear to be almost inevitable (e.g., the genesis of some form of hierarchical organization as societies become larger), while others (e.g., the degree of power sharing in governance) depend heavily on leadership and both individual and collective decisions. Rather than trying to build complex multiparameter models from first principles, it may be more effective to analyze collapse-related dynamics by considering possible trajectories of change and the factors that lead to one trajectory being followed over another. A focus on the resilience of different states and the likelihood of transitions between those states, rather than precise forecasts of behavior, has been successful in analyzing other complex, stochastic systems [80].

Attaining resilience at one scale is expected to require reorganization (and possibly collapse) at smaller scales [81]. The focus of resilience researchers has been primarily on the attributes of a system that help it to maintain its identity, such as ways of retaining institutional or ecological memory in times of change [82], rather than the mechanisms by which identity is lost. As suggested by Holling's adaptive cycle (Box 3), balancing resilience analysis with analyses of collapse is important, because collapses may reveal different but equally important elements of the more general problem of sustainability [30].

Box 2. The Problem of Uninformative Comparisons

Comparisons between social–ecological systems implicitly assume that the systems being compared are sufficiently similar that differences in their responses to major perturbations offer insights into coping mechanisms. However, many historical analyses of collapse have focused on strongly hierarchical societies that were very different from today's highly networked, interdependent societies. In contemporary society, increased access to trade and other cooperative networks facilitates some processes, such as source-sink dynamics and rescue effects [102,103], that make collapse less likely; and other processes, such as transmission of infectious disease or involvement in conflict, that make collapse more likely [104]. Analyses of historical collapses often apply explanations based primarily on local, top–down processes (such as overexploitation of the environment) to cases where networks were clearly an important component of the system (e.g., the cultural connections of the Greenland Norse to Denmark, the warring city states of the Maya, or the trade networks that supported the Pueblo inhabitants of Chaco Canyon; see Table 1).

The problem of uninformative comparison in the study of collapse has been compounded by the examples considered. Collapses of societies whose organization is either networked or polycentric are often framed as narratives of colonization and conquest rather than of collapse, because their histories are told from the perspective of the victors rather than the vanquished [105]. There are also many recent or contemporary examples of collapses arising from network influences, such as the global financial crisis, the impacts of economic sanctions on nation states, or the collapse of chestnut tree populations following the introduction of the chestnut blight pathogen to the United States. The challenge of avoiding collapse in internationally exploited fisheries is similarly complicated by their polycentric nature [36]. In these instances, it is unsurprising that case studies of collapse in isolated social–ecological systems with few lateral connections have little direct relevance.

In our globalized society, we need a theory of collapse that explicitly incorporates the relationships between structure and process. Comparing cases of collapse that exhibit different collapse dynamics in different structural contexts will allow researchers to assess how the relative importance and likelihood of different kinds of collapse mechanism vary across contexts. Furthermore, including both structure and process will lead to the development of a wider variety of mathematical models of collapse, facilitating comparison. Such theoretical development could be used to develop practical methods for estimating the likelihood of collapse, as well as identifying strategies and opportunities to increase or reduce it.

Box 3. Holling's Adaptive Cycle, Reorganization, and Collapse

Holling's adaptive cycle [61,106] offers one potential starting point for unifying ideas about resilience and collapse. It describes an archetypal system dynamic of growth, rigidity, release, and reorganization. In the growth phase, the system accumulates capital and often becomes more connected, both internally (e.g., via social networks or tightness of nutrient cycling) and to other systems. As it grows it becomes more efficient; this process reduces diversity, leading to a second phase, system rigidity. Loss of diversity and the accumulation of low-liquidity capital make the system less resilient to some kinds of perturbation. A perturbation that exceeds the system's ability to maintain itself leads to the release phase and a loss of capital and system fragmentation. The final phase, reorganization, is strongly context dependent. Novelty often emerges during this phase from rearrangements of existing elements and establishment of new interactions. For example, vegetation succession in an abandoned farmland typically undergoes phases of growth (gradual colonization by woody plants, leading to a mature woodland with high accumulated carbon); rigidity (woodland trees dominate available light and nutrients and inhibit the growth of their competitors); release (loss of nutrients or their return to the soil, resulting from such events as insect outbreaks, fire, or logging); and reorganization (resprouting from roots and the colonization of vacant patches by propagules).

Holling's adaptive cycle is a general heuristic model that shows how a tension between efficiency and diversity, or adaptability, can result in dynamic changes that lead to collapse. Although it has inspired a variety of new research in social–ecological systems, the adaptive cycle is not a clearly specified mechanistic model and in its current form it is nearly impossible to test empirically [66]. Many different mechanisms can produce system dynamics like those described by the adaptive cycle; as a result, observing that a system follows the phases of the adaptive cycle does little to clarify how it works. Each of our 13 alternative mechanisms of collapse can produce adaptive cycles, but they will be different in important ways. For example, some mechanisms produce slow collapses while others produce rapid collapses.

Analyses of the processes that underpin adaptive cycles, and their relationships to system structure, can make the adaptive cycle an operational rather than just a heuristic model. If the adaptive cycle is recognized as being not just one but rather 13 different kinds of cycle, then it can be useful for empirical analysis in at least two different ways. First, in analysis of system resilience, considering a diverse set of empirical models based on different collapse mechanisms will clarify how likely a collapse really is and the circumstances under which it may occur. And second, if different kinds of collapse mechanism have different empirical signatures, explicit consideration of empirical data from past and ongoing collapses should give insights into which collapse mechanisms apply to particular situations.

Box 4. Predicting and Avoiding Collapse

Developing consistent ways to characterize collapse and the mechanisms that produce collapse will significantly increase the ability of science and society to monitor, manage, and govern social–ecological change. Our comparison of collapse contexts and mechanisms reveals tensions and trade-offs between strategies that are intended to avoid collapse. For example, collapses caused by socioeconomic fragmentation (e.g., class divides leading to rebellion) may be avoided by building equity and social cohesion, while those caused by contagion (e.g., infectious disease epidemics) may be less likely when systems are modular.

Tensions and trade-offs between collapse mechanisms suggest some degree of conservation of fragility [107], in that strategies that build resilience to one set of challenges may reduce resilience to another. Comparative studies of collapse may be able to identify general strategies for balancing overconnection and modularity, but navigating these tensions in practice will almost certainly require a deep understanding of the specific context, history, and dynamics of the system. Different causes are closely related in most collapses, and in complex ways. In Tanzania, for example, spirit medium Kinjikitile Ngwale used a 'magic potion' that was supposed to turn German bullets into water to build social cohesion and trigger the Maji Maji rebellion of 1905–1907. The rebellion, which spread through and polarized existing networks of control [108], was partly a response to colonial policies demanding that locals grow (inedible) cotton and pay taxes. The backlash of colonial oppression resulting from the rebellion led to a massive famine and rural socio-economic collapse as well as important structural changes in the power relations of local people [108].

Successful implementation of strategies to avoid collapse depends on understanding the mechanisms that might cause collapse. Even if generic early warning indicators of collapse are detectable, responding to them requires an understanding of the mechanisms producing them. For example, rising variance may be a reliable general indicator of a possible collapse [28,109] in a fishery, but the risk of collapse may be rising due to optimization (e.g., excessive, efficient catch of a predatory fish by registered fishers) or a gradual loss of cohesion (e.g., a breakdown in rule compliance and trust between fishers). In the second case, regulatory approaches are unlikely to be successful in reducing the risk of collapse if the problem of a lack of trust is not addressed first. Understanding the alternative mechanisms that cause collapse thus allows appropriate strategies to be developed to monitor, address, and govern relevant processes.

The Need for Empirical Analyses

Our definitions of identity and collapse will need to be refined, both qualitatively and quantitatively, by empirical testing against real-world cases. As resilience theorists ask 'resilience of what, to what' [83], collapse theorists must ask 'collapse of what, based on which (and whose) criteria', and justify the use of 'collapse' by proving that their study system meets the four criteria of collapse. Furthermore, while definitions of system identity and collapse inevitably have a subjective element, clearly justified, shared subjective definitions are vital for communication among people; and alternative subjective definitions can be useful to explore different questions. A good model for the development of standard perspectives is that of the new IUCN ecosystem red-listing process, which has used conservation knowledge to offer a practical definition of ecosystem collapse [62]. The mechanisms of collapse that we have identified are not mutually exclusive, and like our proposed structure–process relationships, they should be treated as hypotheses rather than as fact. While our analysis suggests that some types of collapse correspond to specific system structures, further empirical evaluation is needed to determine whether this hypothesis is correct. Comparing actual cases to our mechanisms in more depth would reveal which mechanisms explain collapse, which mechanisms typically occur together, and which occur separately. This knowledge is essential for predicting and avoiding collapse (Box 4 and see Outstanding Questions).

Summary

The cornerstones of our proposed framework for a theory of collapse include (i) the use of clearly specified criteria for collapse, focusing on the four criteria presented in Box 1; (ii) the development and empirical testing of quantitative thresholds to define collapse; (iii) relating collapse processes explicitly to system structure, as defined using the concept of the heterarchy [70]; and (iv) explicit comparison of alternative hypotheses and models of collapse. Our proposed framework promises to unite the different perspectives around collapse into a new and stronger body of theory, although considerable work remains (Outstanding Questions). Explicitly comparing alternative mechanisms of collapse will allow research on thresholds,

Outstanding Questions

How can we rigorously quantify identity and collapse? Despite some recent progress in both of these areas, the field needs strong and widely accepted methods to move existing debates on from the question of 'whether' collapse has occurred to the question of 'why' collapses occur.

What are the relationships between structure, process, and function in social–ecological systems? Analyses connecting food webs, biodiversity, ecosystem function, and stability have been an important theme in ecology for over half a century, but social–ecological research has a much weaker tradition of structure–process and structure–function analysis. Despite valuable recent contributions from social network analysis, research in SESs often ignores system structure and attempts to transfer principles between systems that are structurally different, such as common property and private property systems.

What can we learn from the comparative analysis of collapse? Comparative analyses will be able to address many exciting new questions. For example, Which mechanisms of collapse are common and which are rare? Are different mechanisms more or less common in different contexts? Which strategies can be used to anticipate, avoid, slow, or hasten collapse? Which factors shape the recovery that follows collapse?

Is small-scale collapse essential for long-term persistence? Resilience research suggests that small-scale, subsystem collapses play an important role in maintaining system resilience, but this proposition has not been tested in social–ecological systems. In ecology, declines and extinctions driven by natural selection are important mechanisms that keep individuals, populations, and ultimately entire communities of organisms suitably matched to a changing environment. Does collapse play an important long-term role in social–ecological resilience and adaptation? And how do different types of collapse in different contexts vary in their consequences for the systems in which they are embedded?

How can analyses of collapses of past human societies and ecological communities be extended to better traps, and tipping points to be connected to the related areas of scenario planning, resilience assessment, and social–ecological transformation. This in turn will facilitate the design and implementation of portfolios of strategies to build resilience to collapse in ways that are robust across multiple possible, but uncertain mechanisms of collapse. A theory of collapse should thus contribute to both the development of new theory and to better, more sustainable management and policy choices.

interpret the risks and opportunities of collapse in the Anthropocene? Past collapses occurred in a different context from the novel, globalized, technology-driven, and overpopulated SESs of the Anthropocene, but they may still be able to offer relevant principles for social–ecological sustainability.

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