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ORIGINAL ARTICLE

Governance in the Face of Extreme Events: Lessons from Evolutionary Processes for Structuring Interventions, and the Need to Go Beyond

Simon A. Levin,[1]* John M. Anderies,[2] Neil Adger,[3] Scott Barrett,[4,5] Elena M. Bennett,[6] Juan Camilo Cardenas,[7] Stephen R. Carpenter,[8] Anne-Sophie Crépin,[9,10] Paul Ehrlich,[11] Joern Fischer,[12] Carl Folke,[9,10] Nils Kautsky,[13] Catherine Kling,[14] Karine Nyborg,[15] Stephen Polasky,[16] Marten Scheffer,[17] Kathleen Segerson,[18] Jason Shogren,[19] Jeroen van den Bergh,[20,21] Brian Walker,[22] Elke U. Weber,[23,24,25] and James Wilen[26]

[1]Department of Ecology and Evolutionary Biology, Princeton University, 106A Guyot Hall, Princeton, New Jersey 08544, USA; [2]School of Sustainability, Arizona State University, Tempe, Arizona 85287, USA; [3]College of Life and Environmental Sciences, University of Exeter, Exeter EX4 4RJ, UK; [4]School of International and Public Affairs, Columbia University, New York, New York 10025, USA; [5]The Earth Institute, Columbia University, New York, New York 10025, USA; [6]Department of Natural Resource Sciences, McGill School of Environment, McGill University, Québec H9X 3V9, Canada; [7]School of Economics, Los Andes University, 111711 Bogotá, Colombia; [8]Center for Limnology, University of Wisconsin-Madison, Madison, Wisconsin 53706, USA; [9]The Beijer Institute of Ecological Economics, Royal Swedish Academy of Sciences, SE-10405 Stockholm, Sweden; [10]Stockholm Resilience Centre, Stockholm University, SE-10691 Stockholm, Sweden; [11]Department of Biological Sciences, Stanford University, Stanford, California 94305, USA; [12]Faculty of Sustainability, Leuphana University, 21335 Lueneburg, Germany; [13]Department of Ecology, Environment and Plant Sciences, Stockholm University, 10691 Stockholm, Sweden; [14]Dyson School of Applied Economics and Management, Cornell University, Ithaca, New York 14853, USA; [15]Department of Economics, University of Oslo, 0317 Oslo, Norway; [16]Department of Applied Economics, University of Minnesota, St. Paul, Minnesota 55108, USA; [17]Department of Environmental Sciences, University of Wageningen, 6708PB Wageningen, The Netherlands; [18]Department of Economics, University of Connecticut, Connecticut, USA; [19]Department of Economics, University of Wyoming, Laramie, Wyoming 82071, USA; [20]ICREA, Institute of Environmental Science and Technology, University Autonoma de Barcelona, 08193 Bellaterra (Cerdanyola), Spain; [21]VU University Amsterdam, 1081HV Amsterdam, The Netherlands; [22]CSIRO Land and Water, Australian Capital Territory Australia, Canberra 2601, Australia; [23]Andlinger Center for Energy and Environment, Princeton University, Princeton, New Jersey 08544, USA; [24]School for Public and International Affairs, Princeton University, Princeton, New Jersey 08544, USA; [25]Department of Psychology, Princeton University, Princeton, New Jersey 08540, USA; [26]Department of Agricultural and Resource Economics, University of California, Davis, California 95616, USA

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**Corresponding author; e-mail:* slevin@princeton.edu

Abstract

The increasing frequency of extreme events, exogenous and endogenous, poses challenges for our societies. The current pandemic is a case in point; but ''once-in-a-century'' weather events are also becoming more common, leading to erosion,

wildfire and even volcanic events that change ecosystems and disturbance regimes, threaten the sustainability of our life-support systems, and challenge the robustness and resilience of societies. Dealing with extremes will require new approaches and large-scale collective action. Preemptive measures can increase general resilience, a first line of protection, while more specific reactive responses are developed. Preemptive measures also can minimize the negative effects of events that cannot be avoided. In this paper, we first explore approaches to prevention, mitigation and adaptation, drawing inspiration from how evolutionary challenges have made biological systems robust and resilient, and from the general theory of complex adaptive systems. We argue further that proactive steps that go beyond will be necessary to reduce unacceptable consequences.

Key words: Resilience; Robustness; Extreme events; Governance; Prevention; Mitigation; Adaptation.

Highlights

- Responses to extreme events should include new infrastructures of all types—informational, social, and built—with predictive and responsive capabilities.
- Mitigation and adaptation options should account for interdependencies that may amplify or attenuate a particular effect on ecosystems or society, and should be proactive as well as reactive.
- Responses to large-scale extreme events must be coordinated across local, regional, and global levels of society.

Introduction

Ecosystems and societies are increasingly being confronted with a variety of extreme events. The magnitude and frequency of extreme precipitation (Du and others 2019), tornados (Tippett and others 2016), drought (Dai 2013), erosion, wildfire and even volcanic events (Farquharson and Amelung 2020) are on the rise, in some cases as parts of cascading chains of effects (Rocha and others 2018; Paine and others 1998; Schoennagel and Turner 2000). Hurricanes and cyclones have intensified over the past 40 years (Kossin and others 2020); and even as we write this paper, we are deep in the middle of a global pandemic with as yet unknown consequences for humans and ecological health. The attribution of extremes is an active area of science (National Academies of Sciences, Engineering and Medicine 2016; Alizadeh and others 2020), and current trends of larger and more frequent extremes are strongly associated with climate change. Extreme events adversely affect ecosystem processes that humans rely on for such critical needs as food, clothing, clean air (Lugo 2020) and water (Ummenhofer and Meehl 2017; Palmer and others 2017), and losses are sometimes abrupt (Turner and others 2020). Ecosystems, societies, and technologies have become increasingly interconnected, opening the possibility of new kinds of extreme events and interactive effects (Lugo 2020). As human populations expand, material consumption per capita grows, and technologies advance, extreme ecosystem changes become more likely, putting human infrastructures and people at risk (Turner II and others 2003a, 2003b). Losses of biodiversity, along with direct mortality and morbidity risks from fire, floods, and heat waves, have significant consequences for human wellbeing (Chapin III and others 1998).

Contemporary societies must act collectively to reduce or prevent extreme events caused by human pressures, and at the same time to constrain the negative consequences of extreme events that cannot be avoided. This challenge is particularly urgent, because we are already experiencing more significant effects that reduce the general welfare and sustainability of the human population, with potentially even larger risks in the future. Some changes occur continuously and gradually over time, while others take the form of more sudden and often potentially catastrophic change, such as shifts in ocean circulation patterns or outbreaks of war. In addition, some are more predictable—the so-called grey rhinos (Wucker 2016)—whereas others are less so—the ''black swans'' (Taleb 2007). Pandemics are neither new nor unexpected, yet experiences like the ongoing COVID-19 pandemic drive home the message that mindsets and governance systems worldwide are poorly prepared to deal with such shocks. Furthermore, extremes are seldom isolated phenomena; often they trigger cascades of consequences (Cottrell and others 2019; Keys and others 2019; Peters and others 2004; Rocha and others 2018).

We define extreme events to include those that have very significant consequences, at the tail of the distribution, for one or more segments of society, now or in the future, regardless of their like-

lihood of occurrence. This definition is broadly consistent with other definitions used to characterize risk in the areas of natural hazards and disasters. For example, McPhillips and others (2018) note that extreme events, such as heat waves and flooding, are of interest because of their potential to cause extensive effects on people and infrastructure. Here we emphasize the fact that extreme natural *variation (*for example, heat waves or precipitation that generate natural hazards*)* must interact with humans and infrastructure in some way to generate an extreme *event.* Thus, we conceptualize disasters as emergent phenomena in coupled social-ecological-technological systems mediated by social, political, and economic forces and technological change in which vulnerabilities are shaped by human processes. Extreme events are therefore triggered by interaction of these vulnerabilities with extreme natural variation (Wisner and others 2004). Recent examples of this process include increasing frequency of weather events of extreme intensity, for example, hurricanes/cyclones (Kossin and others 2020) or dry/hot events (Alizadeh and others 2020), interacting with population growth that is pushing human settlements into sensitive areas that generate very significant destruction through intense wind, rain, and fire, respectively. Other less familiar examples include derechos, intense windstorms capable of forces that have generated economic damages of historic proportions to crops and settlements in the US Midwest (Henson 2020). In this paper, we explore potential mechanisms to mitigate such emerging vulnerabilities and better prepare societies to deal with extreme events. Because the events that societies will experience in the coming decades will be significant, global, and novel, we need to develop new tools to address them. Collectively spreading risks, although effective in many situations, will be insufficient for a number of reasons, not least of which is the fact many of the risks are global in scale. We will draw on examples of extreme events to illustrate limitations of existing response mechanisms and suggest possible ways forward based on lessons from biological evolution that stem from an understanding of both what evolution can and cannot do.

Evolution has equipped organisms and populations with a hierarchy of responses of increasing complexity, cost, and irreversibility (Figure 1) that provide capacity to cope with change across a range of scales and levels of novelty (Slobodkin and Rapoport 1974; Ricklefs 2008). These responses, evolved over long time scales by selection for superior genotypes, resemble a portfolio of useful mechanisms for robust regulation that can be activated in the right context and at the right scale, from the individual (for example, behavior, acclimatization, or adaptation in Levels 1–3 in Figure 1) to the population and ecosystem (for example, changing trait distributions and changes in population genetics in Levels 4–6 in Figure 1). This classification of evolved responses to shocks is analogous to cultural and social responses to shocks in the final column of Figure 1. Social responses range from simple behavioral responses such as avoiding population aggregations during a pandemic to incremental adjustments of industrial processes in response to environmental pressures (ozone loss, acid rain) to cultural and societal transformations on timescales of days, decades, and centuries, respectively.

The evolutionary metaphor is instructive, but it has its limitations. It is largely reactive (Level 1 to 6 responses in Figure 1), even in the dramatic transformations that involve species extinctions, or major transitions like multicellularity that characterize evolutionary history (Maynard Smith and Szathmáry 1995). Human societies have the capacity to be more proactive: to predict and plan, to put in place major changes to minimize the potential for catastrophe, and to enhance resilience; this calls for an expansion shown in Figure 1 beyond evolutionary processes to reflect this potential (Level 7 responses). Dealing with the threats that extreme events pose to our societies will require planning, and proactive shifts such as changes in the institutional structure of the scientific enterprise at all levels to enhance detection, mitigation, and adaptation. We need to look no further than the current pandemic to understand that a reactive approach is insufficient, and we must create new structures to increase preparedness, indeed at cost, and to ensure equity across all sectors of our societies. There is great heterogeneity in the risk exposure of different populations as a result of different kinds of extreme events, and a perhaps even greater heterogeneity in the options available to populations to escape the negative consequences. Transformation of infrastructures of all kinds—informational, social and built—will need to protect the most marginalized populations especially. Change of any kind, let alone transformative change, can be expected to face opposition (Weber 2015), as it creates winners and losers even when elevating the public good, the definition of which can be expected to be more contested in our increasingly polarized world. Nevertheless, opposition (in the form of structural racism, sexism, or neocolonialism) to systemic transformations that

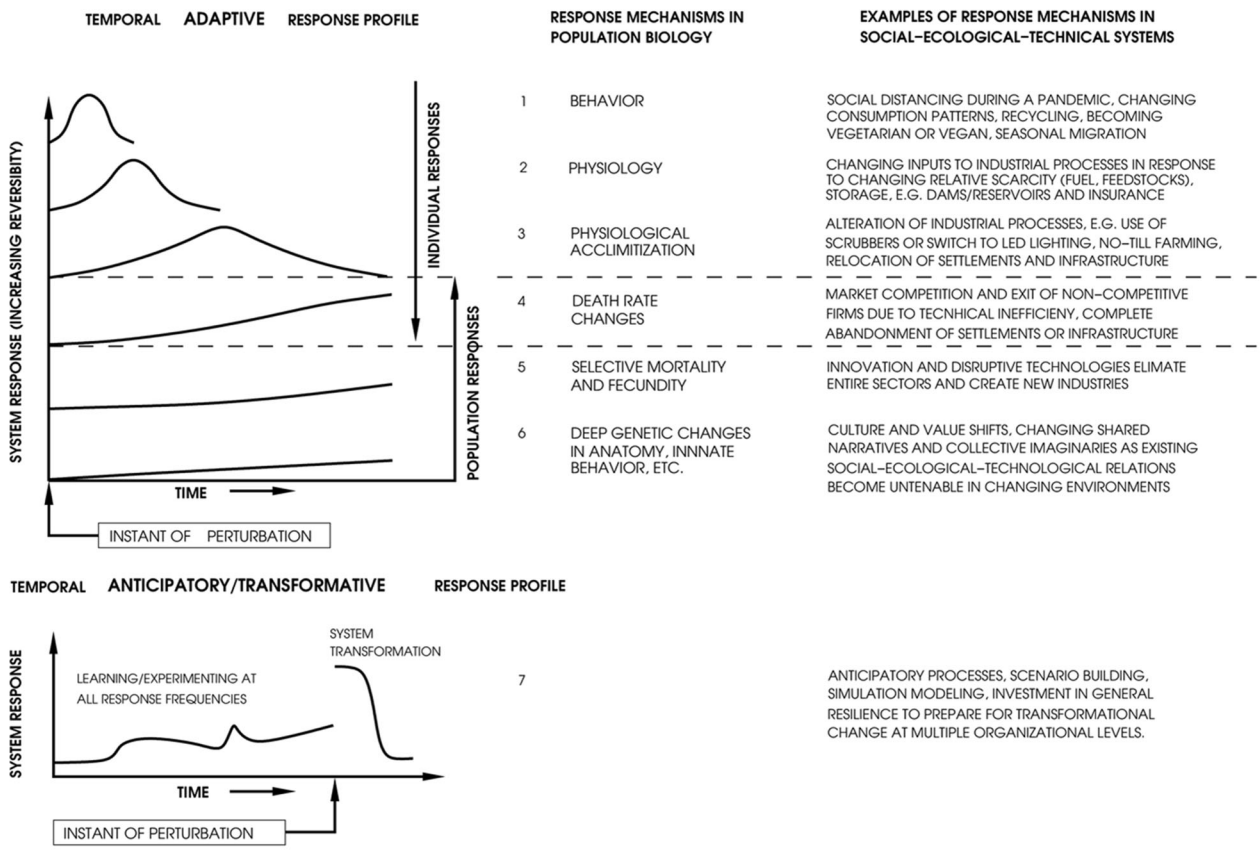

Figure 1. Hierarchical responses to ''extreme events.'' Adapted from Slobodkin and Rapoport (1974). Responses are ranked from levels 1–7 in order of increasing deployment cost and irreversibility. Level 1 responses are low cost, easily reversible (low irreversibility) and rapidly deployed (behavior can change in a matter of seconds), while Level 6 responses are high cost, irreversible, and are very slow to deploy (for example, over decades, millennia, or even millions of years). Human systems have moved beyond the largely reactive Levels 1–6 evolutionary responses proposed by Slobodkin and Rapoport and potentially have anticipatory and imaginary capacity and constitute a new Level 7 response. We argue that Level 7 responses, combined with Level 1–6 responses, will be critical for coping with extreme events in the Anthropocene.

decrease vulnerability and inequalities in vulnerability are obstacles that must be overcome, domestically and internationally.

What does transformation mean, and do we know how to do it? This is a question that confronts not just our societies, but also institutions, companies, and us as individuals. In ecological systems, transformation is generally unplanned—a pest outbreak, a shift from oligotrophic to eutrophic conditions in a lake, or from forest to savanna—and involves changes in key system functions. Responses to market crashes provide a similar example in financial systems: The creation of the Federal Deposit Insurance Corporation and Social Security in response to the Great Depression changed key economic and financial functions that stopped bank runs and kept people out of poverty and stabilized the system in a new equilibrium. When these transformations are emergent phenomena, they may lead to either more or less desirable conditions. When we manage such systems however, leading to suppression of a pest population or recovery from a recession, desirable outcomes can be facilitated by planning and foresight; indeed, true foresight would set in place the tools that will be needed for recovery when unplanned transformations occur. Natural selection can indeed select for such infrastructure when the negative events are part of the evolutionary history of the genome, with the human immune system as a good example. At the system level, ''transformational evolution'' can occur, (Lewontin 1977) suggests, largely through a filtering process that eliminates unstable assemblages; this is close to what Lenton and others refer to as ''sequential selection'' (Lenton and others 2018). But this is a process of elimina-

tion rather than adaptation; if we are to preserve our life-support systems, we need to go beyond this and take anticipatory steps that transform systems before disaster strikes,

Transformations involve major, perhaps discontinuous, changes in the functioning of a system, loss of structural stability in the lingo of mathematics. For the purposes of this paper, we adopt the definition that ''*transformation* is the capacity to create fundamentally different human-environment interactions when ecological, economic, or social structures or shifts make the current system unworkable'' (Folke and others 2021).

Challenges like climate change mitigation will require transformations. We know this because the attempts at solutions over the last thirty years have failed. The global political system seems incapable of addressing these problems. Here, we can only mention the need for a theory of transformation in our societies to deal with the threats of extreme events, without being able to provide answers beyond the broad objectives listed earlier. In part, therefore, one of the messages of this paper is that the increasing challenges posed by extreme events make it urgent to understand when transformations are necessary, how to build the infrastructure to make such change possible, and how to effect transformation.

We will argue that, in general, society must expand its suite of hierarchical responses to threats, adapting current infrastructure when feasible, and developing fundamentally new infrastructures when needed. We then discuss practical considerations related to developing a hierarchical response: what types of investments can provide a generalized capacity to withstand a wide range of potential threats, and how can we mobilize human populations to engage in the collective action necessary to make those investments?

Governance Challenges Related to Extreme Events

Coping with variation at the individual/household level, be it periods of scarcity (famine, drought) or excess (floods, heat waves, destructive winds), requires participation in or provisioning of some type of shared infrastructure. This shared infrastructure can take the form of rules, regulations, and legal structures that enable efficient contracting and exchange markets or physical entities such as dams, canals, and roads. Critically, this shared infrastructure must be provided at the level of the group, whether a village or nation state, and thus presents collective action problems and attendant governance challenges that demand effective governance structures.

For example, shared infrastructures for dealing with familiar and common threats are well-developed; some can be handled by averaging and collectively spreading risks, for example through formal insurance arrangements (club goods enabled by stable legal and financial structures) and other forms of resource pooling (ritual giving and sharing norms). Spreading risk is commonly operationalized via temporal averaging that relies on shared storage infrastructure, such as grain silos and water reservoirs; via spatial averaging that relies on exchange networks and mobility networks, supported by shared infrastructure of roads, marketplaces, belief systems, and so on; and via the formation of cooperatives, which also may provide other benefits (all examples of Level 1 and 2 responses in Figure 1). In some societies, however, such tools are not available. And even with these tools, how can we deal with unfamiliar and unexpected extreme events, especially ones beyond our experience? What kinds of shared infrastructures should we invest in? In some cases, we can still apply the same strategies of spreading risk in the face of uncertainty, or more generally develop strategies for dealing with classes of challenges that share similar features. That is what natural selection does. For example, the vertebrate immune system evolved in response to the certainty that our bodies will be assaulted with a range of pathogens, the exact natures and timing of which are uncertain (a Level 3 response in Figure 1). The degree of certainty depends on scale, and hence generalized responses are needed that rest upon the predictable aspects of classes of extreme events. This is an example of what has been called general resilience, structured to deal with the unpredictable and unknown (Carpenter and others 2012; Pelling 2011; Eakin and others 2014; Biggs and others 2015). Similarly, societies deal with threats such as pandemics and long-term climate change by developing generalized responses (for example, disaster response and public health infrastructures) to provide some certainty as well as some flexibility in response (a range of Level 1–3 responses). We are, however, increasingly facing threats that are sufficiently novel and interconnected that they cannot be clustered into equivalence classes. This demands new governance structures to allow us to mitigate negative effects, adapt to changed conditions, or even transform the systems that caused the problem (Westley and others 2011). Biological evolution provides *reactive*

transformative capacity via Level 4–6 responses on very long timescales and with significant changes in species' frequencies. We suggest that to reduce the potential for large-scale human suffering associated with reactive responses, we must develop a new class (Level 7) of anticipatory transformative capacity. The goal of this paper is to explore the balance among these strategies, as well as between private and public actions, given anticipated changes in the frequency and type of extreme events and emerging knowledge on how systems evolve to cope and adapt.

Biases, Rare Events, and Predictability

Extreme events are commonly classified and distinguished by their frequency (or possibly their predictability), the interplay between short-term and long-term effects, and their consequences for human well-being. Many new extreme events present new opportunities, with positive effects on well-being, but the focus of this paper is on negative events that constitute threats to our ways of life or even our existence. Typically, management strategies for such threats involve tradeoffs: how much to sacrifice in immediate return to reduce longer-term hazards of much larger quantity. Focusing on either immediate returns or long-term hazards exclusively is most likely suboptimal, but decision makers often show a disproportionate focus on immediate consequences (O'Donoghue and Rabin 2015). Another bias, namely loss aversion where the disutility of a loss of a given size is perceived to be far greater than the utility of an equivalent gain (Kahneman and Tversky 1979), suggests that willingness to make tradeoffs of any kind will be low, resulting in massive status-quo bias and inertia (Weber 2015). Risk tolerance is, of course, important here as well, because all responses involve great uncertainties.

Extreme events vary in magnitude and in frequency, and understanding this complexity is key to determining how to respond to them. Individual and collective responses can focus on behaviors that reduce their frequencies by behavioral responses that limit exposure, or on actions that reduce the negative effects of these events. Types of hazards can be classified in the two-dimensional landscape of probability (frequency) and effect. Rare events of low effect include total eclipses of the sun and cold summer days. Moving along the frequency dimension, we find common events, still of low effect, like predictably cold winter days, common colds, or the seasonal rise of gasoline prices (easily addressed with Level 1–2 responses). Moving instead in the effect dimension we find rare events with disastrous consequences, like the 1918 flu epidemic and two world wars. Finally there are common events with huge consequences, such as epidemics and major tropical storms (in the realm of Level 4–6 responses). Many classes of natural events shift position in this landscape in the face of population growth, climate change, technological change and globalization. For example, wildfires in the Western United States are clearly becoming more frequent and more devastating (Abatzoglou and Williams 2016). Management strategies, like fire control or vaccination, whether private or public, are generally designed to move event classes toward lower effect or lower probability, hence decreasing the likelihood or magnitude of negative events. Alternatively, people may migrate from a particular landscape to a more favorable one. Because of tradeoffs among conflicting concerns, there is no unique right way to move. People have different interests, values and preferences; for example, some people prefer to move from colder climes to warmer to escape the vagaries of winter, while others reverse that to escape heat and fire, or even to enjoy winter activities.

For predictable extreme events that are caused by human action or inaction, a combination of private and public actions can simultaneously reduce the probability of the event occurring and the effect of the event once it has occurred. However, if consequences are global, or if it is not known in advance which populations will be affected, the incentives to act to reduce probability or negative effects are very different. In such cases, prevention of an extreme event is a global public good and generally requires global collective action. Although action may be in the collective interest of all nation-states, individual nation-states may be conditionally better off free-riding on others' efforts, making for weak incentives for individual states to act. If effects are localized, however, the individuals affected will have an incentive to act to limit the harm they would suffer otherwise. Similarly, local communities and national governments will have an incentive to organize to limit the harm caused to their group through provision of local public goods, when costs and benefits of such actions typically fall within the same jurisdiction. Local and national authorities can have strong incentives to supply insurance arrangements that would spread the cost of extreme events and thereby reduce the harm to the most heavily affected groups within their own jurisdiction (Hudson and others 2020). An example is the use of fiscal transfers to soften the effect of regional eco-

nomic shocks and disaster relief in response to events like a hurricane or earthquake.

Extreme events have the potential to widen existing inequalities (Hamann and others 2018), and this is clearly proving to be the case with the COVID-19 pandemic (Dorn and others 2020; Tai and others 2020). In the US, poor and minority groups have higher incidence and death rates reflecting underlying health inequalities and higher rates of exposure from working in jobs that require exposure to infection. Countries that are more developed are also typically more effective at supplying local public goods. A failure to reduce the probability of an extreme event occurring thus falls hardest on the least developed countries that are the least likely to have the institutions and infrastructure to supply local public goods. Evidence from across the world shows, for example, that climate extremes perpetuate poverty directly through reducing poor individuals' capacity to accumulate capital, as well as directly affecting their health and labor productivity (Hallegate and others 2015).

Science can help by improving detection of a potentially extreme event. Early warning signals alert us about the conditions that can tip a system into catastrophic change before it happens, strengthening the incentive for collective action to avert a catastrophe (Barrett and Dannenberg 2014). However, as valuable as early warning signals are, they may still come too late to prevent an extreme event from occurring (Biggs and others 2015; Hughes and others 2013; Scheffer and others 2012); hence, the necessity for transformation,

Evolution has shaped the responses of organisms and genomes to environmental challenges, manifested in a hierarchy of responses of increasing importance and irreversibility (Figure 1). These responses can be mapped onto the typology of extreme events in the space of probability of occurrence and severity of effect discussed above. As extreme events become more frequent, a key governance challenge will be to induce investments that enable responses and mechanisms to coordinate across response levels. In the following sections, we explore in some detail how society might develop such hierarchical responses to threats, adapting existing infrastructure when that is feasible, and transforming them in more fundamental ways when needed. Societies must not remain committed to ineffective structures for too long, locking into suboptimal strategies when more far-reaching changes are called for.

High Uncertainty, Novel Hazards, and Scale

It is one thing to develop private measures and shared infrastructures to deal with specific hazards, but preparing for multiple interacting extreme events of unknown nature, timing, and effects requires more generalized capacity to withstand a wide range of potential threats. Even relatively mainstream approaches to integrate science and economics have recently called for analyses that take account of extreme risk, including possible large-scale and many unforeseeable consequences where it may be difficult or impossible to define probabilities (Stern and Stiglitz 2021). Scale mismatches impose unique challenges in this regard (Cumming and others 2006). For example, Peters and others (2020) show that macroscale features are not enough to predict self-accelerating drought effects like wind erosion. Local geomorphology and even small features like fence lines have important effects. This illustrates the critical need to think explicitly about multiple scales to improve predictions. Characteristics of complex systems that enable such generalized response capacity (general resilience) include redundancy, diversity, modular organization, open exchange, and reserves, among other factors (Levin 1999; Carpenter and others 2012; Biggs and others 2015).

Diversity of functions or of responses to external signals, along with modular organization, can provide adaptive capacity and limit systemic risk (Levin 1999; Page 2007). The scale of the system being described is central to whether it is diverse or not, and to the resilience exhibited by the system. Within a species of salmon, for example, genetic diversity (Level 5–6 biological response) confers resilience to exploitation and environmental fluctuations (Schindler and others 2010). For commercial fishing, diversity of harvest portfolios stabilizes livelihoods from fluctuations in stock abundance and market prices (Cline and others 2017). Yet at a broader scale the focus on salmon makes the region vulnerable to disease emergence or mortality during their migration far from Alaskan waters. If the region maintains trading partners and uses its profits to create stockpiles and wealth, such reserves would buffer the region against abrupt losses and allow the region's residents to enjoy a higher average standard of living than they would without such reserves. The value of this wealth, however, depends on the function of larger structures in the form of regional, national and global economies and thus becomes exposed to fluctuations at those scales.

This example of Alaskan fisheries illustrates robustness—vulnerability trade-offs associated with any portfolio of productive assets that operate across different temporal and spatial scales. Given the increased global interdependence of natural, social, and economic systems, there is no scale at which resource pooling or trade (Level 1–2 responses) can be used to hedge against all fluctuations at smaller scales. This raises the question of what types of investments may lead to a generalized capacity to withstand a wide range of potential threats. One potential strategy is to invest in general resilience (Carpenter and others 2012). General resilience, however, is a costly public good that will erode if not actively supported, and can be at odds with maintaining specific resilience to particular threats (Biggs and others 2015). However, failure to maintain general resilience may greatly increase the economic and human costs of extreme events and disasters (Ramachandran and others 2011).

Building Resilience

There is growing evidence on how individuals and institutions address resilience challenges of the social-ecological-technological systems in which they are embedded through collaborative approaches and learning (Folke and others 2005; Walker 2019). The evidence suggests that processes that are flexible and adaptive to local needs rather than rigid with fixed procedures build resilience. However, providing shared infrastructure to support these processes may require fundamental changes that are slow, costly, and potentially irreversible and which sometimes undermine the collective action required to achieve them. Generally, such processes have distinct phases: (1) accepting the need for change, and identifying the changes that are desirable, attainable or inevitable; (2) investigating new options or opportunities for safe-to-fail experiments with resilient approaches; and (3) initiating a desirable pathway for change that is biophysically and socio-economically possible.

Often, processes of local change involve financial assistance from larger scales, such as governments, aid agencies, and philanthropic organizations. Equally important is the role of policy—rules and laws, taxes and subsidies, infrastructure investments and so on—which can either inhibit or facilitate fundamental change. Financial and policy assistance may be given to activities preventing rather than promoting change. Willingness to support change can be limited by fears of unknown or uncertain consequences, inertia, failure to coordinate steps toward new and unfamiliar paths, or powerful stakeholders who prefer the status quo. Thus, it often takes a crisis to initiate both financial and policy support directed at transformation. Planning for transformation involves being proactive, prepared to make use of a crisis before the opportunity passes (Levin and Lubchenco 2008; Chapin III and others 2010; Gelcich and others 2010; Yoeli and others 2017). Nonetheless transformative change is sometimes possible at local or regional scales (Bennett and others 2016). Achieving transformational change at the global scale is particularly problematical because of the lack of effective international governance and the tendency for free-riding.

Transformational change may in some cases be achieved through gradual means, but there are situations in which a dramatic restructuring is essential. Francois Jacob, in his elegant essay (Jacob 1977), pointed out the path dependency of the evolutionary process, and Arthur (1989) and others have described this constraint in technological evolution. Biological evolution does experience discontinuous processes, punctuated equilibria (Eldredge and Gould 1972); but these are disruptive and emergent. Discontinuous, radical change may indeed be necessary in our infrastructures; but we have the capacity to plan those changes, to choose the best among options, and to mitigate the harmful side-effects of change. Energy transformations, especially decarbonization, but more generally the development of robust and reliable energy systems, will require careful planning, to avert major power outages such as struck Texas in 2021.

Recognition that discontinuous, radical, rapid, and disruptive change is becoming more common in the context of emerging knowledge-based technologies and rapidly changing geopolitical challenges has given rise to the need for organized foresight and anticipatory governance. Anticipatory governance is defined as ''a broad-based capacity extended through society that can act on a variety of inputs to manage rapid change such that management is still possible'' (Guston 2008). The phrase ''still possible'' is key. It suggests that we must make very specific investments while we can to prepare for adaptation, if it is within the capacity of existing systems or transform the system, if necessary. Extreme events fall into the latter category. New anticipatory governance structures very different from the old ones focused on promoting investment and growth through stable property rights and prices will be required to prepare systems for potential transformation.

Confronted with the major challenge of governing the future trajectory of extreme event dynamics (Steffen and others 2018), there is now widespread recognition of the need for transformational change of environmental governance at the global scale. Marginal mitigation and adaptation policies, although of great significance, will likely not be sufficient for securing human wellbeing in the longer term. Sustainability transformations involve strategies for reconnecting social and economic development to their foundations in the biosphere, acknowledging the close and intertwined bonds between humans and nature (Folke and others 2011). Work identifying leverage points for anticipated and deliberate transformational change toward sustainability are emerging (for example, Abson and others 2017; Moore and others 2014; Westley and others 2011). Deliberate transformation involves breaking down the resilience of the old and building the resilience of the new. It implies governance systems that have the capacity to transform the direction of development in the face of extreme events.

Many systems, from local to global, are currently on trajectories that will likely lead to being inevitably transformed into something unwanted. In such cases, the choice is between being transformed and undertaking deliberate transformation into some new kind of system. The increasing frequency and magnitude of major extreme events puts a particular emphasis on such transformational change.

Practical Governance and Policy for Extreme Events

Based on our exploration of different types of extreme events, challenges associated with their increasing frequency, and some examples of mechanisms to cope with them, we suggest four key considerations for effective governance in the face of extreme events:

1. Discussions of policy options would benefit from a careful assessment of the risks and benefits of responses (Kreibich and others 2014) and their interactions, including the spread among agents about what types of costs, risks or benefits are important. Distributional effects should be considered explicitly.
2. Appropriate responses will require combinations of infrastructures with traditional ''predictive,'' planning, and ''responsive'' capacities, along with new ''anticipatory governance'' structures that focus explicitly on building capacity to anticipate when traditional approaches are too slow (Quay 2010; Fuerth 2011; Guston 2014).
3. Mitigation and adaptation responses should account for fundamental interdependencies that may amplify or attenuate a particular response.
4. Complex responses to extreme events must be navigated and coordinated at and across local, regional, and global levels (Ostrom 2010).

Policies and measures to cope with extreme events are combinations of two general types: 1. limiting exposure to the costs of extreme events and 2. spreading those costs across space, time, and actors. These policies can be further classified into those actions taken ahead of time based on the state of information about the risks (proactive or ex ante), and those taken in response to an actual event (reactive or ex post). Proactive (ex-ante) steps are taken to reduce the probability of an extreme event occurring (typically Level 4–6 responses in biology), or to lessen the negative effect if one occurs; reactive (ex post) steps can only reduce the effect of an event given its occurrence (typically Level 1–3 responses). Proactive steps are investments based on experience of past events coupled with predictive theory to create new fundamental structures (Level 7 responses). Reactive steps are strategies that leverage fundamental structures for fast, flexible, and reversible responses.

Proactive measures typically entail some significant up-front cost that reduces the probability or cost of an extreme event. Proactive measures to reduce the probability of extreme events include reductions in emissions of greenhouse gases to slow climate change and thereby reduce the frequency of damaging hurricanes and floods. Other proactive measures may reduce the cost of an extreme event such as not building expensive homes on beachfronts threatened by hurricanes or sea level rise, constructing buildings that can withstand hurricanes and earthquakes, and developing and using flexible skills and equipment that may not perform any one task optimally but can switch among tasks in response to changing circumstances. All of these cases incur additional costs now to reduce expected future costs. In this sense, proactive measures are similar to an individual paying an insurance premium now to avoid the possibility of facing large losses in the future. Although the availability of insurance does not by itself reduce the likelihood or overall costs associated with extreme events, it can spread the associated losses across a larger group (assuming these losses are not too temporally correlated), thereby reducing an individual's exposure to risk. Ex post responses typically focus on

reducing the time individuals or groups are exposed to the effects of an extreme event, for example, the amount of time without food or shelter, by restoring system function as quickly as possible through disaster response infrastructure.

In practice, governance entities typically employ combinations of these policy types and must face some inherent trade-offs among them. One may accept small frequent losses to avoid a large, rare loss; for example, cities located on a river can have a flood plain that allows regular small overruns, or a levee that allows no water through until it breaks and causes catastrophic flooding. The Forest Service can let small fires burn, or put out every small fire but let material build up until a huge conflagration erupts. In each case, the policies might be combined with moderate or extensive disaster response infrastructure, respectively. Balancing these combinations of policies and associated hard infrastructures is the central challenge of managing extreme events.

Reactive measures can either take the system back to its previous status quo, or change the system to a new state. The former may be called an elastic or bounce-back response, and may be optimal if the event is rare enough and one occurrence does not increase the probability of subsequent ones (no positive serial correlation). For example, hurricanes may become increasingly common or stronger on the east coast of the United States as a whole, but a hit on any specific site may remain a rare risk. In that case, after a hurricane, it may make sense to rebuild there. If the hurricane causes us to revise our probability estimate of future risks, it may be optimal to change the configuration of, and vegetation on, the beach to absorb storm surges; not build very costly properties near the shore (akin to a to response with a temporal scale and reversibility around Level 3 in Figure 1); or in an extreme case even abandon an area near the ocean and relocate the population (akin to a to response with a temporal scale and reversibility around Level 4 in Figure 1). This mode of response becomes more important for events and risks that have positive serial correlation, or network effects that have become increasingly common because of globalization.

Policies can amplify or dampen the effect of an unusual event. The Dust Bowl of the 1930s is widely perceived as a natural event, but the reason drought and wind had such a devastating effect is that farms in the Great Plains invested too little in erosion control, which required collective action at the regional scale (Peters and others 2020). Soil conservation districts, established by the U.S. government after the tragedy, helped coordinate erosion control by creating districts at appropriate scales. As a consequence, droughts in the 1950s and 1970s of comparable magnitude to the ones that occurred in 1930s caused little erosion (Hansen and Libecap 2004). In this example, government action eliminated the risk of another Dust Bowl. Government didn't and couldn't eliminate the probability of drought, but it was the combination of drought and established farming practices, not drought alone, that caused the Dust Bowl. Now the risk of another dust bowl may be increasing as agriculture expands in the Great Plains and drying events rise in frequency (Lambert and others 2020).

When managers attempt to deploy any or all of these policy principles in practice, extreme events pose an especially difficult problem: they often affect large vulnerable populations that lack agency and are socially and politically marginalized. Quite apart from the well-known issues of decision-making studied by psychologists and behavioral economists—cognitive biases including confirmation bias in seeking and interpreting evidence, status-quo bias and procrastination, loss aversion, and so on—the heterogeneity of the affected populations raises challenges of collective action. It is easy for scientists to identify necessary conditions, but much harder to come anywhere close to sufficient conditions for achieving the change working through the existing institutions and governance structures.

At the international level, the very events that pose existential threats to some societies can be beneficial to others (a fundamental characteristic of diversity): climate change that causes unbearable heat and droughts in some countries and regions of the world can bring mild temperatures and raise agricultural productivity in others. In principle, globalization should increase the scope for insurance: when risks are not correlated across countries, pooling them should provide protection for all. However, mechanisms to aggregate and take action in the overall interests of the globe, and to use gains of some countries to compensate the losses of others must be designed and implemented with much thought and care; we offer some examples below. These protections will depend more on the possibilities for collective action among nations, and less on coercive measures. Hierarchical or authoritarian solutions will not last when it comes to dealing with transnational risks. On the one hand, sovereignty of nations will enter into the equation. On the other, nations do not own the territories in the classical property rights

approach (Young, 1994) to deal with actions to adapt, mitigate, or transform to the risks. However, certain heterogeneities, which might be problematic for collective action problems at the local level, can become opportunities for coordination at the international scale (Keohane and Ostrom 1995).

Tsunamis, for example, are a threat to every country within a certain range, and here interests are more consonant. Tsunamis cannot be avoided by human intervention, but their negative effects can be reduced (Dahdouh-Guebas and others 2005). One key component is an early warning system involving a combination of seismometers, sea level gauges, and tsunameters. It is worth recalling that the Boxing Day Tsunami of 2004 hit Sri Lanka a full two hours after the initial quake off the coast of Sumatra. Had Sri Lankans been warned of the incoming tsunami, many thousands of lives could have been saved.

Tsunamis are a regional threat, and it makes little sense for states to invest in their own early warning system. As with farms and erosion control in the Great Plains, what is needed is coordination. Here, the coordination needs to be undertaken regionally, by the states that border the Indian Ocean. Indeed, such a warning system was launched in 2011. However, detection of an approaching tsunami is not enough.

There also needs to be a system for communicating the emergency to communities at risk. Detection is a regional public good, communication a national and local public good. Not only are both systems needed, but each is only of benefit if the other one is also supplied.

Protection of the stratospheric ozone layer and expected repair of past depletion is surely one of the greatest examples of catastrophe avoidance at the global level. Success was achieved by an ingeniously designed treaty, the Montreal Protocol. Three features of this agreement were particularly important. First, the agreement imposed limits on releases of CFCs that were permanent. Second, the agreement arranged for developed countries to compensate developing countries for their costs of compliance. Finally, the agreement was enforced by a ban on trade in CFCs and products containing CFCs, between parties to the agreement and nonparties. This last measure was critical, because it provided a strong incentive for all countries to participate in the agreement (Barrett 2003).

Of course, the world has been much less successful in limiting climate change. There are many reasons for this, but one is the design of the climate treaties. The Kyoto Protocol fell apart for lack of a means to enforce participation. Leaving aside the decision by the US to withdraw, the Paris Agreement has been more successful in this regard. However, this is only because the pledges countries made in Paris to limit their emissions are, by design, purely voluntary. The consequence of this failure to limit atmospheric concentrations of greenhouse gases is that extreme climate-related events will become more frequent and greater in magnitude, stimulating other responses, including adaptation, undertaken primarily at the local and national level, and possibly solar geoengineering, which is itself a risky intervention and the governance of which is particularly tricky since such an intervention could be undertaken unilaterally.

In domestic politics, proposals to adapt or transform usually run up against powerful vested interests, which have methods at their disposal to stymie the ideas: media that do their bidding to misinform or confuse the public, maneuvers to delay or defeat legislation for change, bringing suits to nullify or weaken any laws that get passed, weakening or slowing down regulation, and so on. In spite of the inevitable emergence of vested interests and power asymmetries, some general conditions and examples of successful change can be identified. First, as Mancur Olson argued in his book *The Rise and Decline of Nations* (Olson 1982), crises can destroy prevailing vested interests and open up the route to major transformations. One would not advocate engineering a crisis to achieve change, but the advice of President Obama's advisor Rahm Emanuel, ''Never let a crisis go to waste'' should be remembered and acted upon. Second, democracies have some checks and balances that can stop very bad things from happening, even though they may not be able to marshal the political will to make good things happen. Amartya Sen observed that ''no famine has ever taken place in the history of the world in a functioning democracy'' (Sen 1999).

Transformations are not without their own risks; huge defects of the Tsarist regime led to the Russian revolution, which created its own, perhaps worse, problems. In the same way, extreme events can lead to transformations and these can lead to other extreme events. If we respond to global warming by injecting sulfur particles into the upper atmosphere, these may have their own, as yet unknown, consequences.

Conclusions

Human actions have accelerated the frequency of extreme events. Now we need to accelerate learning how to deal with them. To mitigate the risks of

global changes, we need to transform the way we manage the atmosphere and the biosphere, including changes in how we source energy and produce food. We suggest that low cost, fast, and reversible responses, while necessary, are not sufficient to cope with global-scale extreme events. Promoting investment in the higher cost, slower, and irreversible systemic responses is a public-good challenge, made more difficult by the rising inequalities and polarizations within societies and globally.

The first challenge may be getting people to recognize the increasing frequency of such events, and the need to deal with them. Humans have trouble when dealing with very low probability/high severity events (Barberis 2013), and therefore we still need to better understand why humans under-or over-estimate the likelihoods of extreme events and incorporate that insight into the design of mechanisms (pricing, insurance, ex ante and ex post mechanisms).

Designing policies for extreme events requires a system overview to assess both reactive measures to reduce losses and proactive measures to reduce risks or to recover or transform the system. Redistribution effects of extreme events and policies to address them are likely to substantially influence the feasibility of some policies. The same is true for cognitive biases that may prevent people from opting for the most rational or societally appropriate response to extreme events. Policies can only succeed if they address these issues.

Ideas from research on complex adaptive systems and resilience emphasize preparing for and dealing with change and building capacity to transform, and offer some guidance to operationalize the three key considerations regarding responses to extreme events:

1. Preemptive measures to avoid extreme events that aim to increase general resilience. Here science points to the identification of systemic risk/regime shifts, the role of diversity (not putting all one's eggs in the same basket) and slow variables (which may seem unimportant now but trigger regime shifts later). Improving system knowledge would help identify positive feedback loops, the sets of slow variables that influence them and their critical thresholds (systemic risk elements). This knowledge can then further inform policies targeting safe or precautious boundaries of the critical thresholds and areas where increased diversity for example could be beneficial so that the system remains in a ''safe'' zone to the largest possible extent.
2. Reactive measures to increase specific resilience to particular events. This consideration focuses on putting good policy responses in place that contain elements of redistribution (in time, space and/or between different social categories: insurance payments, catastrophic help) and a learning process that involves reflection on what has happened and whether future policy needs to change to avoid similar issues in the future.
3. Preemptive measures to mitigate negative effects of future catastrophes that cannot be fully avoided. This consideration focuses on preparing the system so that the negative effects of a catastrophe are reduced, either because individuals leave the location during the event or because the built environment is better able (due to targeted infrastructure investments) to absorb it. Examples include introducing early warning signals (Tsunami warning) and robust infrastructure (erosion control to avoid dust bowls, earthquake proof buildings, and so on).

Effective practices to extreme events require addressing all three of these key considerations. Dealing with extreme uncertainty and extreme events may require societal transformation, which will likely be difficult to achieve due to societal preference for the status quo. Successful transformation requires getting past the state of denial, finding or creating new options, and finally helping to initiate and undertake the transformation. In this paper we have provided suggestions for each of these steps.

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