Resistance, recovery, and resilience: rethinking the three Rs of survival in the Anthropocene

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Abstract:

The concepts of resistance, recovery, and resilience are in diverse fields from behavioral psychology to planetary ecology. These "three Rs" describe some of the most important properties allowing complex systems to survive in dynamic environments. However, in many fields—including ecology—our ability to predict resistance, recovery and resilience remains limited. Here, we propose new disturbance terminology and describe a unifying definition of resistance, recovery, and resilience. We distinguish *functional disturbances* that affect short-term ecosystem processes from *structural disturbances* that alter the state factors of ecosystem development. We define resilience as the combination of resistance and recovery—i.e., the ability of a system to maintain its state by withstanding disturbance or rapidly recovering from it. In the Anthropocene, humans have become dominant drivers of many ecosystem processes and nearly all the state factors influencing ecosystem development. Consequently, the resilience of an individual ecological parameter is not an inherent

attribute but a function of linkages with other biological, chemical, physical, and especially social parameters. Because every ecosystem experiences multiple, overlapping disturbances, a *multidimensional resilience* approach is needed that considers both ecosystem structure (configuration of linkages) and disturbance regime. We explore these concepts with a few case studies and recommend analytical tools and community-based approaches to strengthen ecosystem resilience. Disregarding cultural and social dimensions of disturbance regimes and ecosystem structures leads to undesirable outcomes, particularly in our current context of intensifying socioecological crises. Consequently, cultivating reciprocal relationships with natural disturbance regimes and ecosystem structures is crucial to Earth stewardship in the Anthropocene.

Introduction

> *The paradox, in a nutshell, is this: humans have grown so powerful that they have become a force of nature - and forces of nature are those things which, by definition, are beyond the power of humans to control.*
>
> -Oliver Morton, *The Planet Remade*, 2015

The history of the Earth system is a remarkable story of life causing, responding to, and adapting to catastrophic changes (Schlesinger & Bernhardt 2020). In the dynamic environment of our planetary home, the organisms and ecosystems not suited to disturbance are rare or nonexistent. From individual cells to human societies to the entire biosphere, every aspect of the Earth system is shaped by change.

In the Anthropocene, humans have emerged as a force of nature in a way that perhaps no vertebrate organism ever has (Lewis & Maslin 2015; Keys *et al.* 2019; Folke *et al.* 2021). Humans have influenced much of Earth's terrestrial surface for more than ten thousand years (Ellis 2021), but in the past few centuries, we have become the primary force structuring Earth's habitats, biogeochemical cycles, and disturbance regimes (Steffen *et al.* 2015a; Watson *et al.* 2018; Schlesinger & Bernhardt 2020). Humans are now the largest driver of the extinction and evolution of species, and we have shifted patterns of sediment transport, nutrient cycling, carbon balance, climate, water cycling, and wildfire at global scales (Wilkinson 2005; Benson 2012; Steffen *et al.* 2015b; Cooper *et al.* 2018; Abbott *et al.* 2019b; Hurteau *et al.* 2019). Our physical creations outweigh all life on Earth (Elhacham *et al.* 2020), our bodies and livestock account for ~93% of total vertebrate biomass (Bar-On *et al.* 2018), and we have created novel planetary material cycles, including plastics and persistent organic pollutants, with largely unknown impacts on human health and ecosystem functioning (Nizzetto *et al.* 2010; Bank & Hansson 2019; Hannah *et al.* 2022). From changing the structure of the thermosphere to triggering tectonic tremors (Manney *et al.* 2011; Wilson *et al.* 2017; Mlynczak *et al.* 2022), our direct and indirect footprints have altered all the Earth's aquatic, terrestrial, marine, and subsurface environments (Watson *et al.* 2018; Díaz *et al.* 2019; Kolbe *et al.* 2019; Bochet *et al.* 2020; Ellis *et al.* 2021). The land-cover transformation, amplification of biogeochemical flows, and climate disruption that characterize the Anthropocene are triggering transformations that are likely unprecedented in our planet's past (Diffenbaugh & Field 2013; Kemp *et al.* 2015; Ceballos *et al.* 2020; Armstrong McKay *et al.* 2022; Fricke *et al.* 2022).

The combined effects of these Earth system alterations have caused catastrophic global consequences, including diminished quality of life for humankind (Fig. 1). There has been a pervasive decline of species on Earth in aquatic, terrestrial, and marine environments (Vörösmarty *et al.* 2010; Díaz *et al.* 2019; Fricke *et al.* 2022). Environmental pollution, primarily from burning fossil fuels, causes more than 15 million premature human deaths annually—one in four deaths each year (Errigo *et al.* 2020; Vohra *et al.* 2021). This means that our unhealthy relationship with the Earth directly causes more deaths than all violence, malnutrition, and communicable diseases combined (Landrigan *et al.* 2017; Errigo *et al.* 2020; Fuller *et al.* 2022). Ongoing ecosystem state changes threaten the future of billions of people across every country and socioeconomic condition (Abatzoglou & Williams 2016; Van Loon *et al.* 2016; Dupas *et al.* 2019; Mu *et al.* 2020; Cheng *et al.* 2022; Hannah *et al.* 2022). Our individual and communal survival depends on restoring positive and reciprocal relationships between human societies and the ecosystems we have come to dominate (Kimmerer 2002; Sandifer *et al.* 2015; Bradshaw *et al.* 2021; Chapin *et al.* 2022). In this context of accelerating planetary disruption, understanding how ecosystems respond to change is more critical than ever.

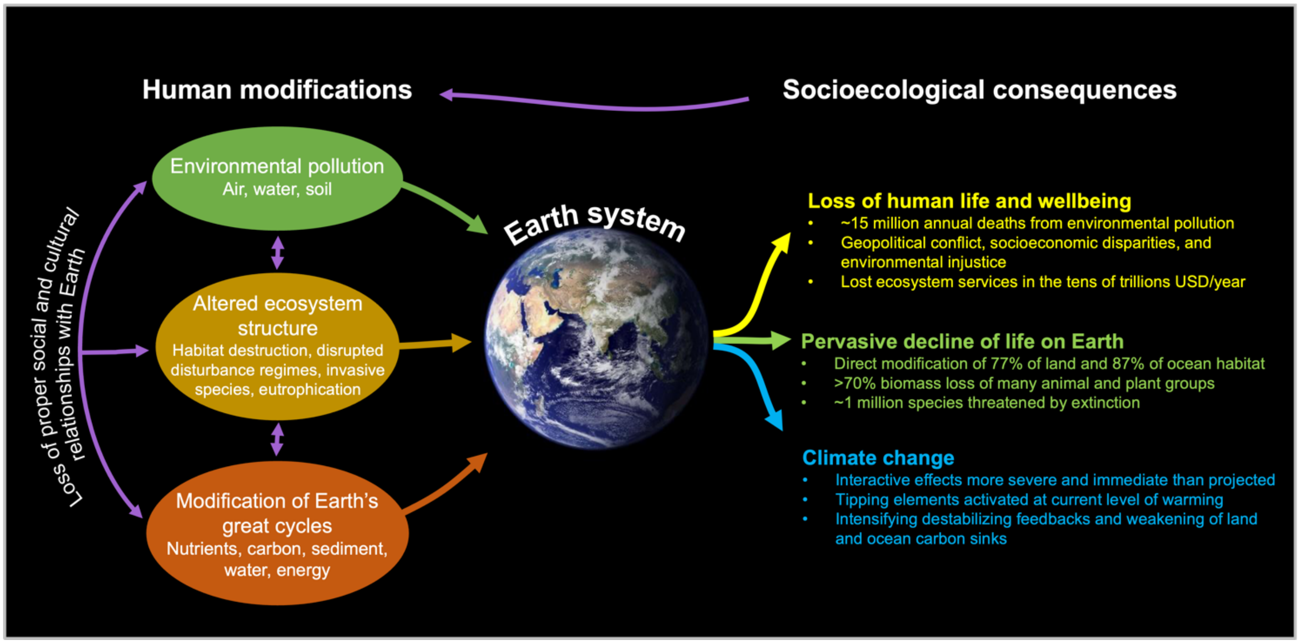

Figure 1. Signs and symptoms of planetary vulnerability in the Anthropocene. Data for specific claims drawn from (*Watson* et al. *2018; Abbott* et al. *2019a; Díaz* et al. *2019; Errigo* et al. *2020; Bradshaw* et al. *2021; Ritchie* et al. *2021; Vohra* et al. *2021; Armstrong McKay* et al. *2022; Fuller* et al. *2022).*

Disturbance, succession, and equilibrium have been central themes of ecology since it emerged as a quantitative science in the 20th century (Tansley 1935; Lindeman 1942; Turner *et al.* 1989; Chapin *et al.* 1994). Across multiple natural and social sciences, a wealth of terminology has developed describing the characteristics of disturbance and system response to ecological and evolutionary change (Callicott & Mumford 1997; Carpenter *et al.* 2001; Redman 2014; Larsson & Abbott 2018; Elmqvist *et al.* 2019; Fuller *et al.* 2019; Barbe *et al.* 2020; Frei *et al.* 2020). However, our ability to predict ecological state changes, such as the collapse of a population or loss of an important ecosystem process, remains limited (Jasinski & Payette 2005; Scheffer *et al.* 2009; Marlon 2020; Schoolmaster Jr. *et al.* 2020; Gouveia *et al.* 2021; Ritchie *et al.* 2021). While deterministic modeling of stochastic events in complex Earth systems has long been out of reach, advances in monitoring and analysis now allow deeper characterization and better prediction of emergent changes and nonlinearities (Loehle 2006; Beven & Alcock 2012; Lum *et al.* 2013; Brunton *et al.* 2016). The development and simplification of multiple sensing technologies have significantly expanded our ability to measure individual and composite vital signs of global ecosystems, including traditional ecological data and near-realtime indices of how information and emotions are moving through human communication networks (Abbott *et al.* 2016; Rode *et al.* 2016; Newman 2017; Zhang *et al.* 2022). At the same time, the development of an extraordinary range of complex systems tools has dramatically enhanced our ability to interpret multivariate data (Barbe *et al.* 2020; Underwood *et al.* 2021; Brunton *et al.* 2022; Heddam *et al.* 2022).

In this context, we convened a group of interdisciplinary researchers and educators to explore how human perception and management of ecosystems affect ecological resilience and vulnerability in the Anthropocene. We begin by presenting new terminology for describing disturbance and then propose a unified framework around what we call the three Rs of survival in the Anthropocene: resistance, recovery, and resilience. Based on definitions from the fields of sustainable development and fluvial geomorphology (Meerow *et al.* 2016; Fuller *et al.* 2019), we define resilience as the combination of resistance and recovery—i.e., the ability of an ecosystem to maintain its state by withstanding disturbance or rapidly recovering from it. We hypothesized that resilience measured in an individual ecological variable is not an inherent attribute but a function of linkages with other social, biological, chemical, and physical parameters, including the disturbance regime (Turner *et al.* 2003; Chapin *et al.* 2022). We present ecological case studies and assess the potential of analytical tools to characterize multidimensional resilience and inform applied solutions. We conclude that successful ecological restoration and planetary sustainability depend on cultivating an ethic of Earth stewardship that recognizes and rehabilitates humanity's unique roles in the Earth system (Steffen *et al.* 2011; Palmer & Stewart 2020; Locke *et al.* 2021; Rockström *et al.* 2021; Chapin *et al.* 2022).

Resilience vocabulary

An advantage and challenge of resilience terminology is its familiarity. Resistance, resilience, and recovery are commonly used to describe a wide range of technical and nontechnical phenomena (Carpenter *et al.* 2001; Allison 2004; Rogers *et al.* 2012; Shade *et al.* 2012; Anderies *et al.* 2013; Elmqvist *et al.* 2019). We recognize the utility and origin of multiple definitions and do not seek to invalidate their use. For the purposes of this paper, we propose the most intuitive and direct meanings based on our opinion and recent scholarship (Chapin *et al.* 2012; Meerow *et al.* 2016; Fuller *et al.* 2019). We note that while some sustainability researchers use a version of the term social-ecological systems (SES) to emphasize human-environment interactions (Anderies *et al.* 2013; Chapin *et al.* 2013; Folke *et al.* 2016), we use the terms ecosystem and ecological as fully inclusive of human dimensions of the Earth system. This is in line with the original definition of the ecosystem concept, and we use these terms deliberately to erode what we see as an unhelpful distinction between society and ecosystems (Tansley 1935; Chapin *et al.* 2012; Abbott *et al.* 2019b). While sustainable development frames economy, environment, and society as competing interests, an Earth stewardship or nature-positive approach sees economy as a nested component of society and society as an embedded and intertwined part of the Earth system (Folke *et al.* 2016; Locke *et al.* 2021; Chapin *et al.* 2022). Human society only exists within ecosystems, and it is is impossible to meaningfully study ecosystems in the Anthropocene without considering society.

An *ecological threshold* describes the boundary between two ecological states or sets of conditions, and a *state change* describes an ecosystem crossing such a threshold, e.g., forest to grassland or clear-water to turbid (Carpenter *et al.* 2020; Cassidy *et al.* 2022). *Ecological resistance* is the capacity to avoid crossing a threshold during or immediately after disturbance. *Ecological recovery* decribes the tendency, degree, and rate of return to pre-disturbance conditions after perturbation. *Ecological resilience* is the combination of resistance and recovery, which therefore describes the likelihood of an ecosystem or ecological variable to be found in a particular state throughout time. *Ecological vulnerability* is the inverse of ecological resilience, describing a system's tendency to transition and stay in a different state. These concepts are summarized visually in Figure 2.

Disturbance is often characterized by intensity, duration, timing, frequency, rate of change, extent, and patchiness. These terms are already quite intuitive, though highly dependent on the observed spatiotemporal scale and resolution (Glasby & Underwood 1996; Poff *et al.* 1997; Kemp *et al.* 2015; Collins *et al.* 2018; Meerow & Newell 2019). For example, a disturbance could be characterized as either a press or a pulse, where the former comes on slowly but potentially lasts longer (low rate of change, long duration), and the latter comes on fast but does not last as long, relative to the timescale of interest (Bergstrom *et al.* 2021). Multiple characteristics of a single disturbance type are often described as the disturbance regime (Mack & D'Antonio 1998; Turner *et al.* 2003; North & Keeton 2008). However, for our purposes, we distinguish between *disturbance characteristics* of an individual disturbance type (e.g., wildfire frequency, extent, severity etc.)

and the *disturbance regime* of an ecosystem, which always includes multiple interacting disturbance types (e.g., wildfire, acidification, logging, climate change, invasive species, etc.) (Atkins *et al.* 2020).

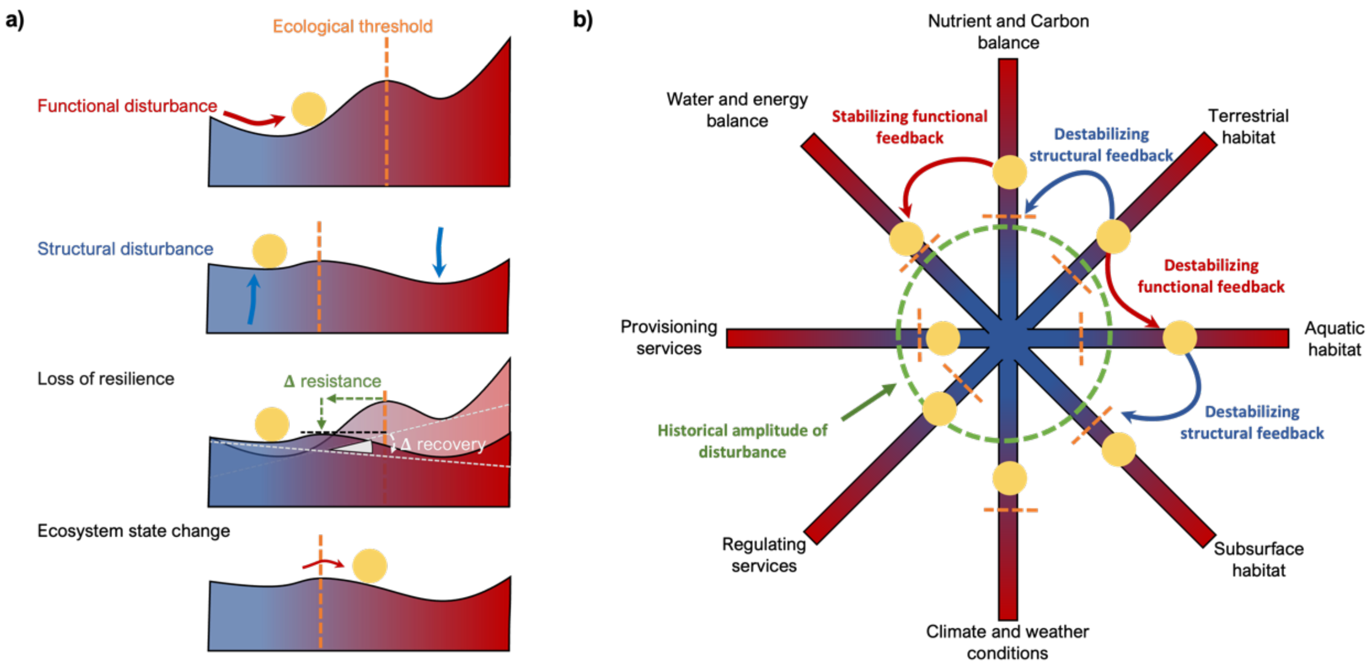

Figure 2. Diagrams of the disturbance and resilience concepts described in this paper. a) Depictions of Ecosystem states (yellow circles), thresholds (orange lines), disturbance types, and response surfaces representing resistance and recovery to disturbance. Functional disturbances change the current ecosystem state, while structural disturbances affect the interacting state factors that regulate the response of the ecosystem to disturbance. b) Top-down view of multiple dimensions of ecosystem state on their respective response surfaces, including feedbacks and thresholds, with thresholds near the center of the diagram representing more vulnerable dimensions. Exceeding a threshold in one dimension is likely to modify the condition and response surface of others, i.e., create a structural disturbance.

We think it is helpful to introduce new terminology for both individual disturbances and disturbance regimes. The state factor concept was originally developed for predicting soil formation (Jenny 1941; Florinsky 2012), and through time it has been applied to ecosystem development and structure (Chapin *et al.* 2012; Tank *et al.* 2020). This concept predicts that a set of initial ecological conditions or *state factors* strongly constrain the development of an ecosystem (Fig. 3). Useful predictions about ecosystem type and processes are possible with knowledge of these state factors: parent material, potential biota, climate, topography, and time since the last major disturbance (Jenny 1941). Human activity has been proposed as an additional state factor, given the extent of anthropogenic influence in the Anthropocene (Chapin *et al.* 2012). We distinguish *functional disturbances* that affect short-term ecosystem processes from *structural disturbances* that alter the state factors of ecosystem development (Jenny 1941; Florinsky 2012; Tank *et al.* 2020). Conversely, disturbances that primarily affect current ecosystem processes would be described as *functional disturbances* (Figs. 2 and 3). This distinction might be informative because it indicates whether a disturbance is likely to affect the short-term status of an ecosystem (e.g., does the functional disturbance exceed the ecological resistance for a given parameter) or the long-term recovery trajectory (e.g., is the structural disturbance severe enough to alter the multidimensional response surface guiding recovery).

We recognize that many disturbances—and especially those controlled by humans—have both functional and structural dimensions. Indeed, there is a continuum between ecosystem processes and state factors depending on the severity of the disturbance and the successional timescale of interest. For example, what might seem like an ephemeral ecosystem process to the geomorphological evolution of a watershed could be an effectively permanent state factor from the perspective of a microbial community (Fisher *et al.* 1998; Shade *et al.* 2012).

Combining these concepts, we define *multidimensional resilience* as an ecosystem's ability to maintain its state under a current or future disturbance regime through a combination of resistance and recovery. We hypothesize that multidimensional resilience depends on ecosystem structure—the configuration of linkages among the state factors and ecosystem processes—which itself is influenced by the disturbance regime (Adler 2019; Frei *et al.* 2020; Mo *et al.* 2020). More specifically, we hypothesize that the physical, chemical, and biological structures of the critical zone—the portion of the ecosystem from unweathered bedrock to the vegetation canopy (National Research Council 2001; Chorover *et al.* 2007)—strongly influence its resilience and vulnerability (Figs. 1-3). For this concept of multidimensional resilience to be relevant for research or management, human participation in the physical and biological structure of the critical zone must be integrated (Chapin *et al.* 2022).

Because many of these terms have emotional connotations in nontechnical usage, we point out that the disturbance and resilience terminology presented above does not connote desirability or ecological value (Elmqvist *et al.* 2019). For example, resilience of can be negative (i.e., unhelpful) when present in undesirable aspects of the system, such as antisocial trends of disregard for the environment or fellow humans. Likewise, a specific disturbance can be positive or negative depending on the ecosystem structure (including human needs and goals) and broader disturbance regime.

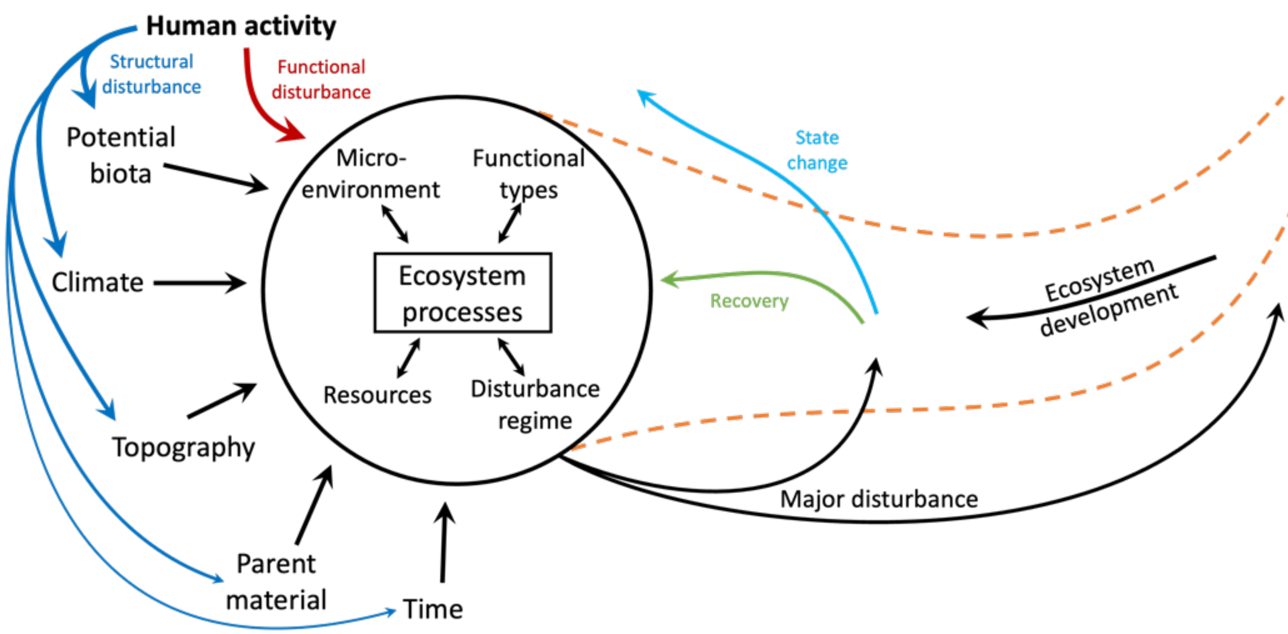

Figure 3. Conceptual diagram of ecosystem development adapted from Chapin et al., (2012). We have added the distinction between structural and functional disturbances as well as the effect of human activity on state factors.

In the following paragraphs, we elaborate these concepts with examples from catchment hydrology and freshwater biogeochemistry to evaluate how ecosystem structure (i.e., the configuration of social, biological, chemical, and physical attributes in the critical zone) influences the timing, direction, and intensity of linkages among multiple responses and consequently multidimensional resilience.

Case Study 1: Artificial resistance through erosion control

Because humans have long congregated along river networks, flood control and fluvial erosion have been areas of focus in ecosystem management for centuries (Allaire 2016; Fang & Jawitz 2019; Tate *et al.* 2021; Sanders *et al.* 2022; Syvitski *et al.* 2022). Human efforts to control rivers and floodplains have yielded both benefits and major problems, including environmental injustice and substantial loss of life (Reisner 1993; Tate *et al.* 2021; Sanders *et al.* 2022; Sowby & Hotchkiss 2022). This highlights the need to consider human culture and infrastructure as integrated components of ecosystems, with similar unanticipated behaviors (Leavitt & Kiefer 2006; South *et al.* 2018; Wohl 2019; Wang & He 2022).

The northeastern United States provides well-documented examples of multiple agrarian and industrial disturbances of river networks (Wolock 1995; Armfield *et al.* 2019). In this region and many areas globally, the provisioning of clean water for drinking, agriculture, and aquatic ecosystems is threatened by low geomorphological resistance to changes in river flow (Davis *et al.* 2009; Abbott *et al.* 2018a; Zarnetske *et al.* 2018; NASEM 2020). Two examples of vulnerability are 1) headwater stream networks with susceptibility to hillslope and channel erosion due to glacial history, and 2) valley and piedmont river corridors with large legacy sediment stores that are coupled closely with receiving waters (Pinay *et al.* 2018; Dearman & James 2019). The legacy of glacial and ice sheet retreat has created bouldery tills and fine glacio-lacustrine clays. This combination of high energy streams that can come into contact with glaci-lacustrine clays through streambank or bed erosion (Davis *et al.* 2009) creates significant stream management challenges. The postglacial context creates low resistance but high recovery regarding sediment transport. Exceeding modest thresholds of stream movement during high streamflows can trigger multiple problems including mass movement (landslides) and persistent high turbidity levels in downstream drinking water reservoirs.

While these environments regularly transported large amounts of sediment naturally during the Holocene, European settlement altered sediment sources and sinks. Forest clearing for agriculture and the construction of many small dams resulted in the accumulation of sediments along the river corridors (Dearman & James 2019; Johnson *et al.* 2019; Jiang *et al.* 2020; Noe *et al.* 2020). This combination of land use and vulnerable critical zone structure is now threatening the provisioning of drinking water for millions of people in the New York metropolitan area.

Over the past several decades, stream and watershed management efforts have been designed to counterbalance the overabundance of sediment sources in river systems to maintain. Engineering-oriented techniques initially focused on increasing resistance to erosion (Fig. 4), including armoring streambanks and hillslopes and dredging to termporarily increase flood conveyance (Bernhardt & Palmer 2007; Wohl *et al.* 2015). However, these techniques have proven very short lived given the artificial disequilibrium (e.g., legacy sediments) and natural characteristics of the critical zone structure (e.g., high sediment availability in postglacial landscapes). Management interventions have so far largely treated symptoms rather than causes while also creating greater problems upstream and downstream of the hard-parth interventions. However, because of the high societal value of the drinking water provisioned by this ecosystem, the inefficient management approach has been acceptable (Davis *et al.* 2009; NASEM 2020). The question is whether society will continue to support this kind of active river management or call for a change. The underlying hypothesis has been that sufficient resources (financial and human capital) are available to respond to the shifting disturbance regime (greater magnitude and intensity of storms, increased persistence and magnitude of precipitation) with ecohydrological expertise continually nudging the system back towards a more "natural" equilibrium in an effort to create a more resistant critical zone structure. As such, watershed and drinking water managers have prioritized extensive mapping of glacial tills and clays and initiated an active management program including streambank and hillslope stabilization, floodplain reconnection, and full-channel restoration (NASEM 2020).

Seeking to enhance river system resilience by maximizing resistance can create rigidity that results in continual or ever increasing management costs and decreasing ecosystem function and safety (Fig. 4). Seeking to preserve or restore local disturbance regimes—including sustainable human land use and other activities—is a much more robust approach with many more co-benefits (Bishop *et al.* 2009; Christianson 2015; Houlton *et al.* 2019). However, overlying regional disturbance regimes that include increasing flow magnitudes and changes in precipitation patterns may require more frequent stabilizing feedbacks from active watershed management in order to maintain clean water provisioning. This highlights the importance of cultivating more meaningful and multidimensional relationship between local societies and the ecosystems they depend on. This avoids undue focus on a single ecosystem service, such as seeing a watershed primarily or exclusively as a drinking water provisioning device.

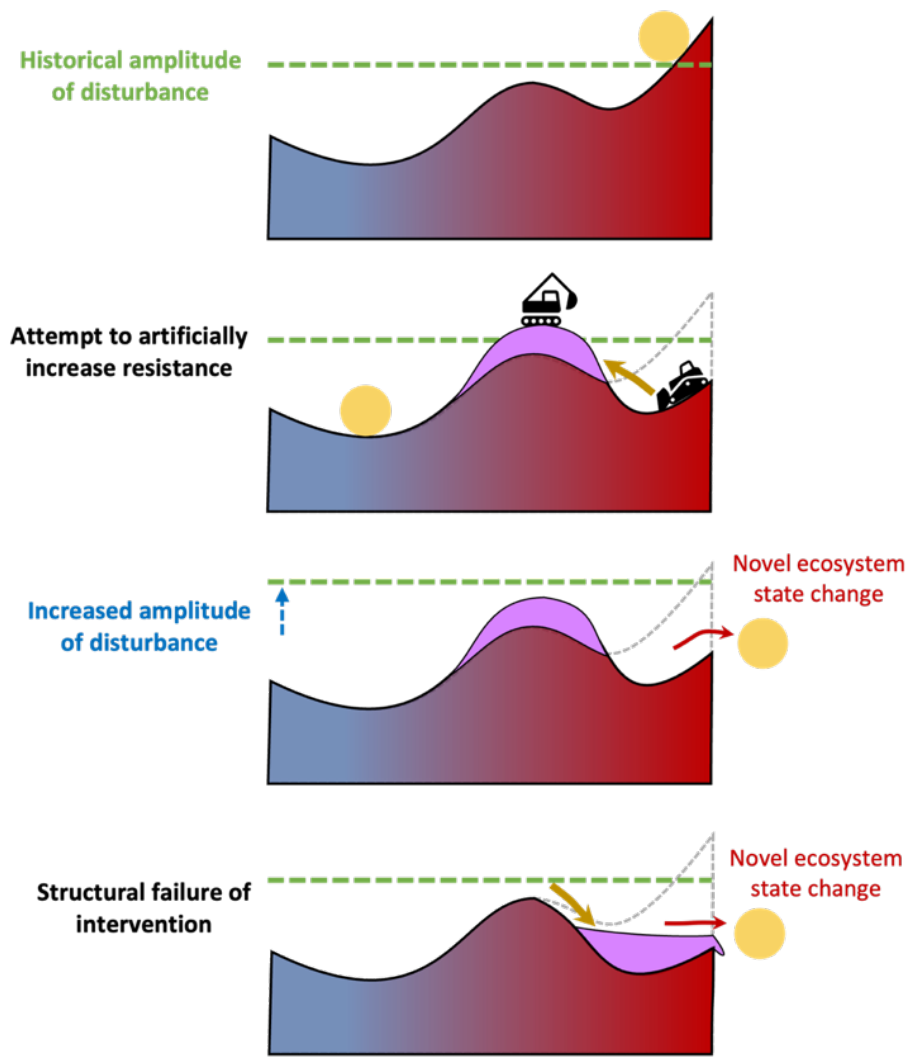

Figure 4. Conceptual examples of how changing disturbance regimes and intentional modification of ecosystem structure can lead to greater vulnerability. Managing for resistance (i.e., modifying structure to impose physical constraints on the system and its dynamic ecosystem states) often leads to rigidity that can result in catastrophic transformations when the system is subjected to a new disturbance regime with increased amplitude of disturbance (e.g., higher flood magnitude).

This case study showcases a broader shift toward *naturalness* as a more resilient and cost-effective management strategy in dynamic environments (Bishop *et al.* 2009; Palmer & Stewart 2020). Recent stream restoration practices recommend restoring naturalness to disturbance regimes by removing obstructions (dams, berms, levees) and buying out flood damaged homes to allow the river system more room to dynamically adjust to increased flows (Fig. 5). This management shift is informed by observations that the more altered and artificial a system is, the more rigid and high maintenance it tends to be(Bishop *et al.* 2009). Additionally, more extreme modifications of critical zone structure and disturbance regime create more severe tradeoffs and compromises(Palmer & Stewart 2020; Abbott *et al.* 2021a).

Case study 2: Coastal forests and sea level rise

Human-caused sea level rise from ice melt and thermal expansion has progressed much faster than expected and is currently tracking the most extreme model projections (King *et al.* 2020; Slater *et al.* 2020; Boers & Rypdal 2021; Heinze *et al.* 2021). This quintessential press disturbance is interacting with the pulse disturbances of extreme storms (Crandall *et al.* 2021; Fowler *et al.* 2021; IPCC 2021). Coastal forests have been categorized into two bands based on proximity to the ocean (Fagherazzi *et al.* 2019; Kearney *et al.* 2019; Mo *et al.* 2020). Stands of mature trees that established before major sea level rise and storm intensification can be found within a meter above the normal high tide. These stands are resistant to storm surges because the adult trees can survive temporary inundation by salt water, partly by accessing fresh groundwater. However, they are not resilient because recruitment cannot occur in salinized soil. As windfall and old age kills adult trees, the mature stands are overtaken by marshes that are more able to survive frequent seawater inundations and take advantage of the increased light availability (Fagherazzi *et al.* 2019).

Above the mature, resistant zone near the ocean, there is an area described as the Regenerative Zone because tree recruitment is still occurring (Kearney *et al.* 2019; Paldor *et al.* 2022). This zone is more distal and higher in elevation, meaning the storm surges less frequently introduce ocean waters and the degree of salinity in soils is less and within the tolerances of germination and seedling recruitment.

This case study shows the interaction between anthropogenic structural disturbances and a relatively unmanaged ecosystem. Sea level rise and storms are interacting structural disturbances that have altered the state factors of coastal vegetation development. The change in hydraulic gradient associated with sea level rise and the increased risk of windfall in saturated soils are precluding the persistence of the near-shore community while also accelerating its decline (Paldor *et al.* 2022). These structural disturbances would change the management options, precluding reestablishment of ecological communities in their former locations, but allowing community shifts were adjacent environments conserved and left dynamic.

Case Study 3: Paleo and present climate change effects on the permafrost zone.

The permafrost zone in polar regions provides a useful example of response to perturbation because of the dramatic climatic changes it has experienced over the past 30,000 years and its importance to Earth's climate over the next several centuries (Lindgren *et al.* 2018; Finger & Rekvig 2022; Schuur *et al.* 2022). The terrestrial and subsea permafrost regions contain nearly 3,000 Gt of organic carbon, more than the sum of all other soil, the atmosphere, living biomass, and cumulative human emissions since the Industrial Revolution (Bar-On *et al.* 2018; Abbott *et al.* 2019a; Abbott 2022). These massive stocks of organic matter have been described as climate-protected, as they have been stabilized by persistent cold and wet conditions, which limit microbial and abiotic decomposition (Ernakovich *et al.* 2022; Schuur *et al.* 2022). Gradual climate warming after the Last Glacial Maximum (LGM), some 26,500 years ago, resulted in over 100 meters of sea level rise, retreat of ice sheets, and widespread development of lakes and peatlands (Lindgren *et al.* 2018; Sayedi *et al.* 2020). These enormous reorganizations were archetypal structural disturbances that altered land-water linkages, long-term carbon and nutrient balance, and distribution of vegetation. These changes created a state of net carbon uptake over large portions of Arctic Tundra and Boreal Forest, which has only recently been forced into carbon release because of anthropogenic climate change (Hayes *et al.* 2011; Turetsky *et al.* 2020; Schuur *et al.* 2022).

Across high-latitude and high-elevation ecosystems, local ecosystem structure modulated to effects of the gradual climate press that caused the transition from the Pleistocene to the Holocene. Organic soil horizons and vegetation strongly influence the exchange of heat between the atmosphere and the soil, creating up to 12ºC of difference between mean annual soil temperature relative to the overlying air (Shur & Jorgenson 2007). The development of soil and vegetation protected many Pleistocene permafrost deposits, imparting thermal resistance that effectively arrested—or at least delayed—the deglaciation process (Shur & Jorgenson 2007; Kokelj *et al.* 2017; Loranty *et al.* 2018; Strauss *et al.* 2022).

Ongoing anthropogenic warming is much more abrupt than the relatively gradual glacial-interglacial transition (Bova *et al.* 2021; Cheng *et al.* 2022), particularly in the permafrost zone, which is warming 3- to 6-times faster than the global mean (Abbott 2022; Abbott *et al.* 2022). This increased amplitude of climatic disturbance (Fig. 4) has surpassed the protective resistance of Holocene-aged soils and vegetation, triggering abrupt thaw and surface collapse in many of the regions with highest carbon densities (Olefeldt *et al.* 2016; Turetsky *et al.* 2020). Additionally, rapid warming is altering permafrost disturbance regimes. Functional disturbances such as wildfire are becoming more common and widespread (Mack *et al.* 2011), accelerating the structural disturbance of permafrost collapse, which together affect long-term carbon, nutrient, and water balance (Larouche *et al.* 2015; Moskovchenko *et al.* 2020; Rodríguez-Cardona *et al.* 2020; Abbott *et al.* 2021b). More acutely, the destabilization of permafrost soils, coastlines, and shorelines is profoundly impacting marine and terrestrial wildlife and the diverse human cultures of the permafrost zone (Chapin *et al.* 2013; Bronen *et al.* 2020; Abbott *et al.* 2022).

This case study demonstrates the interactions between the local structure of the critical zone and global climate change. Perhaps more importantly, it highlights some of the difficulties of creating Earth stewardship when the causes and consequences of environmental degradation are highly separated in space and time. Greenhouse gas emissions from outside of the permafrost zone are eroding resistance and recovery of permafrost ecosystems, including human villages and transportation infrastructure at circumpolar scales (ICC 2022). Communities in the permafrost zone have been innovative in adaptation and local mitigation (Chapin *et al.* 2013; Bronen *et al.* 2020; Abbott *et al.* 2022). At the same time, many community members are using intergovernmental forums such as the Arctic Council and Inuit Circumpolar Council to increase climate mitigation commitments to address the source of the problem: burning of fossil fuels (Johnson 2010; Kristoffersen & Langhelle 2017; Arctic Council 2022; ICCI 2022). This shows the intersection of local community stewardship and global environmental governance, both of which are needed to resolve environmental injustice in the Anthropocene (Errigo *et al.* 2020; Webber *et al.* 2021; Chapin *et al.* 2022).

Case study 4: Hydrochemical recovery from acidification in the stormier present

Critical zone structure in watersheds in eastern North America and central Europe has been impacted by multiple changes to disturbance regimes over the past century. Terrestrial and aquatic ecosystems were subjected to decades of atmospheric acid deposition, which led to reduced soil pH and base cation loss from soils (Likens & Bormann 1974; Wettestad 2018). Environmental legislation on both continents reduced acid deposition starting in the 1980s, creating a natural experiment of recovery for watersheds with diverse critical zone structures (Likens 2013; Daniels *et al.* 2020; Hannah *et al.* 2022). In the decades since, many watersheds have seen streamwater dissolved organic carbon (DOC) and phosphorus concentrations increase (Evans *et al.* 2005; Kopáček *et al.* 2015), while streamwater inorganic nitrogen concentrations have decreased (Driscoll *et al.* 2003). Many studies have explored the mechanisms that may explain these temporal patterns, invoking various explanations including reduced mineralization under low soil pH, stabilization of soil aggregates at high ionic strengths/low soil pHs, and reduced vegetation uptake as a result of base cation limitation (Rosi-Marshall *et al.* 2016; Armfield *et al.* 2019; Cincotta *et al.* 2019).

Concurrently, these regions have been experiencing an increasing frequency of extreme hydrologic events. Large precipitation events have been linked to substantial flushing and export of carbon and nitrogen, thus comprising the majority of annual export in some watersheds (Raymond *et al.* 2016; Zarnetske *et al.* 2018; Kincaid *et al.* 2020). A recent study at Hubbard Brook Experimental Forest suggested that recovery from acidification and increasing frequency of extreme precipitation events interact in important ways, with greater stormflow nitrate export in an experimental watershed recovering from acidification (Marinos & Bernhardt 2018). This suggests that a multidimensional resilience approach is needed to understand the complex biogeochemical responses to acidification, recovery, and changing hydrologic regimes.

Figure 5. Examples of vulnerable and resilient approaches to human development in dynamic ecosystems. Each row shows how a different ecosystem structure responds to the functional disturbance of a flood. The first two rows were inspired by Delgado (2020).

While there are broad regional trends in these responses to reduced acid loading, there is a considerable degree of variability across individual catchments, likely associated with critical zone structure. For example, variability in DOC trends across catchments in New England depended on soil characteristics and depth (Adler *et al.* 2021). Well-buffered, calcite-dominated watersheds are recovering faster than granitic watersheds with limited ability to buffer changes in soil pH. Differences in watershed topography and slope may lead to variability among watersheds in their hydrologic responsiveness to extreme events.

Rethinking the R's in the age of Big Data:

These case studies show how ecosystem structure and disturbance regimes interact to determine multidimensional resilience. To predict and prevent dangerous ecological state changes in the Anthropocene, we now need to dramatically advance our understanding of the nature of these interactions at global scales (Jiang et al. 2018; Turner et al. 2019). In many ecological contexts, resilience and resistance are viewed as mono-dimensional properties—e.g. collapse in a biological population or breakdown in an atmospheric or oceanic current (Liu et al. 2019; Steffen et al. 2018)—rather than as a nested, interacting system that intrinsically depends on the structure and state of the ecosystem. If resilience does indeed emerge from the ecosystem structure—the linkages across physical, biological, and social systems—this adds complexity but could also substantially increase predictive power (Gouveia *et al.* 2021). Indeed, we could be on the cusp of major breakthroughs in humanity's ability to quantitatively monitor and manage ecosystems for resilience. The availability of data from multiple observatories and monitoring networks at site to global scales (Leon *et al.* 2019; Brown *et al.* 2021; Ebeling *et al.* 2021; Heiner *et al.* 2022; Shogren *et al.* 2022) and the emergence of techniques that can analyze such voluminous and intricate data streams (Bergen et al. 2019) create an unprecedented opportunity to identify individual and interactive controls on ecosystem response to disturbance.

Until recently, characterizing multidimensional interactions at necessary spatiotemporal scales has been beyond the scope of disciplinary three- to five-year ecological projects (Abbott *et al.* 2016; Kolbe *et al.* 2019; Thomas *et al.* 2019). With the advent of new technology such as in situ sensors and remote sensing (e.g., lidar), we are amassing high volumes and a wide variety of observational data that can be used to test hypotheses about ecosystem response to disturbance regimes and associated water, carbon, and nutrient dynamics (Demchenko 2013). This big data revolution has had revolutionary effects across disciplines

(Alexander et al. 2015; Li et al. 2012) and is poised to transform ecosystem science as well (Reichstein et al. 2019). The recent emergence of new statistical and machine-learning algorithms has been driven, in part, by the advances in distributed computing and storage that accompany long-term monitoring, but more importantly, by the challenges in mining and analyzing these large, multi-scale, data-rich complex systems (Loehle 2006; Beven & Alcock 2012; Lum *et al.* 2013; Brunton *et al.* 2016).

Collectively, complex-systems tools comprise a variety of approaches including machine-learning algorithms, nonparametric statistics, network analysis, Bayesian inference, stochastic models, and evolutionary computation (Marçais & de Dreuzy 2017; Underwood *et al.* 2017; Shen *et al.* 2018; Frei *et al.* 2021). They can be used for classification, regression, and prediction tasks in the analysis of ecological dynamics across scales. A subset of machine-learning algorithms called 'deep learning' shows promise for advances in classification, anomaly detection, regression and prediction, where state variables are spatiotemporally dependent (Reichstein et al. 2019)—the default assumption for coevolving ecosystem structures and disturbance regimes (Thomas *et al.* 2016; Abbott *et al.* 2018a; Adler 2019). Deep learning models have gained rapid adoption in certain fields such as hydrology where long short-term memory (LSTM) models have eclipsed the performance of existing physics-based models in certain tasks (e.g., rainfall-runoff modeling) and are now being explored for their ability to capture hydrological concepts (Kratzert *et al.* 2019; Jiang *et al.* 2022; Lees *et al.* 2022). Three-dimensional convolutional neural networks have enhanced lidar-based forest inventories by spatially resolving individual tree crowns and distinguishing needle-leaf trees from deciduous (Ayrey & Hayes 2018). Image-based deep learning models have also been used for classification and interpretation of water quality dynamics such as with storm event suspended sediment transport (Hamshaw *et al.* 2018).

These tools are simultaneously revolutionizing the acquisition, cleaning, and analysis of multivariate ecological data (Hamshaw *et al.* 2018; Underwood *et al.* 2021; Wu *et al.* 2022). We can apply complex-systems tools to draw inferences from both terrestrial and aquatic signals of high temporal and spatial resolution (e.g., lidar first returns, time series of rainfall-runoff patterns or concentration discharge monitoring data) that serve as integrators of ecosystem dynamics, and have the potential to reflect the large-scale impacts of disturbances on the Earth system as a whole. For example, machine-learning algorithms are increasingly being used to learn patterns from data for both clustering (i.e., unsupervised) and classification (i.e., supervised) tasks (Bergen et al. 2019). Unsupervised neural networks such as Self-Organizing Maps have been used to cluster catchments with similar combinations of multi-variate catchment attributes (Underwood 2017). Supervised methods, including nearest-neighbor and 'random forests' imputation methods, have been applied to model forest structural parameters including biomass and total timber volume using predictor variables generated from lidar data or orthoimagery (Latifi et al. 2010). Supervised methods are especially useful for cases such as this where manual classification would be too time-intensive, but can also be used to learn something about the multivariate feature interactions that manifest in an outward class or condition (Underwood et al. 2021).

In addition to the technical advances, this complex data revolution is accelerating conceptual crosspollination and opening doors to new collaborations among traditional ecological knowledge holders, researchers, and managers (Kimmerer 2002; Shen *et al.* 2018; Sayedi *et al.* 2020). Even terminology from the study of dynamical systems is helpful when describing ecosystem state and development. Attractors or basins of attraction are self-organizing or favored system configurations, and alternative stable states or multistability is the existence of multiple possible resilient ecosystem configurations (Dudkowski *et al.* 2016). Structural disturbances can erode resilience by creating alternative attractors that alter the recovery trajectory or reducing the resistance of the original ecosystem state (Fig. 2). The flexibility and power of complex system tools have only begun to be tapped. We think that major breakthroughs will occur as collaborations increase among Earth system scientists and local knowledge holders with deep intuitive and quantitative understanding of their systems, managers who know the pressing ecological questions and challenges, geospatial analysts who can collect massive amounts of remotely-sensed data, scientific instrument engineers who can facilitate direct measurements, and data scientists who can manage and implement data workflows, and finally control theorists and complex systems scientists who can help with interpretation and application.

People as a positive part of the ecosystem concept

Reminding researchers and readers not to forget people may sound ludicrous. Most of us are working on global environmental change, constantly engrossed in the causes and consequences of human alteration of the Earth system. However, ecosystem ecology, hydrogeology, and many fields central to critical zone science tend to exclude humans implicitly and explicitly, often focusing on reference watersheds with no direct human influence or using "natural" conditions prior to the Anthropocene as a baseline (Chorover *et al.* 2007; Fandel *et al.* 2018; Abbott *et al.* 2019b; Ellis *et al.* 2021). Indeed, our focus on problems created by humanity can lead to bias against modified ecosystems despite their prevalence and indispensability in creating a sustainable global community (Hagerhall *et al.* 2004; Abbott *et al.* 2019b; Blaszczak *et al.* 2019; Elmqvist *et al.* 2019; Hill *et al.* 2022). Likewise, academic researchers and natural resource managers sometimes view environmental solutions as technical interventions to be imposed on communities rather than a tool for cultivating long-term relationship and cultural change (Chapin *et al.* 2022). In an ideal world, we would think in terms of communities and watersheds rather than administrative management units and environmental policies. There are compelling practical and ethical reasons for including human dimensions of ecosystems on both sides of resilience, i.e., when characterizing disturbance and considering the response. The social solidarity and respect we need to face intensifying ecological crises in the Anthropocene are unlikely in an environment of disciplinary dismissal and divisiveness (Allaire 2016; Abbott *et al.* 2018b; Webber *et al.* 2021).

Meaningful predictions and successful management depend on fully integrating human cultural and social dynamics into our conceptualization of ecosystems (Budds *et al.* 2014; Linton 2014; Abbott *et al.* 2021a; Chapin *et al.* 2022). While consideration of the human dimensions of ecosystems is necessary from a harm reduction perspective, it is arguably more important for the establishment of pro-environmental norms, policies, and individual behaviors (Behailu *et al.* 2016; Schuster *et al.* 2019). Examples of positive human-environment interactions are needed as models and motivators to accelerate cultural change (Kimmerer 2002; Palmer & Stewart 2020; Locke *et al.* 2021; Ansari & Landin 2022; Chapin *et al.* 2022).

Conclusions

We conclude that conceptual and practical rapprochement of human culture and the ecosystems we are a part of can enhance ecological resilience. Specifically, meaningful relationships with and affection for our local environment can lead to sustainable norms, policies, and behaviors that humanity and the Earth system as a whole need urgently. We conclude that resilience emerges from the ecosystem structure—the linkages across physical and biological systems, especially human society. Finally, we recommend modeling human infrastructure and development patterns on natural disturbance regimes. Maximizing resistance is not a reliable strategy for maintaining ecosystem function, including ecosystem services, in the Anthropocene. Instead, we need connected and expansive habitat, disturbance regimes that are as natural and unregulated as possible, and complete and redundant biological communities, including all dimensions of human diversity. While creating and sharing an ethic of Earth stewardship is a multi-generational project, thankfully, we are not starting from zero. There are threads of stewardship and sustainability in every human culture and our species likely has an evolutionary penchant for environmental connection and care. It is our task to emphasize and cultivate these precious legacies.

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