Available online at www.sciencedirect.com

ScienceDirect

Current Opinion in Environmental Sustainability

Balancing efficiency and resilience objectives in pursuit of sustainable infrastructure transformations

Samuel A Markolf[1], Alysha Helmrich[2], Yeowon Kim[3], Ryan Hoff[2] and Mikhail Chester[2]

Efficiency (i.e. optimized use of resources) and resilience principles (i.e. redundancy, diversity, etc.) are often at odds with one another. Despite being particularly acute within infrastructure systems, this tension appears to be under-explored. However, recent advances in ecological and social sciences provide some novel insights into navigating efficiency–resilience trade-offs. Overall, efficiency and resilience are both vital for a system's longevity and striking a dynamic balance between the two appears to be crucial. Striking this balance in infrastructure systems can be catalyzed by the treatment of resilience as a public good, as well as incorporating exploratory models and stakeholder coproduction in the design and implementation process. Ultimately, the dynamic balance between efficiency and resilience can play a central role in our infrastructure's ability to successfully operate in environments that increasingly fluctuate between stable and unstable conditions.

Addresses
[1] Civil and Environmental Engineering, University of California-Merced, Merced, CA, USA
[2] School of Sustainable Engineering and the Built Environment, Arizona State University, Tempe, AZ, USA
[3] Civil and Environmental Engineering, Carleton University, Ottawa, Ontario, Canada

Corresponding author: Samuel A Markolf (smarkolf@ucmerced.edu)

Current Opinion in Environmental Sustainability 2022, **56**:101181

This review comes from a themed issue on **The role of infrastructure in societal transformations**

Edited by **Melissa R Gilbert**, **Hallie Eakin**, and **Timon McPhearson**

For complete overview of the section, please refer to the article collection, "The role of infrastructure in societal transformations"

Available online 13th May 2022

https://doi.org/10.1016/j.cosust.2022.101181

Introduction and background

Recent events like COVID-19 and the 2021 Winter Storm in Texas highlight a fundamental tension between efficiency (i.e. optimized system performance and use of resources) and resilience (i.e. capacity to identify, anticipate, prepare for, mitigate, and adapt to potentially disruptive changes and hazards) [1]. For instance, past recommendations for higher electricity generation reserve levels and increased weatherization of system components (i.e. resilience efforts) in the Texas power grid [2] were not heeded prior to the widespread outages that occurred during February 2021. The lack of resilience efforts was likely due, in part, to the perception that these actions were unnecessary or unjustifiably costly (i.e. not aligned with efficiency objectives) [3]. This tension is intrinsic to the contradictory natures of efficiency and resilience. Efficiency strives to minimize waste (in the form of time, money, effort, resources, and other inputs) and maximize outputs/outcomes [4]. Conversely, resilience is characterized by traits such as robustness, redundancy, diversity, flexibility, agility, and learning that appear to be antithetical to efficiency objectives [5–9]. A description of each of these traits is provided in Table 1. Efficiency is particularly well suited for stable operating conditions and environments, while resilience is conducive to conditions of instability, complexity, and chaos [10]. Likewise, efficiency is bolstered by processes of mechanization and standardization [11], while resilience is often bolstered by factors like creativity, improvisation, and extensibility [7,12].

Infrastructure systems are often built and managed according to predetermined codes and practices (i.e. standardization). Additionally, they are often designed and built with the intent of lasting several decades — partly due to assumptions of system and environmental stability [14–16]. As a result, many of these systems appear to (implicitly or explicitly) emphasize efficiency in their design and implementation — potentially at the expense of resilience. Contrary to other disciplines (e.g. ecology, leadership, and organizational change), the body of knowledge/practice related to infrastructure systems does not appear to contain much exploration of the efficiency–resilience tension. Although outside the scope of our analysis, we acknowledge that there is associated work in many areas of literature including (but not limited to) reliability engineering, robust control, risk management, multicriteria decision making, and decision making under deep uncertainty. Nonetheless, this article places particular emphasis on applying knowledge from the ecological and social sciences to the engineering/infrastructure domain.

Table 1

Description of various traits associated with resilience.

Resilience Traits	Description
Robustness	System's ability to absorb disturbances, often via strengthening and hardening of system components
Redundancy	The capacity or functionality of system components to compensate for each other
Diversity	The variety, balance, and disparity of elements within a system
Flexibility	System's ability to respond to both regular and irregular (non-incremental) changes
Agility	System's ability to transform in response to unexpected changes or opportunities

Source: Adapted from [5–9,13].

Considering the increasingly complex, uncertain, and unstable conditions our infrastructure systems are likely to experience [17], we strive to stimulate more explicit consideration and management of the efficiency–resilience tension within infrastructure systems — and ultimately help strike a dynamic balance between the two. As detailed below, we explore and synthesize key bodies of knowledge on this topic and posit how they can be applied more directly to engineering and infrastructure systems.

Prior to exploring these topics in more detail, we define our conceptualization of infrastructure systems, and provide more context about the scope of our analysis. Infrastructure systems are composed of two key elements: 1) the physical assets/components and 2) the institutions, organizations, and processes that design, construct, manage, use, and decommission the physical assets [8,17,18]. There is also a network component to each of these elements. The physical assets are often connected to each other by the flow of energy and materials, while the institutional assets are often connected to each other (and to the physical assets) by the flow of information [19]. Generally, we consider infrastructure systems to comprise a wide range of entities: power systems, energy systems, water systems, transportation systems, information/communication (ICT) systems, healthcare systems, finance systems, education systems, etc. However, in the context of this article, emphasis is placed on systems that provide crucial goods and services (e.g. reliable access to power/energy, clean water, mobility/accessibility, ICT connectivity, and health care) via large-scale and interconnected physical and institutional networks. Given this context, the remainder of this article is organized as follows. The next section synthesizes some of the key literature from ecology and ecological economics related to efficiency and resilience. This discussion is particularly applicable to the physical components of infrastructure systems. Subsequently, we synthesize some of the key literature from business, management, and organizational theory related to efficiency and resilience. This discussion is particularly applicable to the institutional components of infrastructure systems. The final section posits how some of the key themes from these diffuse bodies of knowledge can be applied to help instill more balance between efficiency and resilience in engineering and infrastructure systems.

Ecological sciences and the 'window of vitality' as a basis for efficiency and resilience across the physical elements of infrastructure

Regarding physical systems and networks, there is an established body of knowledge rooted in ecology and ecological economics that espouses the importance of both efficiency and resilience for the longevity of species and ecosystems [11,20–24]. Efficiency enhances the speed and amount of matter, energy, and information that species and ecosystems can process, while resilience enables species and ecosystems to persevere (and possibly transform) in the face of hazards, stressors, and extreme events. Traits linked to efficiency include centralization, streamlining, and specialization, while resilience is facilitated by traits like dispersity and redundancy 11,25,26. Notably, diversity and connectivity (i.e. higher transmission speed, capacity, and density among system components) appear to be two key features linking efficiency and resilience [5,21,23]. In general, higher connectivity and homogeneity (i.e. decreased diversity) contribute to increased system efficiency and decreased system resilience [23]. Conversely, higher diversity and decreased connectivity translate to systems that are less efficient under stable conditions, but more adaptive to environmental shifts, crashes, shocks, or stressors [23,27–29]. In sum, efficiency and resilience are complementary but often at odds with one another — greater resilience may result in less efficiency, and vice versa [21].

Given the opposing directions in which efficiency and resilience can pull with respect to diversity and connectivity, tensions and trade-offs emerge between the two. However, these tensions may not always play out in straightforward manners. For example, greater connectivity can sometimes facilitate the flow of resources and assistance after a disruptive event — thereby contributing to system resilience [5,23,28]. Similarly, species/ecosystem resilience can sometimes lead to undesirable outcomes if it contributes to the preservation of deleterious system dynamics [11,30]. Overall, the ecological literature posits that systems benefit from both efficiency and resilience. In an unconstrained world, the maximization of both would be advantageous. However, in reality, systems must typically strike a dynamic balance between efficiency and resilience. Systems that exhibit sufficient (and balanced) efficiency and resilience have been described as functioning within the 'window of vitality' [20–22,24]. Empirical examinations of the 'window of vitality' indicate that the efficiency–resilience spectrum in natural systems tends to lean slightly toward resilience [20–22,24]. Given the evolutionary pathway that has led to the 'window of vitality', human/engineered systems may benefit from mimicking natural systems by placing additional emphasis on the resilience end of the spectrum.

In a similar vein, the concept of 'safe operating spaces (SOS)' has emerged as an approach for actively monitoring and navigating multiple misaligned objectives under dynamic and uncertain conditions [31–33]. The idea of safe operating spaces has traditionally been applied to coupled social-ecological systems (e.g. fisheries, watersheds), and centers on supporting human well-being (e.g. equitable access to food, water, shelter, energy, education, economic opportunity) while staying within biophysical planetary boundaries (e.g. land use change, loss of biodiversity, ocean acidification, climate change, nitrogen and phosphorous cycles). Moving forward, there appear to be opportunities to apply elements of the safe operating spaces concept to the efficiency–resilience spectrum. For instance, one could envision a safe operating space bound by a 'floor' comprising performance and efficiency objectives and a 'ceiling' related to physical, sociotechnical, and environmental constraints. Similarly, properties of resilience and adaptive capacity would be crucial to remaining within (and possibly expanding or shifting) this safe operating space under variable or extreme conditions.

Social sciences and 'organizational ambidexterity' as a basis for efficiency and resilience within the institutional aspects of infrastructure

Paralleling the translation of ecologically based concepts to the physical components of infrastructure, leadership and organizational theory appear well positioned to examine efficiency and resilience within the institutional context of infrastructure. These bodies of knowledge introduce and explore the tension between exploitation (i.e. risk-averse decisions) and exploration (i.e. risk-seeking decisions) as a space to ensure organizational longevity [34–37]. Exploitative behaviors resemble aspects of efficiency and include rule enforcement, conformity through routines, rapid decision-making, and disciplinary approaches. Conversely, explorative behaviors include variability in the process, acceptance of failures, and diverse community building — resembling aspects of resilience [38,39]. The effective management of the tension between exploitation and exploration is known as ambidexterity. The crux of ambidexterity is to 1) establish formal (e.g. organizational structures, rules, and regulations) and informal governances (e.g. leadership, trust) that sponsor explorational pursuits while simultaneously maintaining services, and 2) integrate successful explorative endeavors through institutional repositioning [37,40,41].

Organizational ambidexterity is supported by the Law of Requisite Complexity [42], and its predecessor, the Law of Requisite Variety [43]. The Law of Requisite Variety states that a system (re: organization) can appropriately adapt if the organization's range of responses is equivalent to — or greater than — the states in which it must operate [43]. Subsequently, the Law of Requisite Complexity states that, to be adaptable, an organization's internal complexity must match or surpass external complexity [42]. Achieving the requisite complexity (or variety) relies on an organization's ability to sense, learn, and react to the demands of its environment [43,44] — capacities that can align with both efficiency and resilience. Organizations can strive to reduce the range and variety of stimuli to which they are exposed via processes that align with exploitation such as routinization, streamlining, and simplification [36,42]. Similarly, organizations can strive to expand internal capacities to respond to a wider range and variety of stimuli via processes that align with exploration, such as increasing system diversity, variety, and complexity [36,45].

Due to the relative stability of the past, most infrastructure organizations and institutions appear to emphasize exploitative actions and outcomes [18,37], which in turn can accelerate and exacerbate organizational deficiencies in today's increasingly turbulent environments [44]. Ambidexterity and the Law of Requisite Complexity emphasize the importance of striking a dynamic balance between exploitative (efficiency-oriented) processes and explorative (resilience-oriented) processes. Too much emphasis on exploitive processes can result in an oversimplistic perception of external conditions, and hinder an organization's ability to effectively respond to changes, shocks, and surprises [42,32,33]. Conversely, too much emphasis on exploratory processes can be physically and cognitively expensive, and result in an overly responsive organization (i.e. responding to all stimuli regardless of their relevance; inability to distinguish the signal from the noise) [32,42]. Papachroni et al. [46] posit that exploitation–exploration are not mutually exclusive, but instead are complementary and interrelated — further emphasizing that organizations should pursue both behaviors to remain relevant. Similarly, Anderies et al. [33] suggest that different combinations of knowledge systems and policy types are needed to move between multiple safe operating spaces and avoid 'dead operating spaces' [33]. These perspectives parallel the ecological concept of the 'window of vitality' (discussed above), where a system's long-term persistence requires a balance between efficiency and resilience.

Toward a dynamic balance between efficiency and resilience in infrastructure systems

Ultimately, the diverse suite of literature reviewed in this article converges on the idea that both efficiency and resilience are vital for the long-term viability of systems — especially as they navigate recurrent fluctuations between conditions of stability and instability. Additionally, the importance of a dynamic balance between efficiency and resilience applies to both the physical and institutional components of (infrastructure) systems. For instance, relating the 'window of vitality' to the physical aspects of infrastructure systems reveals that a shift toward the resilience end of the spectrum is perhaps warranted — aligning infrastructure systems with the observed tendencies of natural systems. This shift would diverge from the current (implicit or explicit) emphasis on efficiency within infrastructure systems, which is likely due to several factors. For one, many infrastructure systems were designed under the assumption of long-term stability and rigidity. Considering factors like climate change, technological change, and population shifts, these assumptions appear to be increasingly at odds with the environments in which infrastructure must function [15,47]. Said differently, hidden fragilities tend to emerge in systems that become well adapted to a particular set of inputs/forcing (i.e. the Law of Conservation of Fragility) [13,48,49,32,33]. Second, resilience is a system property that is often not readily observable until a disturbance occurs, whereas efficiency is typically easier to quantify (and operationalize) [11,30,50,51]. Similarly, emphasis on near-term conditions and outcomes can reinforce a proclivity toward established governance structures and operational practices [29,30,52,53,54,31,32,33]. As a result, incentives and inertia emerge that tend to align with efficiency and depart from resilience. One potential response would be to place additional emphasis on metrics of variability such as shifts in the magnitude, frequency, duration, and direction of system performance and exogenous factors (e.g. temperature and precipitation). Significant movement in these so-called 'early warning signs' has been posited as an indication of declining system stability and resilience, as well as the possibility of an impending threshold [31].

The above factors can also be catalyzed and exacerbated (either consciously or unconsciously) by *motivational effects* (i.e. stakeholder motives that result in the consideration of certain alternatives and the ignorance or misjudgment of others), *focused thinking* (i.e. deliberate attention to specific issues and perspectives at the expense of others), and *narrow thinking* (i.e. unintentional or deliberate disregard for potential alternatives) [55–58]. For example, the costs (e.g. time, resources, conflict) of pluralistic governance and decision-making can sometimes be perceived as outweighing the benefits (e.g. increased capacity, creativity, and reflexivity) [54]. In turn, this perception can lead to a closing down of problem/solution spaces and a propensity toward existing incentive structures and models of analysis [54]. Finally, misalignments between incentives and impacts can arise from a variety of scale (geographic, temporal, and network) issues. For both efficiency and resilience, what is favorable for one actor or firm may not be favorable for the broader system(s)– and vice versa. Similarly, what is favorable in the near-term may not align with what is favorable in the long-term [13,30]. Efficiency-oriented efforts like standardization align with goals of reducing system variability and increasing predictability. On timescales conforming to things like terms of office, funding cycles, and immediate human needs, reduced system variability is appealing. However, reduced system variability in the near-term can lead to increased variability and risk of crossing critical thresholds in the long-term [32]. Therefore, managing variability appears to be inextricably linked to managing efficiency in the short run and resilience in the long run. Regardless of the impetus for efficiency-focused design and operation, there are a number of potentially dubious outcomes: 1) incomplete assessment or consideration of system context, dynamics, uncertainties, and trade-offs; 2) missed information and learning opportunities, system lock-in, diminished hardiness to shocks and stressors, and reduced safe operating spaces; 3) inequitable participation in the planning and implementation of interventions; 4) defining 'success' from an overly narrow or exclusionary perspective that primarily aligns with dominant agendas and powerful stakeholders; and 5) closing off potential solution pathways and outcomes in favor of 'traditional'/established approaches [30–33]. We conclude our discussion by outlining some potential approaches for assuaging these outcomes.

Within individual organizations and systems, infrastructure managers can enact the Complex Leadership Theory (CLT) framework to enhance organizational ambidexterity and navigate efficiency–resilience tensions [37,59]. Although exploitative and explorative behaviors are both practiced, infrastructure institutions tend to favor administrative leadership (i.e. exploitative behavior) that reduces complexity [39]. CLT can advance resilience efforts by prompting infrastructure managers to consider the long-term consequences of decision making. In particular, CLT can facilitate the emergence of *enabling leaders*, who embrace both administrative and entrepreneurial leadership as operating conditions swing between stable and unstable [37,39,59]. An *enabling leader* is not simply someone who can partake in either behavior. Instead, they are pathfinders who can identify productive tensions and integrate knowledge toward continuous shifts in formal and informal governance under dynamic operating environments [37]. These continuous shifts and responses can be facilitated by exploratory modeling and analyses. Example approaches include design of experiments, stress-testing, worst-case scenario discovery, multiobjective decision making, and robust decision making [47,55]. These exploratory approaches can enable careful examination of rival decision paths, elucidation of system sensitivities and key decision criteria, identification of decisions and actions that produce (un)satisfactory trade-offs between multiple objectives, determination of scenarios that produce key performance thresholds (either positive or negative) and enhance overall confidence in decisions and methodological choices [47,55].

Exploratory modeling can be helpful (but not necessarily prerequisite) for infrastructure managers to recognize and embrace the importance of boundary setting, boundary thresholds, and boundary spanning (when necessary) [31,60]. Whether pursuing efficiency, resilience, or any other objectives, there can be merit in recognizing that infrastructure systems impact, and are impacted by, surrounding social, ecological, and technological systems (SETS) [61]. Considering infrastructure systems as coupled SETS builds upon work within socioecological systems [62–66] and provides an opportunity for further exploring concepts of enabling leadership within complex systems. Effectively identifying and operating within SETS boundaries can be aided by the practice of coproduction — "processes that iteratively bring together diverse groups and their ways of knowing and acting to create new knowledge and practices to transform societal outcomes [54]". Hallmarks of coproduction include (but are not limited to) culturally appropriate engagement with all relevant stakeholders, open and flexible processes, frequent feedback from participants, acknowledging and addressing power dynamics, establishing pertinent boundary objects, clear and frequent communication, and sufficient resources to support sustained coordination and collaboration [54]. Many of these practices (e.g. involving others, group discussion, connectedness, diversity, boundary spanning, etc.) are also linked with cultivating enabling leadership [39]. Although the science and practice of coproduction continue to evolve, potential outcomes of this approach include increased equity, improved processes and capacities, enhanced creativity and reflexivity among stakeholders, creation of new knowledge, deepened awareness of various issues, and broader understanding [54]. Coproduction may also facilitate the cultivation of new knowledge systems and policy mechanisms needed to navigate from one safe operating space to another [33]. Ultimately, these processes and their outcomes can potentially help various stakeholders navigate and establish a dynamic balance between efficiency and resilience across multiple SETS and safe operating spaces under varying conditions.

Although CLT, exploratory modeling, and coproduction can be undertaken in an ad-hoc and 'organic' manner, one possible approach for catalyzing these transformations within infrastructure systems is the formal consideration (and possible regulation) of resilience as a public/common good, and the lack of resilience as a negative externality [11,67,68,54]. The steady improvements in air and water quality achieved via the Clean Air Act and Clean Water Act (and related policies) could serve as aspirational templates for establishing standards and policies for more explicitly addressing and reducing the negative externalities associated with a dearth of resilience. Doing so can complement, and be complemented by, exploratory modeling and coproduction. Ultimately, establishing resilience as a common good can help create incentives for implementing and coproducing attributes like diversity, redundancy, and robustness within infrastructure systems–resilience enhancing traits that can complement efficiency-oriented practices already in place.

The review and synthesis of diverse bodies of knowledge conducted in this analysis underscore the importance of striving to achieve a dynamic balance between efficiency and resilience within infrastructure systems. Furthermore, approaches such as CLT, coproduction, exploratory modeling techniques, and the establishment of resilience as a public good appear to be well positioned to help navigate tensions between efficiency and resilience. However, none of these concepts are a silver bullet. There will be systems and situations where other factors (in addition to or instead of efficiency and resilience) will take precedence. There will also be systems and situations where exploratory modeling and/or coproduction may not be necessary or appropriate. Finally, we acknowledge that the challenges, opportunities, and shortcomings of infrastructure systems cannot be fully distilled down to the tension between efficiency and resilience — especially given the complex, multiobjective, and varied nature of infrastructure systems. Nevertheless, we posit that efficiency and resilience are two of the most crucial 'levers' at our disposal for achieving system longevity, and perhaps more importantly, desirable outcomes for as many people as possible under as many conditions as possible. We are optimistic that the topics and discussions in this article can catalyze continued research and practice aimed at further exploring and critically examining the appropriate balance between efficiency and resilience (among other objectives) — as well as the tools, frameworks, and approaches for doing so. Collectively, these efforts can empower infrastructure institutions and systems to adapt to a wide range of stresses, shocks, and surprises, while helping them thrive under conditions of both stability and instability.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

This work is supported by multiple U.S. National Science Foundation grants including the Urban Resilience to Extremes Sustainability Research Network (UREx SRN) (Award # SRN-1444755) and Resilience Convergence (Award # GCR-1934933).

References and recommended reading

Papers of particular interest, published within the period of review, have been highlighted as:

- • of special interest
- •• of outstanding interest

1. Carvalhaes T, Markolf S, Helmrich A, Kim Y, Li R, Natarajan M, Bondank E, Ahmad N, Chester M: **COVID-19 as a harbinger of transforming infrastructure resilience**. *Front Built Environ* 2020, **6**:148, https://doi.org/10.3389/fbuil.2020.00148

2. Federal Energy Regulatory Commission (FERC) & North American Electric Reliability Corporation (NERC). **Report on Outages and Curtailments During the Southwest Cold Weather Event of February**; 2011, 1–5, https://www.ferc.gov/sites/default/files/2020-04/08-16-11-report.pdf

3. Ball J: **The Texas blackout is the story of a disaster foretold**. Texas Monthly. Emmis Publishing; 2021 (February 19), https://www.texasmonthly.com/news-politics/texas-blackout-preventable/

4. Martin RL: **The high price of efficiency**. Harvard Business Review. Harvard Business Publishing; 2019.

5. Biggs R, Schlüter M, Biggs D, Bohensky EL, Burnsilver S, Cundill G, Dakos V, Daw TM, Evans LS, Kotschy K, Leitch AM, Meek C, Quinlan A, Raudsepp-Hearne C, Robards MD, Schoon ML, Schultz L, West PC: **Toward principles for enhancing the resilience of ecosystem services**. *Ann Rev Environ Resour* 2012, **37**:421-448, https://doi.org/10.1146/annurev-environ-051211-123836

6. Park J, Seager TP, Rao PSC, Convertino M, Linkov I: **Integrating risk and resilience approaches to catastrophe management in engineering systems**. *Risk Anal* 2013, **33**:356-367, https://doi.org/10.1111/j.1539-6924.2012.01885.x

7. Woods DD: **Four concepts for resilience and the implications for the future of resilience engineering**. *Reliab Eng Syst Saf* 2015, **141**:5-9, https://doi.org/10.1016/j.ress.2015.03.018

8. Chester M v, Allenby B: **Toward adaptive infrastructure: flexibility and agility in a non-stationarity age**. *Sustain Resil Infrastruct* 2018, **3**:1-19, https://doi.org/10.1080/23789689.2017.1416846

9. Gilrein EJ, Carvalhaes TM, Markolf SA, Chester M v, Allenby BR, Garcia M: **Concepts and practices for transforming infrastructure from rigid to adaptable**. *Sustain Resil Infrastruct* 2019, **6**:213-234, https://doi.org/10.1080/23789689.2019.1599608

10. Helmrich AM, Chester M v: **Reconciling complexity and deep uncertainty in infrastructure design for climate adaptation**. Sustainable and Resilient Infrastructure. Taylor and Francis Inc.; 2020, https://doi.org/10.1080/23789689.2019.1708179

11. • Stanley C: **Living to spend another day: exploring resilience as a new fourth goal of ecological economics**. *Ecol Econ* 2020, **178**:106805, https://doi.org/10.1016/j.ecolecon.2020.106805

The author presents a series of arguments for why resilience should become the fourth main goal of ecological economic theory (in addition to sustainable scale, efficient allocation, and fair distribution). Before this, ecological economics had paid little attention to resilience and its implications on broader system outcomes and dynamics.

12. Woods DD: **The theory of graceful extensibility: basic rules that govern adaptive systems**. *Environ Syst Decis* 2018, **38**:433-457, https://doi.org/10.1007/s10669-018-9708-3

13. Anderies JM, Folke C, Walker B, Ostrom E: **Aligning key concepts for global change policy: robustness, resilience, and sustainability**. *Ecol Soc* 2013, **18**:8, https://doi.org/10.5751/ES-05178-180208

14. Chester M v, Markolf S, Allenby B: **Infrastructure and the environment in the Anthropocene**. *J Ind Ecol* 2019, **23**:1006-1015, https://doi.org/10.1111/jiec.12848

15. Chester M, Underwood BS, Allenby B, Garcia M, Samaras C, Markolf S, Sanders K, Preston B, Miller TR: **Infrastructure resilience to navigate increasingly uncertain and complex conditions in the Anthropocene**. *Npj Urban Sustain* 2021, **1**:4, https://doi.org/10.1038/s42949-021-00016-y

16. Markolf SA, Chester M v, Helmrich AM, Shannon K: **Re-imagining design storm criteria for the challenges of the 21st century**. *Cities* 2021, **109**:102981, https://doi.org/10.1016/j.cities.2020.102981

17. Chester M v, Allenby B: **Infrastructure as a wicked complex process**. *Elem Sci Anth* 2019, **7**:21, https://doi.org/10.1525/elementa.360

18. Chester M v, Miller T, Muñoz-Erickson TA: **Infrastructure governance for the Anthropocene**. *Elementa* 2020, **8**:78, https://doi.org/10.1525/elementa.2020.078

19. Helmrich A, Markolf S, Li R, Carvalhaes T, Kim Y, Bondank E, Natarajan M, Ahmad N, Chester M: **Centralization and decentralization for resilient infrastructure and complexity**. *Environ Res Infrastruct Sustain* 2021, **1**:021001, https://doi.org/10.1088/2634-4505/ac0a4f

20. Ulanowicz RE: **The balance between adaptability and adaptation**. *BioSystems* 2002, **64**:13-22.

21. Goerner SJ, Lietaer B, Ulanowicz RE: **Quantifying economic sustainability: implications for free-enterprise theory, policy and practice**. *Ecol Econ* 2009, **69**:76-81, https://doi.org/10.1016/j.ecolecon.2009.07.018

22. Ulanowicz RE, Goerner SJ, Lietaer B, Gomez R: **Quantifying sustainability: resilience, efficiency and the return of information theory**. *Ecol Complex* 2009, **6**:27-36, https://doi.org/10.1016/j.ecocom.2008.10.005

23. • Homer-Dixon T, Walker B, Biggs R, Crépin AS, Folke C, Lambin EF, Peterson GD, Rockström J, Scheffer M, Steffen W, Troell M: **Synchronous failure: the emerging causal architecture of global crisis**. *Ecol Soc* 2015, **20**:6, https://doi.org/10.5751/ES-07681-200306

The authors develop a conceptual framework to describe and assess synchronous failure in complex systems. This study is novel because it delineates the characteristics and processes of the simultaneous, propagating, and large-scale disruptions/failures that increasingly comprise the global risk landscape.

24. • Ulanowicz RE: **Biodiversity, functional redundancy and system stability: subtle connections**. *J R Soc Interface* 2018, **15**:20180367, https://doi.org/10.1098/rsif.2018.0367

The author analyzes 25 fully quantified (in terms of conditional entropy) trophic networks to examine the relationship between biodiversity (or lack thereof) and functional redundancy. This study is significant because it quantifies the relationship between efficiency and adaptability in natural systems and bolsters the idea of the 'window of vitality' by which natural systems balance efficiency and resilience (which slight asymmetry toward resilience).

25. Ruth M: **A quest for the economics of sustainability and the sustainability of economics**. *Ecol Econ* 2006, **56**:332-342, https://doi.org/10.1016/j.ecolecon.2005.09.012

26. Hopkins R: The Transition Handbook: From Oil Dependency to Local Resilience. Green Books; 2014.

27. Bodin Ö, Norberg J: **Information network topologies for enhanced local adaptive management**. *Environ Manag* 2005, **35**:175-193, https://doi.org/10.1007/s00267-004-0036-7

28. Scheffer M, Carpenter SR, Lenton TM, Bascompte J, Brock W, Dakos V, van de Koppel J, van de Leemput IA, Levin SA, van Nes EH, Pascual M, Vandermeer J: **Anticipating critical transitions**. *Science* 2012, **338**:344-348, https://doi.org/10.1126/science.1225244 (American Association for the Advancement of Science).

29. Lever JJ, van Nes EH, Scheffer M, Bascompte J: **The sudden collapse of pollinator communities**. *Ecol Lett* 2014, **17**:350-359, https://doi.org/10.1111/ele.12236

30. Eriksen S, Schipper ELF, Scoville-Simonds M, Vincent K, Adam HN, Brooks N, Harding B, Khatri D, Lenaerts L, Liverman D, Mills-Novoa M, Mosberg M, Movik S, Muok B, Nightingale A, Ojha H, Sygna L, Taylor M, Vogel C, West JJ: **Adaptation interventions and their effect on vulnerability in developing countries: help, hindrance or irrelevance?** *World Dev* 2021, **141**:105383, https://doi.org/10.1016/j.worlddev.2020.105383

31. Dearing JA, Wang R, Zhang K, Dyke JG, Haberl H, Hossain MS, Langdon PG, Lenton TM, Raworth K, Brown S, Carstensen J, Cole MJ, Cornell SE, Dawson TP, Doncaster CP, Eigenbrod F, Flörke M, Jeffers E, Mackay AW, Poppy GM: **Safe and just operating spaces for regional social-ecological systems**. *Glob Environ Change* 2014, **28**:227-238, https://doi.org/10.1016/j.gloenvcha.2014.06.012

32. • Carpenter SR, Brock WA, Folke C, van Nes EH, Scheffer M, Polasky S: **Allowing variance may enlarge the safe operating space for exploited ecosystems**. *Proc Natl Acad Sci U S A* 2015, **112**:14384-14389, https://doi.org/10.1073/pnas.1511804112

Through a combination of synthesis and conceptual framing, the authors conduct a very insightful analysis of the role of variance in the management and sustainability of social – ecological systems. A key takeaway is the idea that decreasing system variance in the short term (often in alignment with social/political objectives) is followed by increased system variance in the long term. Therefore, the management of variability is linked directly to the management of resilience.

33. Anderies JM, Mathias J-D, Janssen MA: **Knowledge infrastructure and safe operating spaces in social–ecological systems**. *Proc Natl Acad Sci* 2019, **116**:5277-5284, https://doi.org/10.1073/pnas.1802885115

34. Duncan RB: **The ambidextrous organization: designing dual structures for innovation**. In *The Management of Organization Design: Strategies and Implementation*. Edited by Kilmann RH, Pondy LR, Slevin D. Google Books; 1976:167-188.

35. Tushman ML, O'Reilly CAI: **Ambidextrous organizations: managing evolutionary and revolutionary change**. *Calif Manag Rev* 1996, **38**:8-30, https://doi.org/10.2307/41165852

36. March JG: **Exploration and exploitation in organizational learning**. *Org Sci* 1991, **2**:71-87, https://www.jstor.org/stable/2634940?seq=1&cid=pdf-

37. • Uhl-Bien M, Arena M: **Leadership for organizational adaptability: a theoretical synthesis and integrative framework**. *Leadersh Q* 2018, **29**:89-104, https://doi.org/10.1016/j.leaqua.2017.12.009

The authors develop a framework for leadership traits that enable organizations to become more adaptable. Before this, little attention had been paid to the topic of positioning people and organizations for adaptability — an issue of increasing importance as our systems and environments become increasingly dynamic, complex, demanding, and uncertain.

38. Rosing K, Frese M, Bausch A: **Explaining the heterogeneity of the leadership-innovation relationship: ambidextrous leadership**. *Leadersh Q* 2011, **22**:956-974, https://doi.org/10.1016/j.leaqua.2011.07.014

39. • Havermans LA, den Hartog DN, Keegan A, Uhl-Bien M: **Exploring the role of leadership in enabling contextual ambidexterity**. *Hum Resour Manag* 2015, **54**:s179-s200, https://doi.org/10.1002/hrm.21764

The authors identify operational practices to stimulate exploitative and explorative behaviors within project-based organizations. They also find that leaders do not participate in only one leadership capacity but a combination of both that appropriately respond to stimuli. This article provides insights into how enabling leadership manifests in practice.

40. Turner N, Swart J, Maylor H: **Mechanisms for managing ambidexterity: a review and research agenda**. *Int J Manag Rev* 2013, **15**:317-332, https://doi.org/10.1111/j.1468-2370.2012.00343.x

41. Sovacool BK, Lovell K, Ting MB: **Reconfiguration, contestation, and decline: conceptualizing mature large technical systems**. *Sci Technol Hum Values* 2018, **43**:1066-1097, https://doi.org/10.1177/0162243918768074

42. Boisot M, McKelvey B: **Connectivity, extremes, and adaptation: a power-law perspective of organizational effectiveness**. *J Manag Inq* 2011, **20**:119-133, https://doi.org/10.1177/1056492610385564

43. Ashby WR: An Introduction to Cybernetics. John Wiley and Sons; 1956, https://doi.org/10.5962/bhl.title.5851

44. Hamel G, Valikangas L: **The quest for resilience**. Harvard Business Review. Harvard Business Publishing; 2003 (September), https://hbr.org/2003/09/the-quest-for-resilience

45. Gell-Mann M: **What is complexity?** In *Complexity and Industrial Clusters*. Edited by Curzio AQ, Fortis M. Springer; 2002, https://doi.org/10.1007/978-3-642-50007-7_2

46. • Papachroni A, Heracleous L, Paroutis S: **In pursuit of ambidexterity: managerial reactions to innovation–efficiency tensions**. *Hum Relat* 2016, **69**:1791-1822, https://doi.org/10.1177/0018726715625343

Through a combination of review, conceptual framing, and case research, the authors identify the process by which tension is interpreted and managed at different levels within an organization. Before this study, little was known about how actors interpret and manage the tensions the arise from the pursuit of ambidexterity (i.e. balancing exploitative and explorative processes within an organization). Gaining a better understanding of the process by which ambidexterity is pursued provides valuable insights into how organizations to become more adept at navigating dynamic, complex, and uncertain environments.

47. Moallemi EA, Kwakkel J, de Haan FJ, Bryan BA: **Exploratory modeling for analyzing coupled human-natural systems under uncertainty**. *Glob Environ Change* 2020, **65**:102186, https://doi.org/10.1016/j.gloenvcha.2020.102186

48. Bode HW: Network Analysis and Feedback Amplifier Design. D. Van Nostrand. Co., Inc.; 1945.

49. Csete ME, Doyle JC: **Reverse engineering of biological complexity**. *Science* 2002, **295**:1664-1669, https://doi.org/10.1126/science.1069981

50. Kaika M: **'Don't call me resilient again!': the New Urban Agenda as immunology … or … what happens when communities refuse to be vaccinated with 'smart cities' and indicators**. *Environ Urban* 2017, **29**:89-102, https://doi.org/10.1177/0956247816684763

51. Bruun JA: **Climate changing civil society: the role of value and knowledge in designing the Green Climate Fund**. In *Valuing Development, Environment and Conservation. Creating Values that Matter*. Edited by Bracking S, Fredricksen A, Sullivan S, Woodhouse P. Routledge; 2018, https://doi.org/10.4324/9781315113463

52. Nightingale AJ: **Power and politics in climate change adaptation efforts: struggles over authority and recognition in the context of political instability**. *Geoforum* 2017, **84**:11-20, https://doi.org/10.1016/j.geoforum.2017.05.011

53. Mosberg M, Nyukuri E, Naess LO: **The power of 'know-who': adaptation to climate change in a changing humanitarian landscape in Isiolo, Kenya**. *IDS Bull* 2017, **48**:79-92, https://doi.org/10.19088/1968-2017.154

54. Wyborn C, Datta A, Montana J, Ryan M, Leith P, Chaffin B, Miller C, van Kerkhoff L: **Annual review of environment and resources co-producing sustainability: reordering the governance of science, policy, and practice**. *Ann Rev* 2019, **44**:319-346, https://doi.org/10.1146/annurev-environ-101718

55. Moallemi EA, Zare F, Reed PM, Elsawah S, Ryan MJ, Bryan BA: **Structuring and evaluating decision support processes to enhance the robustness of complex human–natural systems**.

Environmental Modelling and Software vol. 123, Elsevier Ltd.; 2020, https://doi.org/10.1016/j.envsoft.2019.104551

56. Lahtinen TJ, Guillaume JHA, Hämäläinen RP: **Why pay attention to paths in the practice of environmental modelling?** *Environ Model Softw* 2017, **92**:74-81, https://doi.org/10.1016/j.envsoft.2017.02.019

57. Montibeller G, von Winterfeldt D: **Cognitive and motivational biases in decision and risk analysis**. *Risk Anal* 2015, **35**:1230-1251, https://doi.org/10.1111/risa.12360

58. Zare F, Elsawah S, Iwanaga T, Jakeman AJ, Pierce SA: **Integrated water assessment and modelling: a bibliometric analysis of trends in the water resource sector**. *J Hydrol* 2017, **552**:765-778, https://doi.org/10.1016/j.jhydrol.2017.07.031

59. Uhl-Bien M, Arena M: **Complexity leadership: enabling people and organizations for adaptability**. *Org Dyn* 2017, **46**:9-20, https://doi.org/10.1016/j.orgdyn.2016.12.001

60. Marchau VA, Walker WE, Bloemen PJ, Popper SW: Decision Making under Deep Uncertainty. Springer; 2019, https://doi.org/10.1007/978-3-030-05252-2

61. Markolf SA, Chester MV, Eisenberg DA, Iwaniec DM, Davidson CI, Zimmerman R, Chang H: **Interdependent infrastructure as linked social, ecological, and technological systems (SETSs) to address lock-in and enhance resilience**. *Earth's Future* 2018, **6**:1638-1659.

62. Walker B, Gunderson L, Kinzig A, Folke C, Carpenter S, Schultz L: **A handful of heuristics and some propositions for understanding resilience in social-ecological systems**. *Ecol Soc* 2006, **11**:13, https://doi.org/10.5751/ES-01530-110113

63. Ostrom E: **A general framework for analyzing sustainability of social-ecological systems**. *Science* 2009, **325**:419-422.

64. Fischer J, Gardner TA, Bennett EM, Balvanera P, Biggs R, Carpenter S, Tenhunen J: **Advancing sustainability through mainstreaming a social–ecological systems perspective**. *Curr Opin Environ Sustain* 2015, **14**:144-149.

65. Muneepeerakul R, Anderies JM: **Strategic behaviors and governance challenges in social-ecological systems**. *Earth's Future* 2017, **5**:865-876.

66. Béné C, Doyen L: **From resistance to transformation: a generic metric of resilience through viability**. *Earth's Future* 2018, **6**:979-996.

67. Homer-Dixon T: The Upside of Down: Catastrophe, Creativity and the Renewal of Civilization. edn 1, A.A. Knopf Canada; 2006.

68. Farley J, Voinov A: **Economics, socio-ecological resilience and ecosystem services**. *J Environ Manag* 2016, **183**:389-398, https://doi.org/10.1016/j.jenvman.2016.07.065