Capacity to Promote Adaptation

William C. Clark¹, Alicia G. Harley²

¹Harvey Brooks Professor of International Science, Public Policy and Human Development;
Director, Sustainability Science Program, Harvard Kennedy School,

²Post-doctoral Fellow, Sustainability Science Program, Harvard Kennedy School; Lecturer in
Environmental Science and Public Policy, Harvard College

Published on: Sep 10, 2020

DOI: 10.21428/f8d85a02.da23adf2

License: [Creative Commons Attribution 4.0 International License \(CC-BY 4.0\)](https://creativecommons.org/licenses/by/4.0/)

Cite as: Clark, William C., and Alicia G. Harley. 2020. "Capacity to Promote Adaptation." In *Sustainability Science: A Guide for Researchers*, edited by Alicia G. Harley and William C. Clark, 1st ed. Retrieved from <https://www.sustainabilityscience.org/pub/otdky0t3>

Adaptation¹ has long been an important focus of sustainability science, addressed by a broad range of research traditions. Scholars of **risk**² have highlighted the deep and interlinked uncertainties that are a common property of the Anthropocene System and latent in all nature–society interactions ([Keys et al. 2019](#)). Scholars of **vulnerability**³ have focused on places or subpopulations likely to lack or lose access to the resources needed to secure people’s well-being in the face of threats ([Adger 2006](#)). **Resilience**⁴ researchers have explored how the characteristics of the Anthropocene as a complex system both support and constrain adaptation ([Folke 2016](#)). Research on **innovation**⁵ ([Binz and Truffer 2017](#)) and complexity economics ([Elsner 2017](#)) have emphasized how uncertainty and disturbance provide not just threats but also opportunities for novel ways of using resources to advance well-being.

Our review of these various research programs found substantial potential for complementarity among their insights. That potential has often remained unrealized, however, due to siloed scholarship and a related proliferation of different terminologies for similar concepts. We do not seek to adjudicate those differences here but rather aim to highlight the substantive findings that lie beneath them. Our overall conclusion is that an additional necessary condition for sustainable development is the creation and maintenance of a substantial adaptive capacity. We find it useful to distinguish the capacity to adapt from the related capacity to transform on the basis of their relationship to regimes. For our purposes here, we define adaptive capacity as the ability to confront potentially disruptive change in ways that keep the system operating *within* its current regime and thus on something like its current development pathway. Transformative capacity, in contrast, can usefully be seen as the ability to shift a system *between* regimes, e.g., out of regimes supporting unsustainable pathways of development and into regimes supporting sustainable ones. We defer our exploration of research on the capacity to promote such transformations to the [Chapter on Capacity to Transform](#).

1 Findings: Risk, vulnerability, and resilience

The past two decades of research on topics related to adaptation have built a foundation of findings on which efforts to enhance adaptive capacity for sustainable development can build. We cannot do justice here to that rich array of findings here. Instead, we summarize three fundamental results that we find to be of particular importance for sustainability. We refer readers interested in the evidence behind these results to several excellent reviews on which we have drawn extensively: ([Anderies et al. 2013](#); ([Eriksen, Nightingale, and Eakin 2015](#); [Nelson, Adger, and Brown 2007](#)).

Adaptive capacity is necessary for sustainable development: The Anthropocene System is invariably full of **disruptions**⁶: shocks, surprises, novelty, and the unfolding unknown ([Polasky et al. 2011](#)). This implies that even development pathways that are considered sustainable now will eventually be pushed in unsustainable directions. Moreover, assessments concluding that certain future development pathways should be sustainable will eventually turn out to be wrong (e.g., due to uncertainty or external shocks or internal novelty) and thus will require adaptive corrections. The research challenge is better to understand how such adaptive capacity functions, and how it can be strengthened, maintained, utilized, and evaluated.

Adaptation capacity is dynamic: Early work on adaptation, vulnerability, and resilience generally focused on the capacity to produce static assessments relevant to specific risks and action situations. More recent studies have shown that in order to support sustainable development the capacity to carry out such static assessments must be complemented with a capacity to carry out dynamical assessments focused on **adaptation pathways**⁷ ([Leach, Scoones, and Stirling 2010](#)). The argument behind this shift is simple but profound: adaptations, like other attributes of complex adaptive systems, are path dependent with each one setting in place a cascade of subsequent system reactions and adjustments ([Wise et al. 2014](#)). Moreover, the Anthropocene System will always be experiencing multiple adaptation pathways driven by multiple strategic actors working at multiple organizational levels in the context of multiple action situations. Some of these adaptation pathways will invariably interact with one another, further complicating the picture ([Tellman et al. 2018](#)). Sustainability science should therefore strive to improve society's capacity to understand the dynamics of these multiple interacting adaptation pathways and to evaluate not just immediate local benefits of particular adaptive actions but also foreseeable responses to those actions by other actors elsewhere and later.

Adaptation pathways don't reduce risk so much as redistribute it: Adaptations often redistribute risk and vulnerability within the Anthropocene system rather than reducing it in any absolute sense. Research has shown a great variety of circumstances in which adaptations that mitigate immediate and local vulnerability do so by exporting it to other people, places, and times ([Adger 2016](#)). The theory behind such apparent conservation of fragility is well established for linear control systems but still lacking for the non-linear systems that characterize the Anthropocene ([Anderies et al. 2013](#); [Homayounfar et al. 2018](#)). A growing number of case studies, however, convincingly demonstrate how interventions to control short-term variability and associated risks arising from nature–society interactions can initiate adaptation pathways that systematically reduce adaptive capacity over longer periods and larger areas (e.g., [Carpenter et al. 2015](#)). In particular, the discourse of climate change adaptation—especially in the context of development and developing countries—can reinforce existing vulnerabilities and power structures ([Mikulewicz 2020](#)). Sustainability science should continue to broaden its perspective beyond short-term risk reduction to develop a capacity for guiding the risk (re)distribution and trade-offs that adaptation pathways seem inevitably to entail.

2 Building Capacity: Resources, complexity, and power

What determines adaptive capacity for the pursuit of sustainability? Research has demonstrated potentially important and interrelated roles for virtually all of the elements and relationships that characterize the Anthropocene as a complex adaptive system (see the [Chapter on a Framework for Research](#) and [Figure 1](#)). Five components stand out: resources, heterogeneity, connections, systems dynamics, and actors. The summary account of their roles we present here draws heavily on the following reviews, to which we refer the reader interested in the detailed evidence: ([Brown and Westaway 2011](#)); [Biggs et al. 2012](#); [Levin et al. 2012](#)); [de Bruijn et al. 2017](#)).

Resources: Adaptation involves changing how resources are used in the face of disturbance so that they continue to yield a flow of goods and services commensurate with the pursuit of sustainability. Perhaps obviously but nonetheless importantly, the capacity for such adaptations is greater when resources—natural and anthropogenic—are more plentiful. Indeed, some scholars have argued that the same metric of capital assets that are being used in responding to the question “What must be sustained for sustainable development?” can also be used to respond to the question “Who has how much adaptive capacity for sustainable development?” ([Irwin, Gopalakrishnan, and Randall 2016](#)). Other things being equal, richer is almost certainly safer ([Wildavsky 1980](#)). But questions of trade-offs remain, and have not been adequately illuminated by research: How much wealth should be committed to immediate well-being, and how much to building adaptive capacity?

Heterogeneity is a defining characteristic of the Anthropocene System (see the [Chapter on a Framework for Research](#)). It makes important contributions to adaptive capacity in at least two ways ([Baird et al. 2018](#); [Tilman, Isbell, and Cowles 2014](#); [Levin et al. 2012](#)).

- by providing the potential for partially compensating losses in well-being resulting from disturbance to particular places or elements;
- by providing locally nurtured sources of novelty (biological variation, technological or policy innovation) that the larger system can draw on for dealing with post-disturbance realities in new ways.

Different kinds of heterogeneity—ranging from functional redundancy to fundamental diversity—have been shown to make distinctive contributions to adaptive capacity. In general, too little heterogeneity detracts from adaptive capacity. In particular cases, such as national crop yields, added diversity can have a significant stabilizing effect ([Renard and Tilman 2019](#)). Beyond that, however, the picture is less clear. Redundancy and diversity can compete with one another. And both can come at the cost of efficiency relative to more homogeneous systems well adapted to the circumstances of the moment. The challenge, as ever, is getting the balance right for particular action situations.

Connections: The potential contribution of heterogeneity to adaptive capacity can be realized only if it is complemented by appropriate connectivity. Connections, as noted in the [Chapter on a Framework for Research](#), are fundamental attributes of all complex adaptive systems. For the Anthropocene System, research has shown that patterns of connectivity—which elements are interconnected and how strongly—matter for adaptive capacity and can be manipulated to manage it. A sampling of relevant studies is provided in Dakos et al. ([Dakos et al. 2015](#)). These show that in general either too much or too little connectivity can undermine adaptive capacity. A common resolution of this tension in complex adaptive systems is modularity: relatively tight connections among a selective subset of elements in ways that promote complementarities and efficiency, but with those modules relatively weakly and selectively connected to other elements of the system. However, the specific configurations of modularity that would best support adaptive capacity for sustainable development are poorly understood and almost certainly context dependent. Progress in resolving how connections can be managed to promote adaptive capacity has long been hindered by lack of theory-grounded language for providing nuanced characterization of connectivity patterns. That is now beginning to change with the application of network approaches to the assessment of connectivity in Anthropocene Systems ([Henry and Vollan 2014](#)). Even the best of this work, however, still struggles with dynamic assessments of how alternative network configurations should evolve to provide continuing support for the capacity to shape adaptation pathways under changing conditions ([Bodin et al. 2019](#)).

Systems dynamics: The dynamics of nature–society interactions pose two related challenges that must be addressed in building adaptive capacity for sustainable development. The first is associated with the multiple timescales those dynamics entail, the second with their potential for non-reversibility. A sampling of relevant research papers is provided in ([Biggs et al. 2015](#)). We summarize their findings here.

Multiple timescales: The dynamics of the Anthropocene System involve a variety interactive processes operating at multiple timescales. Adaptations can, in principle, address both (relatively) fast and (relatively) slow dynamics. In practice, however, a variety of factors tend to favor adaptations that mitigate the immediate damages associated with fast variables—e.g., natural selection, human cognitive bias, and political short-termism. Too often, this means that the system ends up supporting adaptations to symptoms rather than adaptations that address the underlying causes. Slow dynamics are left unaddressed and may even erode the capacity to guide adaptation pathways over the long run. The net result is that most of the adaptations actually undertaken often end up being too little, and too late, to support sustainable development. Research suggests that adaptive capacity to address the challenge of multiple timescales must include at least two components:

- the ability to create research knowledge about the dynamics of relevant slow processes and how they are likely to shape the long-term vulnerability of various components of the Anthropocene

System (e.g., [Pershing et al. 2019](#));

- the ability to devise governance arrangements that can use such knowledge to support relevant adaptation actions on the ground (see the [Chapter on Capacity for Governance](#)).

Irreversibility: The second challenge for adaptation arising from systems dynamics is the potential for irreversibility or **hysteresis**⁸ latent in the Anthropocene as a complex adaptive system ([Dakos et al. 2015](#)). Its significance is that trial-and-error adaptation, even in its most thoughtful adaptive management varieties, may fail to keep the development pathway within a desired regime. In principal, research can address this challenge by mapping relevant regimes and the thresholds separating them; determining which regimes lead to dangerous declines in inclusive well-being; evaluating the likelihood that adaptive strategies will be able to keep development pathways within desired regimes; and monitoring development pathways with a view toward providing early warnings that inform policy. Research summarized in the reviews cited at the beginning of this chapter has contributed to progress on building capacity for dealing with each of these tasks for particular action situations. That progress, however, has generally been modest. For example, relatively comprehensive mapping of relevant regimes has been accomplished for only a very few action situations (e.g., [Steffen et al. 2018](#); [Meyfroidt et al. 2018](#)). Talk about “planetary boundaries” has gotten far out ahead of what science can justify, often confusing normative issues of risk tolerance with the scientific (but poorly understood) mapping of thresholds separating alternative regimes ([Downing et al. 2019](#); [DeFries et al. 2012](#); [Biermann and Kim 2020](#)). Promising theoretical work on the prospects that appropriate monitoring could detect early warning signs when dynamics are approaching boundaries has proven feasible at the level of organisms and their health but enormously challenging to implement at the level of nature–society interactions ([Scheffer et al. 2015](#)).

Power: Who benefits and who loses from the redistribution of risks that occurs along adaptation pathways is not random. Rather, as already discussed in the [Chapter on Capacity for Equity](#), it is determined by the continuing coevolution of nature and society within which some people have more power than others. Power shapes how risks are articulated, causation is attributed, adaptations are formulated, decisions are made, and outcomes are evaluated ([Eriksen, Nightingale, and Eakin 2015](#); [Wise et al. 2014](#)). The result has been a highly inequitable distribution of risk and vulnerability at all levels of organization: household, community, regional, and national ([Brown and Westaway 2011](#)). Human agency matters in shaping this distribution (e.g., [Tellman et al. 2018](#)). But it is usually the actors with power who have greater capacity to shape adaptation pathways. And they generally do so in ways that protect or promote their immediate interests. The plight of actors with relatively less power is accentuated in the Anthropocene as larger risks are increasingly shifted over larger distances in space and time, rendering even actors with substantial local adaptive capacity increasingly vulnerable to disruptions beyond their immediate control. We conclude that a central, although

relatively late-arriving, message of research on adaptive capacity is that efforts to understand and build it must grapple with questions of power, who has it, and how they deploy it.

The components of adaptive capacity we discuss here are akin to those identified by the research literature on “general” resilience, i.e., they are components that have the potential to enhance adaptive capacity for sustainability in many systems of the Anthropocene and in the face of many disturbances—even ones with which the systems have no prior experience ([Carpenter et al. 2012](#)). But none of these components can be built without costs. We are left with the depressing conclusion that all must therefore be balanced, Goldilocks-like, for each specific action situation. For adaptive capacity, as for other determinants of sustainable development, there are no panaceas. In [Section 2 of the Chapter on Capacity for Governance](#), we discuss what research suggests can be done about resolving these trade-offs.

Footnotes

1. **Adaptation:** response to potentially disruptive change that seeks to limit damage or seize opportunities for improvement to a development pathway within a regime (contrast with transformations, resilience) [↵](#)
2. **Risk:** the prospect of loss or gain under uncertainty of something thought to be of value, often incorporating estimates on the likelihood of a change and consequences if the change occurs [↵](#)
3. **Vulnerability:** the likelihood that a particular subpopulation will lack or lose access to the resources they need to secure their well-being in the face of disruptions [↵](#)
4. **Resilience:** a system’s ability to utilize the “breathing room” provided by its robustness to disturbance to fundamentally change how it uses resources under the new conditions (see also adaptation, transformations) [↵](#)
5. **Innovation:** the **interplay of** actors, institutions, goals, and resources through which new artifacts and practices are invented, selected, adapted, adopted, and brought into widespread use [↵](#)
6. **Disruptions:** shocks, surprises, innovation, and the unfolding unknown [↵](#)
7. **Adaptation pathways:** dynamical, and typically path-dependent, sequences of adaptations in which early adaptations influence the conditions that call for later adaptations [↵](#)
8. **Hysteresis:** the tendency of a system change to be irreversible even when forces that caused the change are reversed [↵](#)

Citations

1. Keys, Patrick W., Victor Galaz, Michelle Dyer, Nathaniel Matthews, Carl Folke, Magnus Nyström, and Sarah E. Cornell. 2019. “Anthropocene Risk.” *Nature Sustainability* 2 (8): 667–73. <https://doi.org/10.1038/s41893-019-0327-x>. [↵](#)
2. Adger, W. Neil. 2006. “Vulnerability.” *Global Environmental Change* 16 (3): 268–81. <https://doi.org/10.1016/j.gloenvcha.2006.02.006>. [↵](#)
3. Folke, Carl. 2016. “Resilience (Republished).” *Ecology and Society* 21 (4). <https://doi.org/10.5751/es-09088-210444>. [↵](#)
4. Binz, Christian, and Bernhard Truffer. 2017. “Global Innovation Systems—A Conceptual Framework for Innovation Dynamics in Transnational Contexts.” *Research Policy* 46 (7): 1284–98. <https://doi.org/10.1016/j.respol.2017.05.012>. [↵](#)
5. Elsner, Wolfram. 2017. “Complexity Economics as Heterodoxy: Theory and Policy.” *Journal of Economic Issues* 51 (4): 939–78. <https://doi.org/10.1080/00213624.2017.1391570>. [↵](#)
6. Anderies, John M., Carl Folke, Brian Walker, and Elinor Ostrom. 2013. “Aligning Key Concepts for Global Change Policy: Robustness, Resilience, and Sustainability.” *Ecology and Society* 18 (2). <https://doi.org/10.5751/es-05178-180208>. [↵](#)
7. Eriksen, Siri H., Andrea J. Nightingale, and Hallie Eakin. 2015. “Reframing Adaptation: The Political Nature of Climate Change Adaptation.” *Global Environmental Change* 35 (November): 523–33. <https://doi.org/10.1016/j.gloenvcha.2015.09.014>. [↵](#)
8. Nelson, Donald R., W. Neil Adger, and Katrina Brown. 2007. “Adaptation to Environmental Change: Contributions of a Resilience Framework.” *Annual Review of Environment and Resources* 32 (1): 395–419. <https://doi.org/10.1146/annurev.energy.32.051807.090348>. [↵](#)
9. Polasky, Stephen, Stephen R. Carpenter, Carl Folke, and Bonnie Keeler. 2011. “Decision-Making under Great Uncertainty: Environmental Management in an Era of Global Change.” *Trends in Ecology & Evolution* 26 (8): 398–404. <https://doi.org/10.1016/j.tree.2011.04.007>. [↵](#)
10. Leach, Melissa, Ian Scoones, and Andy Stirling. 2010. *Dynamic Sustainabilities: Technology, Environment, Social Justice*. Pathways to Sustainability Series. London; Washington, DC: Earthscan. [↵](#)
11. Wise, R.M., I. Fazey, M. Stafford Smith, S.E. Park, H.C. Eakin, E.R.M. Archer Van Garderen, and B. Campbell. 2014. “Reconceptualising Adaptation to Climate Change as Part of Pathways of Change

and Response.” *Global Environmental Change* 28 (September): 325–36.

<https://doi.org/10.1016/j.gloenvcha.2013.12.002>. [↵](#)

12. Tellman, Beth, Julia C. Bausch, Hallie Eakin, John M. Anderies, Marisa Mazari-Hiriart, David Manuel-Navarrete, and Charles L. Redman. 2018. “Adaptive Pathways and Coupled Infrastructure: Seven Centuries of Adaptation to Water Risk and the Production of Vulnerability in Mexico City.” *Ecology and Society* 23 (1). <https://doi.org/10.5751/es-09712-230101>. [↵](#)

13. Adger, W. Neil. 2016. “Place, Well-Being, and Fairness Shape Priorities for Adaptation to Climate Change.” *Global Environmental Change* 38 (May): A1–3.

<https://doi.org/10.1016/j.gloenvcha.2016.03.009>. [↵](#)

14. Homayounfar, Mehran, Rachata Muneeppeerakul, John M. Anderies, and Chitsomanus P. Muneeppeerakul. 2018. “Linking Resilience and Robustness and Uncovering Their Trade-Offs in Coupled Infrastructure Systems.” *Earth System Dynamics* 9 (4): 1159–68. <https://doi.org/10.5194/esd-9-1159-2018>. [↵](#)

15. Carpenter, Stephen R., William A. Brock, Carl Folke, Egbert H. van Nes, and Marten Scheffer. 2015. “Allowing Variance May Enlarge the Safe Operating Space for Exploited Ecosystems.” *Proceedings of the National Academy of Sciences* 112 (46): 14384–89.

<https://doi.org/10.1073/pnas.1511804112>. [↵](#)

16. Mikulewicz, Michael. 2020. “The Discursive Politics of Adaptation to Climate Change.” *Annals of the American Association of Geographers* 110 (6): 1807–30.

<https://doi.org/10.1080/24694452.2020.1736981>. [↵](#)

17. Brown, Katrina, and Elizabeth Westaway. 2011. “Agency, Capacity, and Resilience to Environmental Change: Lessons from Human Development, Well-Being, and Disasters.” *Annual Review of Environment and Resources* 36 (1): 321–42. <https://doi.org/10.1146/annurev-environ-052610-092905>. [↵](#)

18. Biggs, Reinette, Maja Schlüter, Duan Biggs, Erin L. Bohensky, Shauna BurnSilver, Georgina Cundill, Vasilis Dakos, et al. 2012. “Toward Principles for Enhancing the Resilience of Ecosystem Services.” *Annual Review of Environment and Resources* 37 (1): 421–48.

<https://doi.org/10.1146/annurev-environ-051211-123836>. [↵](#)

19. Levin, Simon, Tasos Xepapadeas, Anne-Sophie Crépin, Jon Norberg, Aart de Zeeuw, Carl Folke, Terry Hughes, and Kenneth Arrow. 2012. “Social-Ecological Systems as Complex Adaptive Systems: Modeling and Policy Implications.” *Environment and Development Economics* 18 (2): 111–32.

<http://dx.doi.org.ezp-prod1.hul.harvard.edu/10.1017/S1355770X12000460>. [↵](#)

20. Bruijn, Karin de, Joost Buurman, Marjolein Mens, Ruben Dahm, and Frans Klijn. 2017. "Resilience in Practice: Five Principles to Enable Societies to Cope with Extreme Weather Events." *Environmental Science & Policy* 70 (April): 21–30. <https://doi.org/10.1016/j.envsci.2017.02.001>. [↵](#)
21. Irwin, Elena G., Sathya Gopalakrishnan, and Alan Randall. 2016. "Welfare, Wealth, and Sustainability." *Annual Review of Resource Economics* 8 (1): 77–98. <https://doi.org/10.1146/annurev-resource-100815-095351>. [↵](#)
22. Wildavsky, Aaron. 1980. "Richer Is Safer." *The Public Interest / New York*, 60:23–39. [↵](#)
23. Baird, Julia, Ryan Plummer, Lisen Schultz, Derek Armitage, and Örjan Bodin. 2018. "How Does Socio-Institutional Diversity Affect Collaborative Governance of Social–Ecological Systems in Practice?" *Environmental Management* 63 (2): 200–214. <https://doi.org/10.1007/s00267-018-1123-5>. [↵](#)
24. Tilman, David, Forest Isbell, and Jane M. Cowles. 2014. "Biodiversity and Ecosystem Functioning." *Annual Review of Ecology, Evolution, and Systematics* 45 (1): 471–93. <https://doi.org/10.1146/annurev-ecolsys-120213-091917>. [↵](#)
25. Renard, Delphine, and David Tilman. 2019. "National Food Production Stabilized by Crop Diversity." *Nature* 571 (7764): 257–60. <https://doi.org/10.1038/s41586-019-1316-y>. [↵](#)
26. Dakos, Vasilis, Allyson Quinlan, Jacopo A. Baggio, Elena Bennett, Örjan Bodin, and Shauna Burnsilver. 2015. "Principle 2 – Manage Connectivity." In *Principles for Building Resilience*, edited by Reinette Biggs, Maja Schlüter, and Michael L. Schoon, 80–104. Cambridge: Cambridge University Press. <https://doi.org/10.1017/CBO9781316014240.005>. [↵](#)
27. Henry, Adam Douglas, and Björn Vollan. 2014. "Networks and the Challenge of Sustainable Development." *Annual Review of Environment and Resources* 39 (1): 583–610. <https://doi.org/10.1146/annurev-environ-101813-013246>. [↵](#)
28. Bodin, Ö., S. M. Alexander, J. Baggio, M. L. Barnes, R. Berardo, G. S. Cumming, L. E. Dee, et al. 2019. "Improving Network Approaches to the Study of Complex Social–Ecological Interdependencies." *Nature Sustainability* 2 (7): 551–59. <https://doi.org/10.1038/s41893-019-0308-0>. [↵](#)
29. Biggs, Reinette, Line Gordon, Ciara Raudsepp-Hearne, Maja Schlüter, and Brian Walker. n.d. "Principle 3 – Manage Slow Variables and Feedbacks." In *Principles for Building Resilience*, edited by Reinette Biggs, Maja Schlüter, and Michael L. Schoon, 105–41. Cambridge University Press. <https://doi.org/10.1017/cbo9781316014240.006>. Biggs, Reinette, Line Gordon, Ciara Raudsepp-Hearne, Maja Schlüter, and Brian Walker. 2015. "Principle 3 – Manage Slow Variables and Feedbacks." In *Principles for Building Resilience*, edited by Reinette Biggs, Maja Schlüter, and Michael L. Schoon, 105–41. Cambridge University Press. <https://doi.org/10.1017/cbo9781316014240.006>. [↵](#)

30. Pershing, Andrew J., Nicholas R. Record, Bradley S. Franklin, Brian T. Kennedy, Loren McClenachan, Katherine E. Mills, James D. Scott, Andrew C. Thomas, and Nicholas H. Wolff. 2019. "Challenges to Natural and Human Communities from Surprising Ocean Temperatures." *Proceedings of the National Academy of Sciences* 116 (37): 18378–83. <https://doi.org/10.1073/pnas.1901084116>. ↵
31. Steffen, Will, Johan Rockström, Katherine Richardson, Timothy M. Lenton, Carl Folke, Diana Liverman, Colin P. Summerhayes, et al. 2018. "Trajectories of the Earth System in the Anthropocene." *Proceedings of the National Academy of Sciences* 115 (33): 8252–59. <https://doi.org/10.1073/pnas.1810141115>. ↵
32. Meyfroidt, P., R. Roy Chowdhury, A. de Bremond, E.C. Ellis, K.-H. Erb, T. Filatova, R.D. Garrett, et al. 2018. "Middle-Range Theories of Land System Change." *Global Environmental Change* 53 (November): 52–67. <https://doi.org/10.1016/j.gloenvcha.2018.08.006>. ↵
33. Downing, Andrea S, Avit Bhowmik, David Collste, Sarah E Cornell, Jonathan Donges, Ingo Fetzer, Tiina Häyhä, Jennifer Hinton, Steven Lade, and Wolf M Mooij. 2019. "Matching Scope, Purpose and Uses of Planetary Boundaries Science." *Environmental Research Letters* 14 (7): 073005. <https://doi.org/10.1088/1748-9326/ab22c9>. ↵
34. DeFries, Ruth S., Erle C. Ellis, F. Stuart Chapin III, Pamela A. Matson, B. L. Turner II, Arun Agrawal, Paul J. Crutzen, et al. 2012. "Planetary Opportunities: A Social Contract for Global Change Science to Contribute to a Sustainable Future." *BioScience* 62 (6): 603–6. <https://doi.org/10.1525/bio.2012.62.6.11>. ↵
35. Biermann, Frank, and Rakhyun E. Kim. 2020. "The Boundaries of the Planetary Boundary Framework: A Critical Appraisal of Approaches to Define a 'Safe Operating Space' for Humanity." *Annual Review of Environment and Resources* 45 (1): 497–521. <https://doi.org/10.1146/annurev-environ-012320-080337>. ↵
36. Scheffer, Marten, Stephen R. Carpenter, Vasilis Dakos, and Egbert H. van Nes. 2015. "Generic Indicators of Ecological Resilience: Inferring the Chance of a Critical Transition." *Annual Review of Ecology, Evolution, and Systematics* 46 (1): 145–67. <https://doi.org/10.1146/annurev-ecolsys-112414-054242>. ↵
37. Carpenter, Stephen, Kenneth Arrow, Scott Barrett, Reinette Biggs, William Brock, Anne-Sophie Crépin, Gustav Engström, et al. 2012. "General Resilience to Cope with Extreme Events." *Sustainability* 4 (12): 3248–59. <https://doi.org/10.3390/su4123248>. ↵