Toward a Preemptive Ecology for Rapid, Global, and Increasingly Irreversible Environmental Change:

A Discussion Paper with Implications for Research and Management in the Sacramento-San Joaquin Delta

Draft (11/25/19)

Delta Independent Science Board

Not all Board members agree with each of the arguments or concerns expressed in this discussion paper. This is not an assessment of Delta science, but a paper written specifically to promote discussion with Delta examples in order to develop a deeper understanding that could affect future extensions of Delta science and management.

If you need assistance interpreting the content of this document, please contact disb@deltacouncil.ca.gov.

The premise of this discussion paper is that significant additions to science and management are needed to foresee and preemptively respond to environmental conditions that are changing more rapidly, changing globally, driven by processes beyond regional control, and increasingly changing irreversibly.[1] The combination of these changes is especially challenging for the science of ecology and the preemptive management of species and ecosystems.

Rapid, irreversible ecological change occurred in the Sacramento-San Joaquin Delta in 2002. The rapid decline of the populations of four pelagic organisms during normal water years indicated something new was happening. The pelagic organism decline (POD) was comprehended as being a regime change by 2005. Yet five years after the regime change occurred, caution was advised:

> *Readers should be cautious when evaluating the relative importance of the hypotheses presented in this report. Hypotheses not based on peer-reviewed literature should be viewed with more skepticism but they represent the newest thinking on POD issues and may become new areas of research.[2]*

[1] O. Hoegh-Guldberg et al. (2019) "The Human Imperative of Stabilizing Global Climate Change at 1.5 degrees Celsius" *Science* 365: 1264 (September 29). The impacts on species and ecosystems is best documented in: Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (2019) Summary for Policymakers of the Global Assessment Report on Biodiversity and Ecosystem Services: https://onlinelibrary.wiley.com/doi/full/10.1111/padr.12283. The high level of concern among many scientists about our environmental future and how it might be mitigated can be found in: W. Ripple et al. (2019) World Scientists' Warning of a Climate Emergency. *BioScience* biz088: https://doi.org/10.1093/biosci/biz088.

[2] From the Executive Summary of the Interagency Ecological Program, *Pelagic Organism Decline Progress Report: 2007 Synthesis of Results:* https://water.ca.gov/LegacyFiles/iep/docs/pod/synthesis_report_031408.pdf.

The POD documents that ecologists were not equipped to foresee and address rapid, irreversible change. They did not have models that included tipping points and regime changes. It was appropriate to assure that the POD science was correct, but by the time ecologists were confident in their findings, there was little possibility for corrective management (though in this case correction may not have been possible).

The future may hold significant regime changes sequenced more frequently than the detection and analysis time needed for the POD. Under more rapid change, as is forecast, we will also need an ecology and related environmental sciences that support preemptive management.

Context and Purpose

People have extensively modified the Sacramento-San Joaquin Delta since the 1850s. Rapid change is not new, but the nature of rapid change that is beginning to be experienced has new qualities. The Delta Independent Science Board, working in conjunction with the Delta Science Program and the Delta Plan Interagency Implementation Committee, is assessing the adequacy of environmental and ecological research in the Delta, how well that research is addressing emerging challenges, and how it might be improved. This paper is a part of that process. Each member of the Delta Independent Science Board has contributed to this document, but there is not a consensus among the members around the full content of this paper. This paper is written to inform and stimulate discussion around controversial yet important issues.

1. The Changing Reality We Face

Climate change and the additional drivers of the sixth mass extinction are disrupting the entire Planet. While the Sacramento-San Joaquin Delta has long been difficult to understand because it has experienced rapid, local human-driven change for 150 years, the new drivers of Delta change are different for four reasons:[3]

a) Rapidity of Environmental Change.

The pace of change is accelerating. New projections for climate change are putting higher probabilities on more extreme scenarios that will have more serious consequences for people and the environment.[4] We are already observing how environmental extremes occur more frequently with less time for any recovery

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[3] S.N. Luoma et al. (2015) Challenges Facing the Sacramento-San Joaquin Delta: Complex, Chaotic, or Simply Cantankerous. *San Francisco Estuary and Watershed Science* 13(3): https://escholarship.org/uc/item/3nd0r71d.

[4] Underestimation of the speed of arrival of climate change is documented in the Summary for Policymakers of the 2019 *IPCC Special Report on the Ocean and Cryosphere in a Changing Climate*: https://www.ipcc.ch/srocc/home/. See also: N. Oreskes et al. (August 19, 2019) "Scientists Have Been Underestimating the Pace of Climate Change" *Scientific American*. California's *4th Climate Assessment* (2018) documents the speed of climate change and provides scenarios for the future by region. Underestimation was first reported in: S. Rahmstorf et al. (2007) "Recent climate observations compared to projections" *Science* 316: 709.

processes to function. Greater extremes increase the likelihood that thresholds will be crossed, increasing the risk that these changes will be highly disruptive.[5] While ecosystems have undergone rapid changes over the past 150 years, these changes have been episodic. Now, rapid change is continuous, and will be so into the foreseeable future.

Under these conditions, understanding and managing ecological systems present special challenges. The intricacies of how different species are affected by and respond to environmental changes and in how species interact with one another make comprehending and managing ecological systems under rapid change especially difficult. Under these circumstances, the established approaches of scientific research, even aided by new monitoring, informatics, and computing technologies, may no longer be sufficient to enable scientists to assess reasonable future scenarios, let alone predict and inform management into the future. Systems may change so rapidly, continuously, and fundamentally that the results of research may no longer apply by the time they are translated into practice. The speed and acceleration of change may outstrip the capacity of existing approaches to environmental science and ecology to develop predictions that hold long enough to be implemented, let alone ameliorate rapid change.

b) Globality of Environmental Change.

Many particular places have experienced rapid environmental change and consequent ecological disruptions in the past. The Sacramento-San Joaquin Delta is a prime example of a system disturbed by human intervention that has become more difficult to understand. Now, all places will be changing, compounding the difficulties of managing environmental conditions and ecosystems. Ecologically, what is different is that ecologists concerned with change in one place will no longer be able to look to other places with comparable but less disturbed habitats to provide models of how disrupted places might best be ecologically restored. Unmanaged habitats that have been changing more slowly have also provided individuals from populations of species lost in disrupted areas to be used in ecological restoration. With climate change driving environmental change, there will be rapid change everywhere, leaving neither models of “more natural” systems nor good reserves of species for use in restoration. Species will be going extinct locally and even globally, species still in their original locations will be under environmental stress, and many species will be shifting to, and affecting species dynamics in, new locations. The globality of environmental change challenges local and regional ecosystem management.

[5] Three key sources on environmental thresholds and tipping points are: J. W. Rockstrom et al. (2009) “Planetary Boundaries: Exploring the Safe Operating Space for Humanity.” *Ecology and Society* 14(2): 32 and A. D. Barnosky et al. (2012) “Approaching a State Shift in Earth’s Biosphere” *Nature* 486(7401): 52 to 58, and The National Academy of Sciences (2013) *Abrupt Impacts of Climate Change: Anticipating Surprises,* National Academy Press.

c) Irreversibility of Environmental Change.

Even if they are aggressively mitigated soon, the greenhouse emissions and biospheric feedbacks driving climate change, will drive environmental change and thereby affect ecosystems for several centuries. Even if adequate sequestration of carbon dioxide from the atmosphere proves possible, we have no evidence that the geosphere, let alone the biosphere, will return to previous conditions. Indeed, it is increasingly recognized that we are in the 6th mass extinction of Earth's species due to a variety of anthropocentric drivers, including climate change. Thresholds and irreversibility have become a focus of concern for a significant number of environmental scientists.[6] It may prove possible to genetically modify species to enhance their ability to fit into rapidly changing environments. It may prove possible to recreate species that go extinct. But these possibilities are probably irrelevant to ecosystem management for decades to come.

d) The Drivers Are Beyond Regional Control.

Sea level rise; higher air, water, and soil temperatures; and changes in the hydrographic cycle are globally driven and beyond regional control. The drivers cannot be managed, we can only respond to and work with them.

Forest ecosystem science provides a dramatic example of what the future may hold for Delta science. We already see significant changes in how forest ecosystems are being monitored, understood, and managed. In the western United States, the frequency, size, and intensity of wildfires have increased dramatically, largely due to climate change. Trees stressed by drought and heat are more susceptible to disease and insect infestation, which then make the trees more susceptible to fire. As fires reduce forest canopy, evaporation and transpiration are reduced and more water runs off forest lands. Fire also affects the quality of forest runoff. The types of science now being used to understand and manage western forests are changing in response to accelerating, region-wide, and increasingly irreversible environmental changes.[7]

Climate scientists are reconsidering the roles of forests in carbon sequestration for climate mitigation. Rapid carbon sequestration could shorten the period of environmental change driven by the greenhouse effect but using forests for sequestration may also have serious environmental consequences and risks, including the risk that sequestered carbon could rapidly be lost to fire.

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[6] For reviews of ecological threshold thinking, see P.M. Groffman et al. (2009) "Ecological thresholds: The key to successful environmental management or an important concept with no practical application?" *Ecosystems* 9: 1 to 13; John Wiens *Ecological Challenges and Conservation Conundrums* (2016); and M. Scheffer et al. (2001). "Catastrophic shifts in ecosystems" *Nature* 413: 591 to 596.

[7] T. Schoennagel et al. (2017) "Adapt to more Wildfire in Western North American Forests as Climate Changes" *Proceedings of the National Academy of Sciences*. J.L. Crockett and A.L. Westerling (2018) "Greater Temperature and Precipitation Extremes Intensify Western U.S. Droughts, Wildfire Severity, and Sierra Nevada Tree Mortality." *Journal of Climate* 31: 341 to 354.

Environmental changes are affecting forests everywhere in the West, and no one expects forests to return to their previous state. Different tree species are proving better fits for the new conditions at different locales and are changing the habitats for other plant and animal species, including valued wildlife. Few of these changes were even a possibility to be considered in the forest science of three decades ago. Now this is the type of forest science being done. The framing of research and specific projects on the agenda of forest science only a decade ago are being revised or reconsidered due to the new forest dynamics and habitats.

Water planners in California are now formally integrating climate change into their planning processes and accelerating the upgrading of engineered structures. Rates of sea-level rise and new frequencies and extremes for floods and droughts must be considered.[8] Hydrological risks make planning more difficult, new measures for estimating water reliability and environmental flows are needed, but the science of hydrology probably does not need new ways of doing research. Similarly, the public goals of supplying water and providing protection from floods and droughts will change little as climate changes, even as the challenges of meeting public goals become greater. For ecological systems, however, the situation is more complex, largely due to differential responses between and interdependencies among species.

Climatological and associated hydrological changes and uncertainties are important drivers of ecological change, but the dynamics of how species abundances will change, how species will redistribute geographically, and how they will interact with each other during rapid, global, and irreversible environmental change are only beginning to be studied and are not yet to the stage where future scenarios can be developed. This means that it is difficult to assess which ecological factors can be managed or which stresses mitigated or ameliorated under rapid, global, and irreversible change. It is also not clear what goals might be desired for management actions in a rapidly changing ecological system.

Rapid, global, and increasingly irreversible changes in the environment are becoming more and more apparent. Trends are steeper, extremes are more extreme and more frequent, and systems are undergoing major shifts as thresholds are being crossed. Shifts in species distributions are changing the webs of species interactions.[9] Microbes and insects are exhibiting rapid evolutionary changes. Even basic hydrological processes such as the water cycle are speeding up, more in some places (such as central and northeastern United States) than in others (northwestern and southeastern

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[8] See for example: Hydrosystems Research Group. University of Massachusetts, Amherst and California Department of Water Resources, "Decision Scaling Evaluation of Climate Change Hydrologic Risk to the State Water Project," Final Report, May 2019. See also the program, speakers, and topics at the "summit" on September 17, 2019: Planning for Change: Climate Change Vulnerability and Adaptation: https://water.ca.gov/News/Events/2019/September-19/Planning-for-Change.

[9] Camille Parmesan (2006) "Ecological and Evolutionary Responses to Recent Climate Change" A*nnu. Rev. Ecol. Evol. Syst.* 37: 637 to 669.

United States).[10] These changes are occurring everywhere. And increasingly these changes have become irreversible.

Foreseeing and being able to provide management advice in the face of rapid, global, and irreversible change, however, have not been front and center in how ecologists think about ecosystems, do their research, and formulate advice for environmental managers.[11] This suggests environmental scientists and ecologists in particular are likely to need new ways of thinking about the Delta to better anticipate and preemptively respond to foreseeable accelerations in its dynamics. Interpreting the implications of new scientific findings for management and communicating significantly new interpretations to policy makers and managers will become even more challenging.

Rapid technological, social, and economic changes are also occurring.[12] Some of the technological changes have improved the quality and speed of environmental monitoring and modeling, enhancing the ability of ecologists to detect and interpret rapid environmental change. However, lags and gaps between scientific understanding and meeting the needs of managers persist. To understand why different approaches may be needed, it is useful to focus on ecology, and look at how understandings of environmental dynamics and change have developed.

2. Ecology and Change: Some history

The assumption that change in Nature is slow has a long history. In 1830 the English geologist Charles Lyell persuasively argued that the physical processes that formed the Earth had been slow or mildly cyclical and had taken place through processes still observable in current times.[13] For practical purposes, slow change in geological time can be treated as no change in ecological time, a simplification that helped ecologists focus on the many interrelationships between species by assuming ecosystems were in relative equilibrium. Evolutionary change was also presumed to be a slow and fairly

[10] T.G. Huntington et al. (2018) “A new indicator framework for quantifying the intensity of the terrestrial water cycle” *Journal of Hydrology* 559: 361 to 372.
[11] We note again that environmental scientists are doing research on rapid environmental change in that they are documenting change after the fact and forecasting the implications of the past into the future. Research in addressing the biosphere’s feedbacks with climate change are especially notable, see, for example: A.C. Spivak et al. (2019). “Global-change controls on soil-carbon accumulation and loss in coastal vegetated ecosystems” *Nat. Geosci* 12: 685 to 692. Game theorists are also taking on rapid change: P.C. Trimmer et al. (2019) “Rapid environmental change in games: complications and counter-intuitive outcomes” *Scientific Reports* 9(1): 7373.
[12] Thomas L. Friedman provides an excellent lay summary of how technology and social systems are also changing faster along with basic information on the acceleration of climate change in *Thank You for Being Late: An Optimists Guide for Surviving in the Age of Accelerations* (2016, Chapter 6 for climate change).
[13] Stephen Jay Gould (1988) *Time’s Arrow, Time’s Cycles: Myth and Metaphor in the Discovery of Geological Time*.

continuous process.[14] This presumption was challenged in 1972 by Niles Eldredge and Stephen Jay Gould, who argued that evolution occurs in small bursts that lead to quick, marked changes as multiple species evolve in response to changes in each other, likely changing ecosystem structure as well.[15] And although some ecological framings considered change in the dynamics of populations and ecosystems, they assumed ecological systems were inherently stable and would return to a (relatively) stable state if perturbed.

With the advent of computers, the development of cybernetics, and Cold War planning, systems thinking blossomed as an applied field and impacted scientific thinking generally.[16] Debates ensued about the fundamental nature of systems, for example over whether ecosystems with more species diversity were more stable or whether more stable physical environments led to more species diversity.[17] In spite of the new interest in system dynamics, the “balance of nature” or stable equilibrium view of nature continued to dominate ecological thinking and practice. The environment during the time period in which ecology developed as a science was unusually stable, and “physics envy” promoted a search for general models and theories about how nature worked. This view lent itself to mathematical theory. Change in more complex systems become more difficult to characterize, and model, let alone calibrate model parameters based on data from monitoring. Environmental extremes have been regarded as outliers and generally ignored, especially in formal models. This perspective became the basis of environmental management. The dynamics of systems were considered to be orderly and deterministic.

By the 1970s, however, awareness of the temporal variability of natural communities became undeniable. A conceptual paradigm shift ensued, and acceptance of non-equilibrium views began to take hold.[18] In 1972, C.S. (Buzz) Holling developed a model of temperate forests going through phase changes during which different species are

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[14] The discussion of fast and slow in evolution is relative to whether the species is a mite or a redwood tree. Many insects have multiple generations (some more than twenty) per year and thus can evolve very rapidly. This became quite apparent as insects developed resistance to insecticides used in agriculture, yet the dominant mindset that evolution occurs slowly has remained until recently.

[15] N. Eldredge and S.J. Gould (1972). “Punctuated equilibria: an alternative to phyletic gradualism” In T.J.M. Schopf, ed., *Models in Paleobiology*.

[16] For a recent review of systems thinking, see: Jeremy Lent (2017) *The Patterning Instinct: A Cultural History of Humanity’s Search for* Meaning Prometheus Books. Chapter 19.

[17] A classic work is Robert M. May’s *Diversity and Complexity in Model Ecosystems* (1974). A more recent overview is provided by A. Ives and S.R. Carpenter (2007) “Diversity and Stability of Ecosystems” *Science* 317: 58 to 62.

[18] John A. Wiens (1977) “On competition and variable environments” *American Scientist* 65: 590 to 597. For discussions of paradigm shifts in ecology, see K. Cuddington and B. Beisner (Eds.) (2005) *Ecological Paradigms Lost*, Elsevier Academic Press, Burlington, MA, and John A. Wiens (2016) *Ecological Challenges and Conservation Conundrums*, Wiley, Chichester, UK.

dominant. Holling laid the foundations for two important ways of thinking today: resilience enhancement and adaptive management.[19] In the last quarter century, conceptual models of coupled human-natural systems have also emerged, notably those used in the Millennium Ecosystem Assessment[20] and that proposed by Jianguo Liu.[21]

Climate change is eliminating some species and spatially redistributing other species both directly and indirectly. Temporal shifts in biological events (e.g. when plants bloom and need pollination, when birds migrate, when fish spawn) are also occurring. Species redistribution ecology is documenting the shifts and what drives them.[22]

The emphasis is on why species move rather than to where they are moving and what to do about it—the focus of invasion ecology. The term "novel ecosystems" is being used, in juxtaposition with invaded or disrupted systems, and attention is being given to better ways to work with change rather than always fighting it.[23]

To a large extent, these more recent developments in ecology are new ways of looking at longstanding problems, rather than ways of addressing rapid, global, and irreversible change *per se*.

3. A Closer Look at Rapidly Accelerating Environmental Change

Rapidly accelerating environmental change alone, apart from the global and increasingly irreversible nature of change, will quite likely require a rethinking and readjustment of how ecological science is designed and conducted, as well as interpreted for and communicated to managers.

Rapid environmental change has several components that individually and collectively challenge current approaches to environmental science, and ecology in particular:

- First, the *rates of change* are much higher than they were during the past century, in which ecology developed and matured as a science. This is critical because:

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[19] C.S. Holling (1973) "Resilience and Stability of Ecological Systems" *Annual Review of Ecology and Systematics* 4: 1 to 23.

[20] Millennium Ecosystem Assessment, *Ecosystems and Human Well-Being: A Framework Document*, Island Press. 2003.

[21] Jianguo Liu (2017) "Integration across a metacoupled world" *Ecology and Society* 22(4): 29.

[22] Marine ecologists have made some progress on the task of sorting between which distributional shifts in species are climate induced and which are more appropriately thought of as "invasions." C.J.B. Sorte et al. (2010) "Marine range shifts and species introductions: comparative spread rates and community impacts" *Global Ecology and Biogeography* 19: 303 to 316.

[23] T.C. Bonebrake et al. (2017) "Managing consequences of climate-driven species redistribution requires integration of ecology, conservation and social science" Biological Reviews 93(1).

  - The steps of the scientific process – developing hypotheses, obtaining funding, gathering observations or conducting experiments, interpreting and validating conclusions, publishing results, and then obtaining additional funding to dig deeper – take time, and it is not obvious how any of these steps can be sped up.
  - The accumulation of past scientific and experiential knowledge of scientists will become dated more rapidly and consequently be less reliable for designing experiments, interpreting findings, and drawing implications for management.
  - Incorporating new scientific findings into management practices also takes time.
- Second, the rate of change is *accelerating*: the rates of carbon accumulation in the atmosphere, reductions in species populations or extinctions, and many other natural and socioeconomic factors are steepening. [24]
- Third, these elements of change create *increased variability* in environmental features, making it more difficult to produce the confident predictions that have long been the hallmark of science – "average" or "normal" conditions occur less often.
- Fourth, increasing variability brings *more frequent extremes*. Droughts in California and other parts of the world are becoming longer and drier; extreme temperature records fall with increasing regularity; the magnitude and frequency of extreme rainfall events and flooding are increasing—the list goes on.
- And fifth, as systems become more variable and extremes more frequent, the likelihood increases that *thresholds or tipping points* will be encountered. When thresholds are passed, systems may undergo abrupt changes, so-called "regime changes," leading to unanticipated consequences.[25]

To complicate matters, different aspects of managed and unmanaged ecosystems are responding to rapid environmental change at different times in different places with different frequencies and intensities. As a result, the changes are discordant in time, space, and context. The acceleration of change is a key part of the setting in which ecological science now needs to work. Scientific understanding needs to consider new processes and interactions between processes in new ways. The upshot is that scientific understanding has become more difficult. As rapid environmental change continues, extremes will become more extreme and irreversible thresholds will inevitably be breached more often. The critical question is how science can help to

[24] Climate change will be the fastest-growing cause of species loss in the Americas by midcentury. R.J. Scholes et al. (Eds.) (2018). *IPBES: Summary for policymakers of the assessment report on land degradation and restoration of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services*. Bonn, Germany: Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services.
[25] See the National Academies of Sciences report on *Abrupt Impacts of Climate Change. Anticipating Surprises* (2013).

anticipate more frequent and sudden changes, and whether these dynamics can be mitigated.

4. How Have Scientists Responded to Rapid, Global, and Irreversible Change?

During the past few decades, some scientists have begun to reframe the nature of environmental problems and how to respond to them. Here are several new approaches.

New Resilience Thinking.

One way of dealing with the effects of accelerating change on ecological and social systems is to enhance the resilience of such systems to change. As change and uncertainty increase, there has been an almost universal call from scientists and resource managers, as well as from wealth managers, city planners, child psychologists, hospital administrators, electricity grid analysts, transportation engineers, politicians, and many others to increase the resilience of systems to future threats. The word "resilience" has great appeal in times of global rapid change, uncertainty, and irreversibility.

There are multiple scientific definitions of resilience, but they all relate to how a system responds to a disturbance.[26] The new resilience thinking, especially as portrayed by one of its leading proponents, the Stockholm Resilience Centre of Stockholm University,[27] has expanded the term to incorporate "tipping points," "adaptability," and "transformability" into a broader concept of the ability of a system to buffer perturbations under continuous change, including surprises, and maintain a functional state, hopefully retaining much of its earlier character.[28] Understanding tipping points is a critical part.[29] The resilience concept has evolved from a system's ability to return to its previous state after a single perturbation to a system's ability to handle ongoing global change while avoiding highly disruptive shifts.

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[26] For a review and discussion of the conventional scientific meanings of resilience, see: Lance H. Gunderson (2000) "Ecological Resilience in Theory and Practice" *Annual Review of Ecology and Systematics*: 31: 425 to 439 and B. Walker and D. Salt (2006) *Resilience Thinking: Sustaining Ecosystems and People in a Changing World,* Island Press, Washington, DC.

[27] Stockholm Resilience: https://www.stockholmresilience.org. R. Biggs, M. Schluter, and M.L. Shoon (2015) *Principles for Building Resilience: Sustaining Ecosystem Services in Social-Ecological Systems*. Cambridge University Press.

[28] C. Folke et al. (2010) "Resilience Thinking: Integrating Resilience, Adaptability, and Transformability." *Ecology and Society* 15(4): 20.

[29] Most of the science of tipping points has been based on marine and lake systems. For a more prospective review, see: R. Biggs et al. (2009) "Turning Back from the Brink: Detecting an Impending Regime Shift in Time to Respond to It" *Proceedings of the National Academy of Sciences* 106(3): 826 to 831. See also: M. Sheffer et al. (2009) "Early warning signals for critical transitions" *Nature* 461: 53 to 59.

Most importantly, the new resilience thinking as elaborated by the Stockholm Resilience Centre defines the *system* as the *coupled social – ecological system*, not simply the ecological system.[30] In this new resilience thinking, how well scientists, managers, and people overall recognize the consequences of change and then modify their behavior and management of the ecosystem are as critical as the dynamics of ecological systems themselves.

Broadly speaking, the shift to resilience thinking is a shift away from optimizing the design of systems for meeting current objectives toward working with a changing system to maintain future functionality. Resilience thinking may be working toward a dynamic vision of coupled human-natural system sustainability. At the same time, while agreeing that including the human response is critical to “ecological” resilience, to do so effectively the human response needs to be based on an understanding rooted in coupled human-nature systems research. Doing coupled human-natural systems research, however, is a lengthy process because it takes additional time to integrate the research of social and natural scientists and to collectively interpret findings of coupled systems models. This runs counter to the need for faster science and management during rapid change.

Horizon Scanning.

Scientists take stock of the state of a science and frequently assess future challenges as they design their research. With the complexity of problems humanity is facing, the disciplinary nature of scientific knowledge, and the limits to what any one person can know, it has become necessary to formally organize scientists into teams to scan more formally to prepare for the future. Horizon scanning formalizes the process of “taking stock” and collectivizes the process in light of new challenges to assess future trends. The scans are broader and deeper than scientists from any one discipline can conduct, and are aimed at detecting wholly new phenomena. The scientific literature, science news, and experiential knowledge of scientists are deliberately assessed for unusual findings or new trends.

[30] Coupled human-natural system, or social-ecological system, research was also initiated a quarter century ago as it became more clear to ecologists that people needed to be included in the system under study, and even more so in the Anthropocene, see: B. L. Turner II et al. (2016) “Socio-Environmental Systems (SES) Research: what have we learned and how can we use this information in future research programs” *Current Opinion in Environmental Sustainability* 19: 160 to 168.

Horizon scanning is a set of formal collective approaches to taking stock and looking forward that is used in public health, medicine, and other fields.[31] Horizon scans are best formally planned, undertaken by interdisciplinary teams of scientists, and peer reviewed.

This combination makes this approach new to science as traditionally described and practiced, although interdisciplinary science teams have been horizon scanning informally for decades. Through formal horizon scanning, scientists seek to foresee phenomena that they would have missed or were less likely to discover by acting individually. Artificial Intelligence and other approaches to mining massive amounts of data ("Big Data") for patterns can be important elements of horizon scanning.

Horizon scanning, as a process of looking ahead, inevitably deals with the speed of environmental, technological, and social change. By formalizing the process, making it interdisciplinary, and more deliberately addressing the speed of change, horizon scanning may be a practical approach to identifying key issues for research. Because horizons are scanned from the platform of existing knowledge and science, however, it is not clear that this approach can deal with rapidly changing conditions that produce surprises, lead to shifts to quite different system states (i.e., regime shifts), or increase the frequency of extreme events.

Elicitation of Expert Judgment.

The Delphi method was developed during the Cold War to elicit and narrow the range of the judgments of experts with respect to the consequences of introducing different technologies into defense systems. Over the decades, numerous other uses have been found for the technique, and it has been modified and enriched over time. The reports of the Intergovernmental Panel on Climate Change are, as a whole, a product of experts collectively assessing the scientific literature.

Due to the rapidly emerging nature of climate science and evidence of climate change, the need for predictions, and the high risks of climate change, confidence judgments are also elicited. In the IPCC assessments, there has been considerable learning in the process of eliciting confidence judgments, and the process has been improved from one assessment to another. The IPCC approach is best when interactive among experts so that different types of expertise can be shared, but "group think" also needs to be avoided. Sometimes, the assessment of the quality of the scientific information is done with policymakers and managers because they may ask different questions about the

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[31] A key scientific article providing a historical review and summary of lessons learned is: E. Amantidou et al. (2012) "On Concepts and Measures in Horizon Scanning: Lessons from Initiating Policy Dialogues on Emerging Issues" *Science and Public Policy* 39: 208 to 221. The key example of horizon scanning being used for environmental issues can be found in the tenth annual effort to scan for conservation issues found in: W.J. Sutheland et al. "A Horizon Scan for Emerging Issues in Global Conservation in 2019" *Trends in Ecology and Evolution* 34(1): 83 to 94.

nature of confidence than scientists would.[32] Formal techniques for the elicitation of expert judgment may help obtain sufficiently reliable expert knowledge more quickly than regular scientific processes, but expert elicitation is not a substitute for hypothesis testing through field work, monitoring, and modeling.

Scenario Assessment.

Scenarios provide a way to structure thinking about the consequences of possible futures and possible ways to respond to them. Formal approaches to scenario building and assessment date to military planning in the 1960s. Royal Dutch Shell is credited for the development and formal use of corporate scenario planning in the 1970s.[33] Climate change scenarios have been at the core of climate science for assessing climate system responses and for communicating the impacts of climate change to inform climate mitigation and adaptation policy. Scenarios facilitate discussion of the future among scientists. The Millennium Ecosystem Assessment used scenarios stressing alternative future global governance structures. Scenario assessment has become a recognized area of study and teaching. The strengths and weaknesses of different ways of doing scenario assessment as well as proposed innovations are regularly reviewed. Climate scenarios and their adequacy are especially significant.[34] Scenarios are an important way of giving complex issues some structure. Choosing which scenarios to use is an art, but once chosen they facilitate discussion among interdisciplinary researchers and with those who use the findings of research.

Other Responses to Rapid, Global, Irreversible Change.

In 1998, Jane Lubchenco argued that science was facing new challenges and called for a new "commitment on the part of all scientists to devote their energies and talents to the most pressing problems of the day…"[35] In 2010, ecologist William Schlesinger called for a new ecology that bridged theory and practice in order to respond to change

[32] For a review and update on the elicitation process, see: K.L. Mach et al. (2017) "Unleashing Expert Judgment in Assessment" *Global Environmental Change* 44: 1 to 14.

[33] P.J.H. Shoemaker and C.A.J.M van der Heijden (1992) "Integrating Scenarios into Strategic Planning at Royal Dutch Shell" *Strategy and Leadership* 20(3): 41 to 46. Kees van der Heiden (2006) *Scenarios: The Art of Strategic Conversation,* 2nd Edition. John Wiley. G. Ringland and P. Schwartz (1998) *Scenario Planning: Managing for the Future* John Wiley and Sons. P. Cornelius et al. (2005) "Three Decades of Scenario Planning in Shell" *California Management Review* 48(1): 92 to 109.

[34] See, for example: R H. Moss et al. (2010) "The Next Generation of Scenarios for Climate Change and Assessment" *Nature* 463: 747 to 756. For a recent review by the co-directors of Stanford Environmental Assessment Facility, see: K.J. Mach and C.B. Field (2017) "Toward the Next Generation of Assessments" *Annual Review of Environment and Resources* 42: 569 to 597.

[35] Jane Lubchenco (1998) "Entering the Century of the Environment: A New Social Contract for Science" *Science* 279(5350): 491 to 497.

more effectively.[36] In 2012, ecologist Margaret Palmer called for "actionable science" that produced the science that policy makers and managers needed.[37] In 2017, twenty-nine ecologists elaborated the foundations of translational ecology.[38] Translational ecology and actionable science are appeals to scientists to make stronger links between research, from design to interpretation of results, and the needs of managers and policymakers so as to improve the application of science and to speed up the process.

Speeding up the translation of research to decision making would be a positive response to more rapid change. Yet no new research approaches are proposed. Rather, translational ecology and actionable science affect the choice of research topics and encourage researchers to be more dedicated to linking with managers. Translational ecologists do expect to spend more time making the connections between science and management.

5. Conundrums for Ecology Highlighted by Rapid, Global, and Irreversible Change

Rapid, global, and irreversible change creates a fundamental conundrum for ecology, and for science more broadly. It becomes increasingly urgent that environmental science and ecology in particular has the ability to foresee and preemptively respond to change. Actions to deal with the environment need to be taken quickly and modified on the fly. Science must be nimble enough to provide information and guidance when they are needed. Yet because change in the Anthropocene is human-driven, an integrative human-natural systems approach is necessary. Doing coupled systems research, however, requires *time* to bring scientists from multiple disciplines together, learn how to communicate across disciplines, agree on a framework, combine disparate data into models, interpret the findings, and make management recommendations. It is important to realize that the management response to change is integral to ecosystem resilience.

The scientific process depends on scientists engaging in serious discussions. With less time to do solid science, experts will need to consider different ways of learning more quickly from field knowledge, interpreting a situation, and coming to a shared judgment. Expert elicitation methods, widely used to assess future possibilities in policy, business, medicine, economics, and even warfare, may provide a useful approach. Structured discussion and judgments become increasingly important as the accelerating pace of change requires more complex models at the same time that research results may be less certain due to the faster rate of change.

Environmental science needs to become a more discursive process to complement new ways of doing field and laboratory research. Reconciling the time required to produce reliable science in complex systems with the speed and disruptiveness of environmental change will be difficult.

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[36] William H. Schlesinger (2010) "Translational Ecology" *Science* 329: 609.
[37] Margaret A. Palmer (2012) "Socioenvironmental Sustainability and Actionable Science" *Bioscience* 62(1): 5 to 6.
[38] C.A.F. Enquist et al. (2017). "Foundations of Translational Ecology" *Frontiers in Ecology and Environment* 15(10): 541 to 550.

There is another conundrum that strikes at the heart of the scientific process. Science has credibility because research and its results are replicable. This sets a higher standard than other approaches to understanding. Yet during rapid, global, and irreversible environmental change, replication, or even complementary research that helps confirm earlier findings, will be more difficult or impossible because the underlying conditions and dynamics are changing too rapidly. The assumption that the system that supplied the observations and results of research can be managed on the basis of those results may no longer hold in an era of rapid change. The subjects of study may not hold still long enough for the results of a scientific study to be applicable.

6. Conclusion

History has given us the laws and regulations, organizational structures, types of scientific expertise, ways of thinking, and science agendas we now have. The organization and approaches of science seem tightly interlocked and securely anchored in the past. Now changes in the complex webs of interactions among geologic, biological, and social dimensions of the environment are accelerating and taking people and the Delta in new, uncertain, and potentially dangerous directions. The past will not always serve us well as a guide to the future.

Ecology continues to respond to new challenges. New, more rapid, and continuous monitoring technologies, better informatics, and improved computational modeling will surely help. Formal horizon scanning by interdisciplinary teams, with attention given to possible tipping points that would result in regime shifts, appears to be a constructive approach to systematically looking forward in a faster moving, more uncertain future. Ecological modeling with tipping points and regime shifts under different environmental drivers could help to conceptually prepare for the possibility of a regime shift and eventually to foresee and manage to avoid undesirable shifts. Scenario thinking will also be helpful. Formal processes of eliciting expert judgment will likely become more and more helpful. Accelerating the synthesis of findings and improving communication with managers will surely help. Perhaps there are other approaches to be developed in a new preemptive ecology.

Ecology and the environmental sciences have expanded their repertoire of capabilities as environmental challenges arise. The new challenge is to foresee change and be able to respond preemptively.