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# Preparing Scientists, Policy-Makers, and Managers for a Fast-Forward Future

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## ABSTRACT

Ecosystems in the Sacramento–San Joaquin Delta are changing rapidly, as are ecosystems around the world. Extreme events are becoming more frequent and thresholds are likely to be crossed more often, creating greater uncertainty about future conditions. The accelerating speed of change means that ecological systems may not remain stable long enough for scientists to understand them, much less use their research findings to inform policy and management. Faced with these challenges, those involved in science, policy, and management must adapt and change and anticipate what the ecosystems may be like in the future. We highlight several ways of looking ahead—scenario analyses, horizon scanning, expert elicitation, and dynamic planning—and suggest that recent advances in distributional ecology, disturbance ecology, resilience thinking, and our increased understanding of coupled human–natural systems may provide fresh ways of thinking about more rapid change in the future. To accelerate forward-looking science, policy, and management in the Delta, we propose that the State of California create a Delta Science Visioning Process to fully and openly assess the challenges of more rapid change to science, policy, and management and propose appropriate solutions, through legislation, if needed.

## KEY WORDS

California, climate change, ecology, environmental change, extreme events, governance, management, policy, rapid change, Sacramento–San Joaquin Delta, thresholds, uncertainty

## INTRODUCTION

The environment is changing more rapidly than it did during the prior century, and the rate of change is accelerating. Extreme events are occurring more frequently and with greater intensity. Ecosystems are being pushed beyond their recent historical range of variation. These changes—driven by alterations in climate, land use, economics, and a host of other forces—challenge how scientists, policy-makers, and managers can address environmental problems.

The occurrence of more rapid environmental change and greater extremes have been highlighted in numerous scientific publications (e.g., Hobbs and Cramer 2008; Lindenmayer et al. 2010; Barnosky et al. 2012; Beach and Clark 2015; Bradford et al. 2018; Vosen 2020; Ripple et al. 2021) as well as in popular literature (e.g., Friedman 2016). In California, for example, the Sierra Nevada mountains had a historically low snowpack in 2015 that was unprecedented in the last 500 years, while 2010–2020 also included some of the largest snowpacks on record (Belmecheri et al. 2015). An unusually hot summer across California in 2020 included the highest temperature reliably recorded on earth: 130°F (54°C) in Death Valley in August.

Rising temperatures, longer droughts, extremely wet years, and unprecedented wildfires in California have raised public awareness of the increasingly likely prospect of a fast-forward future. In response to this challenge, scientists, policy-makers, and managers of the Sacramento–San Joaquin Delta have initiated new science programs, improved policy guidelines, and implemented better management practices. These improvements are significant. Yet, we argue that a more substantial, integrated, and anticipatory transformation in Delta science, policy, and management is needed. Environmental changes may be swift, create unprecedented conditions, and produce surprises. To cope with rapid change, new ways of doing science, developing policies, undertaking management, and thinking about the environment are needed. These new and foreseeable challenges are sufficiently important that we conclude this paper with a recommendation that the state of California consider initiating a new Delta science, policy, and management visioning process to inform new legislation and regulations on how to better foresee, organize, and work with more rapid and uncertain environmental change in the Delta.

We have written this paper as scientists for scientists, while we also hope to speak to policy-makers and managers. Scientists need to take the lead in showing how systems respond to rapid change, while policy-makers need to establish the directives or boundaries that set priorities on how to respond to those changes, given societal goals. From these decisions and policies, managers must then try to meet legislatively determined objectives informed by the "best available science" within the boundaries set by policy. The challenges of foreseeing how the future might unfold, establishing common goals, and working with rapid change and greater extremes must be understood as extending across the traditional domains of science, policy, and management. Adapting to more rapid change is not simply a matter of better science, or better policy, or better management. These must be tackled in concert.

In this article, we consider how scientists, policy-makers, managers, and stakeholders can better anticipate and address rapid change. Part 1 elaborates on the difficulties of doing science under rapid change. Part 2 argues that a more systematic use of horizon scanning and scenario analysis, informed in part through expert solicitation, is needed to better anticipate the future. These approaches for anticipating the future need to be formally instituted and interactively integrated across the work of scientists, policy-makers, and managers. Part 3 encourages greater use of coupled socio-environmental systems thinking, and distributional and disturbance ecology, as ways of understanding and addressing change, both expected and unexpected. Part 4 argues that Delta governance must be much more anticipatory to improve how Delta science, policy, and management cope with change and surprise. Part 5 explores the possibility of establishing a new Delta Blue Ribbon Task Force in California to lead a visioning process to elaborate and prepare for the transition to anticipatory science, policy, and management in the Delta. Part 6 summarizes our conclusions.

## 1. THE NATURE OF THE PROBLEM

Ecological systems vary across space and change over time. This variation makes it difficult to replicate research, and interpret meaningful information in ecology (Fraser et al. 2018). The Delta environment has been radically transformed over the past 150 years, and multiple forces continue to drive change (San Francisco Estuary Institute 2014). Annual variations in streamflow, temperature, seasonal timing, pollution inputs, and salinity gradients—complicated, for example, by invasions of new species or a levee collapse—have made it difficult to establish baselines and detect trends (Nobriga and Smith 2020).

The case of the pelagic organism decline in the Delta (Box 1) is a good example of the scientific challenges of detecting and explaining rapid change. A more recent example is how nitrogen and phosphorous from agriculture and municipalities (Dahm et al. 2016), increased in concentration as a result of low flows that reduced dilution and increased residence time. This resulted in a rapid rise of cyanobacterial algal blooms in Delta waterways (Lehman et al. 2020). In the past, environmental change and variation were expected to stay within defined limits (Milly et al. 2008). Now, however, rapid and accelerating changes, a greater frequency and magnitude of extreme events, and the potential crossing of multiple unknown thresholds are confounding ecological science and challenging its applications to policy and management.

*There are three reasons why more rapid change and greater uncertainty are more difficult for science, policy, and management:*


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### Reason 1

First, ecological systems may change too rapidly for scientists to be able to understand them, much less have their research findings incorporated in policy and management.

The speed and acceleration of changes may compel scientists to change how investigations are conducted and interpretations are derived. To ensure reliability and accuracy, the research and information-dissemination process usually involves many steps: identifying and refining a hypothesis, finding colleagues with appropriate skills, designing a research project, convincing funders, obtaining approvals and permits, doing the research, analyzing data and interpreting findings, presenting research talks, submitting papers for peer review, responding to reviewers' comments, and submitting final manuscripts for publication so that others can use and build upon the work. These steps entail time-consuming interactions with other scientists, editors, science administrators, and managers. This practice is part of the shared learning process of science, but it may take years or even a decade to complete. Within the Delta, doing science to inform policy and management can be even more complicated because policies and management decisions are determined at multiple organizational levels and by many agencies with different missions. The slowness of conducting and

**BOX 1**

### The Pelagic Organism Decline

The pelagic organism decline (POD) in the Delta in 2002 was a rapid change between a prior and subsequent regime—a tipping point. The rapid decline of populations of four pelagic organisms—Delta Smelt (*Hypomesus transpacificus*), Longfin Smelt (*Spirinchus thaleichthys*), Threadfin Shad (*Dorosoma petenense*), and Striped Bass (*Morone saxatilis*)—during normal water years indicated that something quite different had happened. By 2005, the POD was understood to be a regime change, yet in 2007 caution in interpreting the science was still 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. (Baxter et al. 2008).*

Delta scientists were caught by surprise, and were not in a position to inform a management response before a threshold was crossed. Multiple historic drivers interacted to force the tipping to a new Delta regime, and the final cause was the invasion of a non-native clam (*Corbula amurensis*) that consumed phytoplankton, which had previously fed other estuarine species. This new species, in turn, reduced the food supply to larger pelagic species. Scientific understanding of the combination of causes that pushed the Delta ecosystem into a new regime only began to emerge well after the event (Sommer et al. 2007; Mac Nally et al. 2010). Part of the difficulty in identifying and interpreting the threshold crossing was that the diverse but fixed sampling regimes were not designed to detect the change.

This interpretation, however, is still not settled. Recent analyses show that our understanding of environment-recruitment relationships for multiple species in San Francisco Bay and the Delta may change with the addition of newer data to previously published accounts, particularly if sudden declines associated with the regime change were not considered in prior analyses (Tamburello et al. 2018). Additionally, the pattern of a sudden decline in populations of several fish species, apparent in the results of a single series of surveys, is not so clear when multiple surveys are combined (Stompe et al. 2020). There may have been multiple tipping points, one in the early to mid-1980s before the introduction of *Corbula* in 1986, and another around 2000 as species adjusted behaviorally to the consequences of the introduction. More data do not necessarily produce more accurate predictions when the environment is changing rapidly, especially when thresholds are crossed.

corroborating research reduces its usefulness during a time of more rapid and uncertain changes.

Under some conditions, the scientific process can be accelerated. With the onset of the COVID-19 pandemic, for example, scientific research to develop a vaccine was dramatically sped up. Because microorganisms reproduce quickly under laboratory conditions, however, epidemiological research on a virus can be conducted much more rapidly than ecological research on larger, longer-lived organisms such as Chinook Salmon (*Oncorhynchus tshawytscha*) or Sandhill cranes (*Grus canadensis*). Moreover, understanding how ecosystems function can take even longer. The research approaches currently dedicated to understanding ecological systems may not be able to keep up with the rapid pace of environmental change.

Extreme events and thresholds exacerbate the effects of the speed and acceleration of environmental changes on the scientific process. Many species and ecosystems are stressed when extreme events intensify and become more frequent, leaving less time for systems to recover between events. For example, the 2012-to-2016 drought had a profound effect water flows and salinity profiles in the Delta, which affected not only water management but also populations of native fish, and the abundance and distribution of invasive aquatic plants (Durand et al. 2020). Crossing a threshold can set an ecological system into a dramatically different regime (e.g., the POD; Box 1).

Extreme events and thresholds create outliers: conditions that do not fit the patterns and responses that scientists and managers expect under "normal" conditions. The Delta is now experiencing multiple disruptions, and ecosystem responses to more than one disturbance are more likely to result in regime changes (Paine et al. 1998). In addition, the effects of an extreme event or a threshold may not be immediately apparent, further complicating attempts to attribute effects to causes. For example, a major dieback of a non-native perennial plant, pepperweed (*Lepidium latifolium*), in tidal salt marshes in San Francisco Bay in 2015 was apparently driven by a salinity increase caused by the extreme drought conditions of 2011 to 2012—a 3-year time lag (Wigginton et al. 2020).

Ill-informed management responses during extreme events can exacerbate the problem. Durand et al. (2020) describe how "in 2014, measurement and modeling errors led to depletion of cold water behind Shasta Dam and high temperatures below Keswick Dam ... killing 95% of larval winter-run Chinook Salmon." During more rapid change and greater uncertainty, managers need to be informed in real time as scientists amend predictions for the future, to reduce the likelihood that their decisions will create more problems than they solve.

It is difficult to anticipate thresholds and determine the causes of unforeseeable outcomes. Under such conditions, regression analyses or predictive mechanistic models built from past data may not provide reliable predictions, limiting their effectiveness in guiding management. There is some evidence that there may be early-warning signals that indicate when a threshold is being approached (Scheffer


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et al. 2009). Mesocosm experiments may be used to corroborate early-warning signals and acquire insights into ecosystem dynamics (Nagelkerken et al. 2020). Swain et al. (2020) suggest some additional ways to reduce the uncertainty in attributing extreme events to climate change that might be applicable to other environmental changes or other stressors.

### Reason 2

Second, as changes in the Delta accelerate uncertainty also increases.

Uncertainty can usually be reduced by gathering more data, which can improve understanding of underlying natural processes (Wiens 2008), but this is not always the case. Fortunately, new tools and technologies are dramatically increasing the speed, precision, and accuracy with which environmental changes can be measured and tracked. Advances in the use of satellites, drones, species detection through environmental DNA, and other technologies, including continuous monitoring, can generate massive amounts of data about environmental conditions and the mix of species. Big Data and artificial intelligence make it possible to analyze past observations in new ways, while the Internet speeds the communication and sharing of scientific findings. Better computer models are providing glimpses into the Delta's complexities (Cloern et al. 2017). But more data and more rapid data collection alone will not suffice; data gathered at one time will become dated and less relevant for management at a later, time as conditions change. Models need to be dynamic, and incorporate the factors that drive changes which might possibly later unfold. Sampling should be designed to accommodate changes in the system, although establishing a monitoring program for unanticipated changes is challenging.

### Reason 3

Third, science needs to be undertaken and interpreted transparently, and the findings must be readily available.

Transparency means that methods, assumptions, potential biases, analytical procedures, and results be reported as fully as possible, so the work can be evaluated and interpreted by policy-makers and managers (Parker et al. 2016). This is the first step. To be useful in policy and management, the results of monitoring and research studies must also be synthesized, translated into understandable terms, and then communicated to managers and decision-makers. Synthesis and communication have been an important role of the Agricultural Extension Services or the Sea Grant Program for decades. In a rapidly changing environment, only more scientific resources and greater effort, especially applied to synthesis, can ensure that scientific findings will be applicable when policy and management decisions must be made.

## 2. ANTICIPATING POSSIBLE FUTURES

Scientists routinely take stock of the state of their science and assess future challenges as they select topics for research; Delta scientists are no exception.

However, such assessments tend to be narrow when done by individual scientists within a discipline. This approach can lead to increased specialization rather than broader understanding. In response to (1) the growing complexity of problems, (2) increasing scientific specialization, and (3) the limits to what any one person can know, scientists are forming interdisciplinary teams to take stock of knowledge and identify new phenomena that may emerge. Scenario analysis and horizon scanning are already used by research teams in the Delta, and are integral to the "Delta Adapts: Creating a Climate Resilient Future" process led by the Delta Stewardship Council (2020). We advocate for a more systematic and integrated use of these approaches, along with increased use of expert elicitation and dynamic planning, to guide Delta science, policy, and management. These methods are ways of conducting "anticipatory science" or, more simply, looking ahead through formal processes (Lindenmayer et al. 2010; Bradford et al. 2018).

## Scenario Assessment

Scenario assessment is a disciplined way of breaking out of the expectation that the future will follow a trajectory extrapolated from the past into the present. Scenario assessment is a way to consider what might develop under specified "what if" alternative assumptions about the future (Wollenberg et al. 2000; Peterson et al. 2003; van der Heiden 2006). Scenarios provide a way to structure thinking about the consequences of possible future trajectories and possible ways to respond to them, including identifying new research priorities. Coupled with simulation models, scenarios are an effective way of exploring the consequences of different assumptions or information in complex systems—such as ecosystems—where there are multiple pathways of interactions.

The use of different scenarios is at the core of scientific assessments of possible futures. At a global scale, the Millennium Ecosystem Assessment used scenarios (Alcamo et al. 2003). Scenario analyses have figured importantly in climate research and the projections of future climate processes and consequences by the Intergovernmental Panel on Climate Change (IPCC) (Moss et al. 2010; Mach and Field 2017). Exploration of the implications of alternative scenarios informs policy-makers about which aspects of ecological systems should be of highest concern (Van Winkle and Dale 1998). Cloern et al. (2011) used scenarios to project the effects of changing climate on multiple features of San Francisco Bay–Delta ecosystems under two models of climate change. Although the scenarios differed in their projections (because the underlying climate models made different assumptions), the analysis suggested that extreme events might become more frequent, with an increasing probability that ecosystems might be pushed over thresholds to new regimes. These are important messages for policy-makers and managers.

## Horizon Scanning

Horizon scanning formalizes the process of "taking stock," assessing trends, and looking for emergent, trend-changing phenomena. The scans are broader and deeper than scientists from any one discipline can conduct. Through formal, collective horizon scanning, scientists seek to foresee phenomena and prepare


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for new challenges that they would have missed or be unlikely to discover individually. The process draws on the scientific literature, news of emergent phenomena not yet scientifically explained, and the experiential knowledge of scientists as well as new data to detect unusual findings and new trends. Artificial Intelligence and other approaches for analyzing massive amounts of data for patterns can facilitate horizon scanning.

Horizon scanning has been used in public health, medicine, and other fields for years. Amanatidou et al. (2012) and Sutherland et al. (2019) applied the technique in several assessments of emerging issues in conservation biology. However, horizon scanning has not been used extensively in environmental science, policy, and management. As a process of looking ahead, horizon scanning almost inevitably deals with the speed of environmental, technological, and social change. By formalizing the process, making it interdisciplinary, and explicitly addressing the speed of change, horizon scanning may alert scientists, policy-makers, and managers to possible future conditions; and identify new, critical issues for research, in order to inform future policy and management.

### Expert Elicitation

Horizon scanning and scenario analysis rely on expert judgment. Expert elicitation, the in-depth polling of experts on issues with high uncertainty or controversy, has increasingly become a part of science. One of the most widely used forms of expert elicitation, the Delphi method, was developed during the Cold War to elicit and narrow the range of judgments of experts who considered the consequences of introducing different technologies into defense systems. The method has since been modified, enriched, and applied in numerous other areas to assess and predict the future (Rescher 1998). Eichler et al. (2020) used a modified Delphi process to obtain input from diverse stake-holders that could be used in a rapid appraisal of agricultural landscapes in western Mexico, with the overall goal of assessing progress toward sustainability. The IPCC reports are examples of deliberations among hundreds of experts from different disciplines who collectively assess the scientific literature. In the Delta, Mac Nally et al. (2010) built and ran a model that helped explain the POD that partly depended on parameters determined by eliciting expert judgment. Because scientists, policy-makers, and managers frequently ask different questions; differ in their assessments of the quality of scientific information; and express confidence in the assessments in different ways, the assembly of experts should include a diversity of both skills and perspectives (Mach and Field 2017).

### Dynamic Planning

Scenario analysis, horizon scanning, and expert judgment align with what Herman et al. (2020) call "robust planning"—identifying static alternatives that may perform acceptably under a wide range of future conditions. "Dynamic planning," on the other hand, aims to identify adaptation policies that respond to situations experiencing long-term changes, which include extremes and thresholds with multiple sources of interacting uncertainties. Herman et al. (2020) review approaches to optimal control in a dynamic future in the context of water-resource planning under climate change which may be broadly applicable to rapid change in the Delta.

### Summary

Scenario analysis, horizon scanning, expert elicitation, and dynamic planning are complementary and should be used together, or at least interactively. Scenarios can be adjusted through horizon scanning. Scenarios should be based on “what if” analyses stemming from dynamic planning. Expert elicitation is needed to fill in missing information in the process of scenario building and dynamic planning, until the science can be done to confirm that information. As the future unfolds in real time, past scenario analyses may prove to be right or wrong in different ways. Earlier hypotheses may be corroborated or not. In short, all of these formalized approaches are ways of learning that are especially useful for understanding complicated ecosystems (Mach and Field 2017).

## 3. FRAMING FUTURES

Delta water and environmental management agencies employ their own scientists and also fund the research of corporate, university, and NGO scientists. The ways in which agencies frame and pose questions shape much of the science that gets done in the Delta. Over time, the framing of questions has become institutionalized in legislation, court rulings, and agency structures. In an era of rapid change and greater frequency of extremes, fresh ways of thinking and doing science in the Delta are needed that will need fresh housing within agencies. Several existing approaches to doing ecological science offer possibilities.

### Distributional Ecology

As environments change, the distribution and abundance of species change in response, albeit with sometimes substantial time lags. These shifts produce a continuing turn-over in the species that are present in an area, which presents a moving target for management and restoration. The aim of distributional ecology is to understand these changes. The focus is not just on where species are, but also on how they may respond spatially to changing conditions, now and in the future.

Biogeographers and ecologists have been interested in distributional dynamics since von Humboldt recognized ecological zones in the early 19th century (Wulf 2015). More recently, sophisticated models and statistics have been developed to relate species distributions to habitat suitability (Elith et al. 2010; Franklin 2010; Guisan et al. 2017), and these tools have been coupled with climate models to forecast the distribution of species under future climate-change scenarios. Pinsky et al. (2020), for example, modeled the distribution of marine species under climate-change scenarios. In California, projections of the future distributions of birds indicate that, as climate changes and habitats shift, species will respond differently, thereby creating assemblages that have no contemporary analog (i.e., “novel ecosystems”) (Stralberg et al. 2009; Wiens et al. 2009). Similarly, Moyle et al. (2013) assessed the vulnerability of freshwater fishes to changing climate in California. Rapid change is included in the distributional models through its


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incorporation in the underlying climate models and the resulting effects on habitat (vegetation types, in the case of California birds).

Although distributional models can project future changes based on past and current relationships, they cannot predict changes stemming from drivers or changes that are not included in the underlying models (Dormann 2007). The effects of extreme events or tipping points, for example, are difficult to determine and are not usually considered; these could lead to even more uncertain distributional dynamics. These aspects of environmental change are challenging models of distribution (Woodin et al. 2013), and new ways of thinking are being tested.

### Disturbance Ecology

A disturbance can alter an ecosystem or divert it from whatever trajectory of change it had been following. At the same time, disturbances are often an integral part of a system; for example, in the way fire is necessary for some trees to reproduce (Weatherhead 1986). The effects of disturbances have been a focus of ecological thinking and research for a century. Initially, a disturbance was viewed as moving an ecological system away from a stable state (e.g., a "climax community") to which it would then return in the absence of further disturbance. More recently, ecologists have recognized that disturbance may be frequent enough to keep a system in flux or cause it to change into something quite different (Pickett and White 1985; Turner 2010). The process of draining a wetland for farming, for example, transforms the landscape and changes it into something else; restoring the farmland back to a wetland does the same.

Disturbances such as hurricanes or earthquakes occur naturally, of course, but human-caused disturbances drive many of the changes in the Anthropocene (Newman 2019). Much of California is subject to both lightning-caused and human-caused fires that re-set vegetation succession and have cascading effects on other species and ecosystem processes. People are affecting the frequency and intensity of fires, both directly and as a consequence of climate change (Keeley and Safford 2016). As a result, disturbed systems are more vulnerable to further disturbance. Management plans should recognize the potential for disturbances to occur, and be designed to foster the survival of remnants and spatial heterogeneity that promote desired recovery patterns and processes (Dale et al. 1998).

In the Delta, species and ecosystems are affected by severe droughts and extraordinarily wet years, which can re-set many aspects of aquatic ecosystems. Such disturbances are examples of extreme events, which are expected to become more frequent and of greater magnitude. Thinking of extreme events as drivers of disturbance ecology may provide an appropriate perspective to understand and anticipate the effects of rapid change (Newman 2019).

### Resilience Thinking

As ecological systems have become increasingly stressed by more rapid climate change, by altered disturbance regimes, and by the other manifestations of rapid change, "resilience" has become a much-desired attribute of systems. Resilience is a key part of systems thinking that has its roots in General Systems Theory, which was first developed in the 1940s. Systems thinking recognizes and analyzes the inter-connectedness of all parts of a system, and has been adopted by a variety of disciplines. People in many areas of activity—wealth managers, city planners, child psychologists, hospital administrators, electricity systems analysts, as well as environmental scientists and resource managers—now seek to enhance the resilience of the systems they manage. The intent is to maintain desired features of a system despite changing environmental conditions.

"Resilience" has multiple meanings (Angeler et al. 2018; Falk et al. 2019) and, consequently, misunderstandings abound. The term frequently refers simply to the ability of a system to quickly spring back to its previous state after a disturbance. However, it can also refer to (1) the potential of a system to remain in a particular configuration and maintain its functions despite disturbance (also called "robustness"), (2) the ability of the system to reorganize after a disturbance-driven change, or (3) the time it takes to return to equilibrium after disturbance (Gunderson 2000; Walker et al. 2002). In ecology, "resilience" now refers broadly to the ability of a system to buffer or cope with perturbations under changing conditions, while avoiding regime changes and retaining most of its species and functions (Walker and Salt 2006). The greater the resilience of a system, the more likely it will be able to persist or retain its basic structure and function when environmental conditions change rapidly, extreme events occur, or thresholds loom.

Explicitly directing management toward fostering system resilience can be an important way to adapt to rapid environmental change. For example, Beller et al. (2019) applied the concept of resilience to the Delta, focusing on how landscape attributes could be managed to ensure that water temperatures are suitable for native fish while maintaining landscape connectivity and recognizing the needs of agriculture. Managing for resilience entails keeping a system within acceptable boundaries, rather than aiming for a specific (stable) state of the system or specific system outputs. Of course, as systems change more rapidly and encounter more extremes and thresholds, managing for ecosystem resilience becomes more difficult. It may be more appropriate to apply the concept of resilience to management itself, to foster the capacity of management to continuously adjust to changing conditions.

## Coupled Human–Natural Systems Thinking

Resilience thinking is increasingly cast in the broader context of coupled socio-ecological systems (Walker and Salt 2006, 2012; Gunderson et al. 2010). It's not just that the environment is changing rapidly; human societies, economies, and the technologies that support them are also undergoing rapid and accelerating change (Friedman 2016). The coupling of complex ecological systems with even more complex social systems leads to nonlinear dynamics with thresholds, feedback loops, time lags, and surprises (Liu et al. 2007).


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Dealing scientifically with all this complexity is a formidable challenge, but it is reality. Attempts to manage Delta ecosystems or enhance their resilience in the face of rapid change are by themselves unlikely to be adequate, unless the rapidly changing socio-ecological context is also considered. Putting people into the system highlights that the resilience of a system may depend on how quickly scientists can detect system change, and how quickly policy-makers and managers can respond to change. In a coupled-systems framing, the social system characteristics—especially the scientific, policy-making, and management responses to change—are as critical in determining resilience as the natural system response.

Formal modeling of coupled human–natural systems requires highly interactive teams of researchers from multiple disciplines. Team-members start with different assumptions and terminologies, use different conceptual frameworks, and have expert knowledge in different aspects of the larger picture. A broader, coupled-systems frame of mind makes interaction and shared learning possible. Yet the actual process of doing empirical research at broader scales and more interactively has numerous complications that make it considerably more time-consuming. Consequently, coupled systems frameworks may not be well matched to the speed of social, technological, and environmental change. The complexity of coupled systems suggests that research should be framed more fully and incorporate data for multiple variables, while the speed of change may not allow sufficient time to systemically model and empirically evaluate the multiple and diverse complexities that create growing uncertainty.

A broadly coupled human–natural systems approach to thinking about the Delta is long overdue. The state of California has tried to resolve "Delta problems" through natural-science analysis and natural-science-based technical remedies, while giving less emphasis to systematically addressing the human drivers of Delta problems. Recent efforts to expand the role of historians, geographers, and other social scientists in the Delta science community make human–natural system thinking more likely (Biedenweg et al. 2020).

## 4. ANTICIPATORY, ADAPTIVE DELTA GOVERNANCE

We use the term "governance" to refer to all the processes of public institutions that affect how Californians interact with the Delta. Most regions have polycentric governance: overlapping hierarchies of federal, state, regional, county, and municipal governing bodies, management agencies, and court systems (Thiel et al. 2019). The complications of polycentricity are perhaps even exaggerated in the Delta, and are exacerbated by the immense importance of water in a heterogenous environment that is semi-desert on average.

To the extent that Californians working through multiple venues have worked well together, it has been because they have found sufficient common cause. Early in this century, that common cause needed strengthening (Little Hoover Commission 2005). In 2006–2008, a Blue Ribbon Task Force played an essential role in leading scientists, policy-makers, managers, and stake-holders through a Delta Visioning process that led to the Delta Reform Act of 2009. The Delta Stewardship Council, through the process of developing and updating a Delta Plan, has played a central role in elaborating and updating that shared vision. With more rapid change and bigger surprises ahead, however, the process of governance needs to accelerate and be more adaptable.

To deal with a rapidly changing and uncertain environment, science has to support policies that, in turn, support appropriate anticipatory, adaptive science. Legislative mandates and policies establish the boundaries or "guard-rails" within which month-to-month and long-term management is carried out. Perhaps more so in the Delta than other regions, most scientists are employed by management agencies, and the priorities of management have consequently directed the bulk of Delta science. In times of rapid change, however, new science needs to be directed as well toward directly informing policy-makers about likely future conditions, so that they can keep up with the changes and more frequently adjust the policy guard-rails for management.

Encouragement to prepare for more rapid and uncertain change has been evident for some time. The Delta on Fast Forward: Thinking Beyond the Next Crisis (Delta Science Program 2016) alerted scientists, policy-makers, and managers to the increased likelihood of crossing thresholds that result from accelerating climate change and increased variability. Delta scientists have been striving to better coordinate their efforts and link them to management in accordance with the goals of the Delta Science Plan (Delta Science Program 2019). The Delta Science Plan has numerous references to climate change and to the rapidity and uncertainty of change. Indeed, the opening paragraph of the first chapter of the Delta Science Plan states:

> *Climate change, increasing water demands, invasive species, and land use change impose rapidly changing conditions and greater variability onto the system.*

The current "Science Needs Assessment[1]," being written under the leadership of the Delta Independent Science Board and the Delta Plan Interagency Implementation Committee, includes involving Delta scientists and management agency leaders in addressing how to respond to the challenges of more rapid environmental change. These efforts to accelerate and improve science for management in the Delta parallel broader efforts of environmental scientists and ecologists to be more relevant to management needs (Lubchenco 1998; Schlesinger 2010). Palmer (2012) and Bradford et al. (2018) have called for "actionable science" to produce the scientific guidance that policy-makers and managers need. A group of ecologists has promoted "translational ecology" (Enquist et al. 2017), appealing to scientists to forge stronger links between research and its synthesis

1. The Science Needs Assessment is still unfolding. Its final product is expected before the end of 2021 and will be posted on the web.


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for application in order to accelerate the incorporation of science into management and policy (Carpenter et al. 2009).

Translational ecology, actionable science, and more rapid and applied synthesis encourage faster and more flexible development of science to inform decision-making in the context of rapid change. But policy-making and management must also be nimbler and more flexible to keep pace with rapidly changing conditions and deal with surprises (Bradford et al. 2018). Doing this rests upon broad collaboration—among scientists in different disciplines, among managers stationed in different agencies at different levels of government, among legislators and judges who make and enforce environmental laws and regulations, among stake-holder groups and the public whose lives and livelihoods will be affected by decisions now and in the future, and among all these groups with one another. For half a century, it has been known that solutions require multi-disciplinary efforts and stake-holder cooperation. Too often, however, the cultures, methods, languages, and infrastructure of different disciplines, agencies, and stake-holder groups create barriers. As a result, participants in these groups are drawn inward rather than reaching out to others in common cause. Some environmental laws and regulations may further restrict broad, integrative actions, and polarize positions among people who should be seeking common ground. All of these barriers limit the insights and restrict the flexibility needed to respond to rapid and unanticipated changes.

## 5. A NEW DELTA VISIONING PROCESS FOR ANTICIPATORY, ADAPTIVE DELTA GOVERNANCE

The challenges of more rapid and increasingly uncertain environmental change are likely to be so great that a major new effort is needed to integrate Delta science, policy, and management so they can adapt to rapidly changing and more extreme conditions. We suspect new legislation will be needed to redirect management agencies toward the severity of the changes that are likely ahead. To determine whether new legislation is needed and what it might entail, we recommend the Governor appointment a Blue Ribbon Delta Science, Policy, and Management Task Force. We are recommending something comparable to the 7-person Blue Ribbon Task Force led by Phil Isenberg and appointed by Governor Schwarzenegger in 2006. The Task Force's report in 2007 and implementation plan in 2008 were the basis for the Delta Reform Act of 2009. Over a similar period, a new task force could thoroughly explore the issues we are raising in this paper, deeply engage in comparing alternative approaches to addressing the issues, hold hearings and deliberations so that the public can also become engaged in the issues, and then make recommendations.

During what will likely be at least a 3-year process before new legislation is in place, we recommend the creation of a new inter-disciplinary science unit for the Delta that is tasked to facilitate scenario analysis, horizon scanning, and the formal practice of eliciting expert judgment, while also promoting the use of new frames of analysis. We propose establishing this wholly new science unit with its own funding because it will not only need to work with all the existing management units but also work with the legislature to keep policy-makers informed. It could be a special unit of the Delta Science Program and work with the Interagency Ecological Program and the Delta Plan Interagency Implementation Committee until new legislation is put in place. Several science-staff positions within the new unit could also be assigned to work with particular key agencies, helping the agencies adapt their science agendas and personnel to better foresee and adapt to more rapid environmental change. The Delta Stewardship Council, Delta Protection Commission, Delta Conservancy, and other organizations can expand their education and outreach activities to reach water and environmental stake-holders and Delta residents, keeping them informed of changing options under rapidly changing environmental conditions. The Delta Independent Science Board might assess the progress made after 18 months or so.

The next Blue Ribbon Task Force visioning process should stress the challenges of doing science for anticipatory, adaptive policy-making and management (Muiderman et al. 2020). The Delta Science Visioning Task Force should be supported by a full-time team of innovative scientists, policy-makers, and managers working collaboratively. The Task Force and support team need to build a common understanding of the forces that shape current conditions and identify shared goals for the future. The approaches described in this paper can be used to suggest pathways toward desirable future conditions. At least five critical issues that need to be explored:

1. How can science more quickly and effectively inform policy and management of the implications of new conditions or changes in foreseeable conditions?

2. How can policy processes and management agencies become more adaptive to new conditions?

3. What is the best way to house the new forward-looking science unit so that it has the necessary autonomy to “follow the science” while also being positioned to inform and effect Delta policy and management?

4. How are other regions handling the complications of more rapid and uncertain environmental change, and can their experience be adapted to fit the Delta?

5. Mount (2020) identifies numerous federal and state laws that constrain the way the Delta can be managed. How can these and other such constraints best be tackled?

Of course, other critical questions will be raised as the proposed Blue Ribbon Delta Science Task Force gets underway.



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## 6. CONCLUSIONS

Rapid change is upon us. Extreme events are becoming more extreme, more frequent, and more costly. Thresholds are more likely to be encountered, often leading to irreversible changes. Uncertainty will increase. Coping with these changes requires accelerating the speed with which we gain understanding of rapid change and its consequences, and incorporating that understanding into policy and management in a complex Delta. Delta science has been amazingly adaptive (Norgaard et al. 2009), yet merely re-allocating the existing science resources to the new challenges will probably not be sufficient. We cannot assume that ecological systems will vary as they have in the past. We cannot assume that traditional management approaches will be sufficient to deal with the surprises that lie in store. The need for new, strategic initiatives is urgent. Without a concerted effort, scientists, policy-makers, and managers may be overtaken by the rapidity of change and find themselves constantly reacting to, rather than anticipating, changes.

As new environmental challenges have emerged, ecology and the environmental sciences have expanded their repertoire of tools and approaches. The methods we have described for looking forward and for re-framing how to think about managing the Delta can help scientists, policy-makers, and managers foresee and understand the implications of more rapid and increasingly uncertain change. New, more rapid, continuous, and strategically aligned monitoring technologies, better informatics, and modeling based on complex systems dynamics will also help.

By themselves, however, these suggestions are unlikely to prove sufficient. Attending to an uncertain future will require broad participation in a bold and strategic Delta Science Visioning process that addresses science, policy, and management together. Without this, we cannot envision how the immense challenges we face can be successfully met.

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