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PERSPECTIVES

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Climate change effects: the intersection of science, policy, and resource management in the USA

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Abstract. Perhaps no subject is more intriguing and complex than climate change and its effects on ecosystems and their biological communities. Changes in precipitation and snowmelt patterns, sea level rise, increased intensity of storms and wet-weather events, thawing permafrost, changes in vegetation and wildlife composition and distribution, and other effects present significant policy and land management challenges. Scientific modeling and analyses demonstrate that the effects of a changing climate are complex, with high variability over time, space, and species, including effects on benthic organisms. The variable effects of a changing climate complicate decision making, rendering scenario planning, adaptive management, and other management learning tools increasingly important. The very complexity of effects presents particularly difficult challenges for policy makers and resource managers because the available science often is highly uncertain. Thus, other decision support tools are needed to help managers anticipate and respond to local and regional conditions. Effective policy and management require relevant science to inform decision making. Key needs include more assessments of ecosystem and species trends and their possible linkage to climate change and a better understanding of the interplay of multiple variables, how different management regimes might affect ecosystems and species survival, and how to apply risk management tools and adaptive management to resource issues.

Key words: climate change, climate adaptation, resource management.

Tango of Science, Technology, Policy, and Politics

Drought, fire, invasive species, eroding shorelines, land fragmentation, wetland losses, and deteriorating water quality are the stuff of news headlines. They are also the daily fare of resource managers across the US. Their resolution resides in a complex tango of science, technology, policy, and the politics of place and the nation. These challenges are familiar, although they are evolving in both scope and scale. For water systems, threats include high levels of water extraction, pollution, wetland drainage and river channelization, deforestation and related sedimentation, invasive species, and over-harvesting of species. Resolution of these familiar challenges often eludes policymakers and resource managers in the midst of complexities, competing values, institutional limits, political obstacles, and financial constraints.

New Challenges—Climate and the Landscape

New challenges loom while familiar challenges persist. Perhaps no subject is more intriguing than climate change. The effects of a changing climate cut a broad swath across the US lands and waters. Their extent and scope underscore the relevance of national (and international) actions to reduce greenhouse gases (GHGs). However, whether or not such measures are implemented, the effects of climate change will continue to unfold as a result of existing (and persistent) accumulation of GHGs in the atmosphere. These effects are not speculative and are sometimes dramatic:

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- The fire season in the US is much longer than it was 3 decades ago. One assessment indicates the fire season is 78 d longer now than in the 1970s (Westerling et al. 2006).
- Some locations are experiencing earlier snowmelt and changed precipitation patterns (Stewart et al. 2004).
- Annual precipitation for most of North America is increasing, with a 58% increase in heavy rainfall events in the eastern US over the last 50 y. Elsewhere, the already dry southwest is experiencing prolonged periods of drought (Karl et al. 2009).
- In parts of Alaska, permafrost temperatures are now at 0°C and permafrost is thawing (CCSP 2008b).
- Other parts of Alaska are experiencing accelerated coastline erosion. At one location, the coast eroded 35 m between 2001 and 2003, and the current pace is 48 m/y. Overall, the pace of coastal erosion in northeastern Alaska has doubled over the past 5 decades (Jones et al. 2009).
- Some wildlife species are migrating northward and to higher altitudes (Moritz et al. 2008).
- The Rocky Mountains are undergoing an accelerated intrusion of invasive species and the spread of pests like bark beetles—a spread unchecked by winter cold (CCSP 2008b).

These landscape changes are not solely the consequence of a changing climate, and not all changes necessarily present management and conservation problems. In this context of change and uncertainty, measurement, metrics, indicators, scientific data, and analysis are imperative across the many dimensions of natural resource management and policy.

Policy makers and managers can easily perceive the relevance of biology, hydrology, geology, ornithology, benthology, and many other disciplines for natural resource management decisions. But many puzzles accompany efforts to inform policy decisions with science (Briggs 2006). These puzzles include challenges of selecting policies and management actions when the available science is complex and evolving, climate effects are still unfolding, and no readily apparent management response to reduce impacts is available for some effects.

Policy and Management amid Complexity

Among the central challenges for users of scientific information in a policy context is the matter of complexity. These complexities take many forms, and include the complexities of nature itself and complexities that come from the dynamic context of virtually all natural resource management activities. These activities present the intersection of people and place, and human action itself is dynamic. Knowledge, too, is dynamic. Science is a perpetual discovery process, and the knowledge generated through scientific and other inquiries is never final.

Complexity, change, and incomplete knowledge combine to present uncertainty. Resource managers and policy makers must make decisions on a daily basis, frequently in a context of incomplete, inconclusive, or ambiguous information. These uncertainties are compounded by limits on the ability to predict future conditions, whether as a consequence of the butterfly effect heralded in chaos theory (e.g., Hilborn 2004) or simply from the inevitable surprises of human action. Despite uncertainties, some laws mandate actions. Often, managers must make resource management choices even where future conditions are uncertain and comparative effectiveness of different management strategies is unclear. A number of analytic and modeling tools can assist decision makers within these contexts of uncertainty (Prato 2007). The challenge often resides in making policy makers aware of these tools and in communicating their potential uses and limitations.

Multiple Variables

Complexities also arise from multiple variables associated with natural resource management issues. In September 2002 in the Klamath Basin, an estimated 12,000 to 30,000 fish died, washing up on river banks. The die-offs occurred after a Bureau of Reclamation decision to reduce water flows in the basin by 25%. That action was taken after the National Research Council had concluded that scientific information was insufficient to justify earlier agency decisions to require higher water flows in implementing Endangered Species Act requirements. Scientists concluded that the fish had died of "gill rot" associated with higher water temperatures. There was little dispute that lower water flows were associated with higher temperatures, but assessments varied regarding the degree to which water flows, water quality, something else, or all of the above caused fish die-offs (McHenry 2003).

Consider other examples of this complexity. One study of mollusk egg masses showed complex interactions among climate change, ultraviolet light exposure, other stressors, and microevolution (Byrne and Davis 2008). The study concluded that these interactive effects are difficult to predict, suggesting a need for experiments that examine multiple stressors concurrently. This perspective was affirmed by a 2008 study on noncoral benthic invertebrates in tropical coral reefs. Przeslawski et al. (2008) noted that the magnitude and duration of exposure to each stressor were important. Physiology, mobility, and habitat requirements of the species also were important. Stressors, the authors concluded, "will not act independently and many organisms will be exposed to multiple stressors concurrently" (Przeslawski et al. 2008, p. 2773). Policy makers seldom delve into these sorts of scientific details, but these details are, nonetheless, building blocks to understand land and water health, possible effects of climate change, and how different management regimes might improve or degrade ecosystem functioning. The complexity of these details often translates into uncertainties about management regimes and their effects, leaving decision makers with discretion and underscoring the potential importance of decision processes in which new information can shape and inform ongoing management choices.

Temporal Framework

Complexities also reside in the temporal framework of resource management decisions. What is the goal in restoration? For the Everglades, is it the predrainage condition of the 1800s, or the 1930s, or some other point in time? And what is feasible, with only a portion of the original landscape available for restoration? These questions about goals involve values: what landscapes do people want? What land uses do they value and anticipate? But these value questions intersect with science. How much restoration is possible? How will the amount, timing, and distribution of water affect vegetation and wildlife, terrain, and water quality?

The goals articulated in Everglades Restoration legislation and implementation documents refer to restoration of the defining characteristics of the Everglades. But, increasingly, resource managers and scientists face questions about what, specifically and operationally, that means. Some areas have been dramatically transformed by invasive species, altered water and soil chemistry, and peat subsidence. Moreover, southern Florida faces rising sea levels and salt water intrusion not anticipated at the time of articulation of the initial restoration vision.

Managers face questions about how much water should flow, when, where, and with what distribution. Answering these questions requires a clear sense of restoration goals. Answering these questions is important for project selection, priority-setting, and performance evaluation. Answering them is a prerequisite to using adaptive management because judging the success of field tests requires agreement on goals. Clarity of the specific goals becomes especially important as agencies move from programmatic and planning phases to project selection, design, and implementation.

Uses of Information

Complexities also have a practical dimension. What information decision makers need depends on how they want to use it. Consider the challenges of information depth vs information breadth. Information depth is obtained by studying a particular species through the lens of a particular scientific discipline, whereas information breadth is obtained by merging general insights drawn from multiple scientific disciplines about multiple variables (e.g., weather, precipitation patterns, plant and wildlife composition) and overall ecosystem functioning. In some circumstances, decision makers need detailed particular knowledge of one species, but in other circumstances, they need broader knowledge of an ecosystem and its functioning.

How does one determine the appropriate mix of depth and breadth, particularly when time and resources are limited (a general condition of resource management decision making)? Consider the example of wildland fire and forest health. Resource managers who are setting priorities and undertaking projects to remove excess vegetative fuels need metrics for assessing whether their actions are improving forest health. But what are the appropriate metrics? Does a set of broad indicators exist that, if monitored and evaluated, would give insight into whether forests are less likely to experience catastrophic, unnatural fire intensity and more likely to sustain other forest attributes, such as biodiversity? Are more detailed indicators of individual species and their life cycles necessary to evaluate forest health? Is it a combination of both? If both, is there a manageable set of indicators that could be monitored and evaluated within available budgets and human resources?

Answering these questions depends in part on perceptions of what matters. For scientists steeped in inquiries about ecosystems, their components, and functioning, each detail and every increment of knowledge adds value. But for resource managers, with limited time and resources, too many indicators and too much detail can exceed financial capacity to generate and maintain information on these indicators and exceed their time and ability to interpret them. Thus, managers often want broader, clustered sets of indicators that, while imprecise about landscape particulars, can provide general information about ecosystem health.

Responding to Complexity

Complexities characterize many ecosystem policy and management issues, but they need not paralyze decision makers. Indeed, legal requirements under the Endangered Species Act, the Clean Water Act, other statutes, and various restoration initiatives often obligate policy makers and managers to take action and make resource management choices. Strong partnerships between scientists and decision makers and use of a variety of tools and strategies can facilitate effective actions in the context of complexity. These tools include, for example, scenario planning; use of modeling to evaluate different management options; and adaptive management that incorporates ongoing learning, assessment, and management adjustments to new information and knowledge. In some circumstances, complexities can be untangled by evaluating the intersecting components of complexities and addressing those for which action is feasible. The effects of climate change add new layers of complexity to resource management that amplify the relevance of these tools and strong partnerships between scientists and decision makers.

Science, Society and Values

Even when decision makers are armed with scientific knowledge, the matter of communication across specializations and experiences presents challenges for those striving to inform policy and management decisions with that science. Such communication challenges can be especially acute between scientists and those who speak the language of philosophy, politics, and personal choice. Mistrust often flourishes because interested participants in decisions might conclude, ‘‘If I don't understand you, I don't believe you.'' Many scientists seeking to inform policy and land management decisions appreciate these challenges and complexities. These complexities mean that both scientists and managers must make choices about which information and data, which measures, what analysis, and what research to undertake. The appropriate choices are neither self-evident nor absolute.

Policy and management challenges do not present themselves as predefined problem sets. Defining the scope and scale of the relevant problem can, itself, raise both scientific and social questions. Is the relevant boundary for accumulating and applying information a backyard, a stream, a watershed, a continent, or a world? Through what processes should decision makers draw the boundaries for a problem set and decision-making focus? Answering these questions demands scientific insights. But these questions are as much matters of human communities, values, and social constructs as they are matters of scientific distinctions and categories.

Science vs Values

For all the issues and challenges raised earlier, the most distinctive challenge in any interface of science and policy pertains to context. Policy making, fundamentally, is about values. Scientific information per se cannot determine what we want, desire, or prefer. Policy makers ask, ‘‘What values do we care about?'', How clean is clean enough?'', ‘‘How do we allocate which resources to what priorities?''. Scientists ask, ‘‘What is reality?'' and ‘‘How does the world work?''. Understanding ‘‘what is'' is not the same as exploring and illuminating responses to the questions of ‘‘what do we care about?'' and ‘‘where do we want to go?''.

With this general context as a backdrop, thinking about climate change and its effects on ecosystems and biological communities presents particular decision-making challenges. In both international and domestic arenas, many policy makers increasingly express the need for action to reduce GHGs. At the same time, nationally and internationally, the effects of a changing climate are already evident. These effects underscore the need to think about management in that context. Outlining a framework for action requires an understanding of the character of the problem. That framework also requires actions and a governance context to link science to decisions.

The role of science in decision making is fluid and varying. The relationship of scientists with decision makers unfolds along a continuum of low engagement to high engagement. That continuum can be described as clustering into 5 potential roles for scientists (Lach et al. 2003). At the end of the spectrum with minimal engagement is a reporting role in which scientists report or provide their research to decision makers. A slightly more active engagement includes reporting and interpreting scientific information. In the 3rd role, scientists report, interpret, and then integrate their scientific information and analysis into a set of policy or management options. Beyond this integration, some scientists actually might advocate particular options (Lackey 2007). At the far end of the spectrum are circumstances in which scientists actually participate in making policy choices. What is the appropriate role of scientists? How can relevant scientific information inform policy and management decisions? These questions pertain both to the role of scientists in making policy and resource management decisions and to scientist–policymaker relationships and how information is conveyed and discussed (Gibbons et al. 2008).

A joint fact-finding model described and used by the US Geological Survey and others offers one model of active interaction among scientists, the public, and decision makers. Under that model, scientists, decision makers, and citizens collaborate in the scoping, conduct, and use of technical and scientific studies to improve decision making (USGS 2004). Studies on knowledge use show that mechanisms, such as joint fact finding, that link researchers to users, include information dissemination efforts, and provide for adaptive research outputs are keys to good information flows and uses of knowledge. The user context also can significantly affect whether and how scientific and technical information are used. Mere reception of knowledge by users does not imply use (Landry et al. 2001, Lawton 2007). Lack of interaction between researchers and intended audiences can present a significant problem that limits relevance and perceived credibility of certain research intended to inform public policy decisions. Consider the following scientist–decision maker interaction as an example.

The Everglades Restoration Example

Perhaps no restoration effort is as rich with scientific underpinnings as is Everglades restoration. Over many decades, scientists have presented a wealth of research on a breadth of issues that include but are not limited to research on the paleoecology of this unique system, multiple species, mangroves and sediment accretion, tree islands, water flows, and water quality. Yet tying this research to Everglades restoration decision making presents all the issues outlined earlier. For example, debates over water-quality metrics often turn, not on science, but on interpretations of law. Decision makers face the complexities of how to meet the needs of the endangered Cape Sable Seaside Sparrow while restoring water flows that might inundate its nesting sites. Decision makers face other conundrums, such as determining how much water should flow in a much altered topography with significant peat subsidence so that flows will cause pooling rather than traditional sheet flows.

These kinds of questions at the intersection of science and policy raise an institutional question: are current governance mechanisms adequate to ensure that science informs decisions and that key science issues are explored? Some argue that scientists must be at the decision table; other scientists resist this notion, preferring a separation of science inquiry from policy and management decision making (Lackey 2007).

From these questions also springs some confusion about what are matters of science and what are matters of policy. Again, consider the Everglades and the Cape Sable Seaside Sparrow. On the one hand, policy makers are charged with protecting the endangered sparrow. On the other hand, federal policy calls for restoring water flows across the southern Everglades. Changes in land structures and sparrow distribution over the past 100 y mean policy makers and land managers might need to choose which Cape Sable sparrow habitat to protect and which areas to expose to hydrological changes resulting from restoration actions designed to advance broader Everglades restoration goals. Scientists focused on the sparrow and its well-being might view choices that adversely affect some sparrow habitat as ignoring science, but the policy maker has a broader portfolio and, nearly always, must find a balance among competing values and goals.

The Climate Change Context

Given this general decision-making backdrop, the world of climate science presents additional challenges. Global climate models are improving the ability of scientists to project (though not predict) future conditions. But the ability to project at scales <50 km with any confidence is limited. The effects of changing climate at local and regional levels are highly complex and varied. Some projections estimate increases in water shortages and their duration, whereas other projections are much less austere. Downscaled modeling might assist resource managers in some contexts, but other risk management tools can help resource managers make decisions in a context of uncertainty about projected local conditions.

One thing seems certain—changes at higher latitudes are especially rapid and pronounced (Karl et al. 2009). However, even at higher latitudes, the climate dynamic is fraught with complexity. For example, consider how permafrost is thawing. Actual permafrost degradation varies depending on warming rates, landscape position (i.e., wetlands, uplands), hydrology, surface ponding, water flows, soil texture, ice content, and so on. Changes along coasts also are notable—sea level rise along the Georgia coast, for example, could result in a 20% decline of salt marsh (Craft et al. 2009).

Vignettes of Complexity—the Known, the Unknown, and many Surprises

A few vignettes amplify this science saga and further illustrate why science does not always offer clear policy or management direction.

Freshwater ecosystems

Inquiry into the effects of climate change on benthos and other biological communities is expanding, but much remains unknown (Raddum and Fjellheim 2002, Daufresne et al. 2003, Allan et al. 2005, Ryan and Ryan 2006, Strayer 2006, Clarke 2009, Heino et al. 2009, Moss et al. 2009, Ormerod 2009). Consider one modeling effort that looked at 2 scenarios used by the Intergovernmental Panel on Climate Change to cover possible climate change outcomes. The modelers combined these scenarios with a global hydrological model to estimate "future losses in river discharge from climate change and increased water withdrawal" (Xenopoulos et al. 2005, p. 1557). They linked these results to known relationships between fish species and changes in water availability. The investigators predicted riverine fish richness over the next 70 y in >300 basins globally and calculated that by 2070, "discharge was forecast to decrease by up to 80 percent" in more than 130 investigated rivers with available fish data (Xenopoulos et al. 2005, p.1559). About half "were predicted to lose more than 10 percent of their fish species" when climate change and water consumption impacts were considered (Xenopoulos et al. 2005, p.1559).

Scientists know something about climate impacts on freshwater systems, yet what is known is often at a coarse scale. So, what's a manager to do? In its 2008 Preliminary Review of Adaptation Options, the Climate Change Science Panel explored strategies for applying science relevant to managers, using concepts of resilience, risk management, and adaptive management (CCSP 2008a). An agenda for action requires contemplating the problem set, but that problem set involves remarkably devilish details of the sort illuminated with a few tales.

Migrating warblers

First is the tale of migrating warblers as told by Strode (2003). Warblers migrating from South America to the north are sensitive to photoperiod as the trigger for their trip north. These warblers depend on caterpillar larva as a key food source. Larvae—and the vegetation upon which they dine—emerge in response to the temperature cues of warming weather. In the northern reaches of the Great Lakes, warming temperatures are causing earlier emergence of budding plants and caterpillar larvae. In the reaches south of the Great Lakes, no significant temperature changes and associated early emergence of larvae are occurring. What is the result of these complex changes? Observers are seeing an uncoupling of the warblers' spring arrival based on length of day with food availability in northern Minnesota, which is changing as temperatures change. The birds have as much as 20 fewer days to get to northern Minnesota to exploit optimal habitat conditions that are now emerging earlier than in the past.

Harlequin frogs

Consider a 2nd brief tale told by Pounds et al. (2006), this time focused on one species of frog in Costa Rica subject to mortality from a particular pathogen (a chytrid fungus). The parasite prefers, perhaps requires, a band of low temperatures, and a warming climate would seem to diminish its prospects. Thus, scientists perceived a paradox: why, with a warming climate, is the parasite thriving and resulting in a >60% decline in this particular frog species? It turns out that the changing climate is causing increases in nighttime low temperatures, but these nighttime lows are still within the tolerated temperature range for the parasite. At the same time, as nighttime lows increase, daytime cloud cover is increasing, resulting in slightly lower daytime temperatures. Hence, conditions, day and night, are suitable for the parasite. The moral of this brief tale is that reality is tricky.

Pine beetles

A 3rd tale, a tale of the mountain pine beetle as told by Nijhuis (2004), also is instructive. Pine beetle infestations are part of the natural processes in lodgepole pine forests of the western US. Periodically, especially during variable, naturally occurring warm periods in the past, the beetle has spread and killed trees. However, their spread was checked historically by cold winters that affect the beetle's life cycle. Warmer temperatures are now producing 2 phenomena. First, the beetles are moving higher up and attacking white pine bark. Second, they are now able to complete a full life cycle in a single year, resulting in an unchecked spread from year to year. A 2002 beetle outbreak in British Columbia devastated 4.05 million hectares—an area the size of Switzerland—in just 1 y.

Aquatic macroinvertebrates

Irons et al. (1993) looked at ecological adaptations of aquatic macroinvertebrates in the subarctic streams of Alaska. They concluded that the presence of an unfrozen stream bottom is critical for the normal functioning of northern stream ecosystems. Unfrozen stream bottoms and ecosystem functioning depend on groundwater inputs and to a lesser extent air temperatures. Changes in precipitation and temperature are likely under a scenario of global climate warming, but these changes and their effects are not straightforward. According to Irons et al. (1993), a reduction in groundwater caused by reduced late-summer and autumn rain and winter snow might cause extreme freezing of stream beds, even with warmer air temperatures. Irons et al. (1993) noted that economically important fisheries might depend on the presence of unfrozen refuges for the successful overwintering of their food species. But scientists do not have good data on overwintering mortality in different habitats. The authors concluded, "Knowledge concerning overwintering of aquatic invertebrates is a major gap in stream ecosystem theory" (Irons et al. 1993, p. 106).

Vernal pools

The author of one study on vernal pools in California looked at the sensitivity of these pools to changes in temperature and precipitation associated with climate projections (Pyke 2005). Pyke (2005) faced a challenge in this study. The ensemble of global climate models provided projections for California in the year 2100 that differed in both magnitude and sign for temperature and precipitation. One projected warmer temperatures and more precipitation. The other projected cooler temperatures and drier conditions. As Pyke (2005) looked at the sensitivities of branchiopods to changes in vernal pools that might result from climate change, he observed that ecological outcomes would hinge on a balance of 2 factors: 1) more extensive colonization by slower developing predators that would benefit from longer vernal pool periods of inundation and 2) increases in the fraction of pools within the landscape that are suitable for reproduction of brachiopods. Pyke (2005) concluded that the relationship of vernal pools, fecundity, and species diversity, abundance, and persistence are highly complex. Thus, vernal pools are not likely to be readily used as simple climatic indicators. These findings highlight the difficulty of predicting ecological responses in complex ecosystems and communities across a range of spatial and organizational scales.

Lessons for the Decision Maker

What lessons might a decision maker tease out of these several tales? These lessons are important as policy makers and managers think about the nexus of climate change, biological communities, and ecosystem management.

The 1st lesson is that changes underway are incredibly complex. Think of Costa Rica, where nighttime low temperatures are rising but daytime temperatures are actually cooling. Think, too, of the complexities of species interaction with their surroundings. This complexity warrants consideration of different adaptation and risk management strategies in different circumstances. In its preliminary review of adaptation options, the Climate Change Science Panel highlighted resource management strategies in 7 categories that included ecosystem protection, stressor reduction, strategies to conserve representative instances of many ecosystem types and species, strategies to protect >1 example of ecosystem and species types, habitat restoration, species relocation, and protection of refugia in less impacted areas (CCSP 2008a).

Second, and related to complexity, is the variability over time, space, and species of the changes unfolding. Think about the caterpillar larvae on which warblers dine, or look again at California's vernal pools. Observers are seeing major changes in the timing of larval hatching in northern Minnesota but no change just several hundred miles to the south. As we enter a world in which decisions are affected by climate change, downscaling information from continental and regional to local scales might be important in some management contexts. But other risk-management and adaptive management tools to assist managers are important in the absence of downscaled models, which might be expensive and time-consuming to produce. Moreover, even where the effects of a changing climate vary at a fine scale, effective risk management strategies might benefit from a more regional, landscape-scale focus to reduce stressors, protect multiple ecosystem types, and maintain connectivity among different habitat types.

The 3rd lesson is the ever-presence of change. The world is generally dynamic, but changes appear to be especially rapid in high latitudes, such as the Arctic. Does this pattern invite a focus for initial adaptation efforts and priority-setting? What areas are most vulnerable to change? Vulnerability assessments to help policy makers set priorities will help ensure that scarce public resources are directed at highest-priority challenges. However, setting priorities might require both an understanding of vulnerabilities and an assessment of where action is most likely to be effective in achieving conservation and resource management goals.

A 4th lesson is the tremendous diversity of effects on species and places. Some places are becoming drier, some wetter. Some places are becoming warmer, some not. These effects are emerging within the context of existing, often significant, other stressors, including, for example, land fragmentation, dams that dramatically alter water flows and species movements, contaminants that alter water quality, water withdrawals for irrigation and other purposes, and the presence of invasive species. For species, several scientific overviews report that climate is affecting species' ranges and generally is pushing them toward the poles and to higher elevations. Climate is affecting phenology—timing of flowering, egg-laying, and migration. Climate is affecting morphology—body size and animal behavior. In the 2008 decision by the Interior Department to list the polar bear as threatened (50 CFR Part 17; 2009), decision makers found that, in an area with longer ice-free periods, bear skull size and weight were diminishing. Climate also might result in shifting genetic frequencies.

With these characteristics—complexity, variability, dynamism, and diversity—policy makers and managers face tremendous uncertainties. They might have information on general trends, but the devil is in the details, and details matter. However, the details themselves are in flux and the knowledge base of these details is limited.

Adaptation—Familiar Strategies

Adaptation and risk management strategies are imperative because scientists have concluded that currently accumulated levels of GHGs will result in a changing climate for many decades even if all nations were to turn off the GHG switch tomorrow. This backdrop sets the stage as decision makers think about management responses to the landscape effects of a changing climate. Is this picture hopeless? What options for adaptation are available? The *Preliminary Review of Adaptation Options for Climate-Sensitive Ecosystems and Resources* (CCSP 2008a) suggests options that include reducing existing anthropogenic stressors, protecting and restoring diverse ecosystems, and protecting diverse species through a variety of measures.

In many ways, resource managers must continue to use long-standing conservation tools. Those tools include recognizing the potential importance of land conservation and protection of interconnecting wildlife corridors. A recent meta-analysis of interconnecting corridors found "a highly significant result that corridors increase movement between habitat patches by approximately 50% compared to patches that are not connected by corridors" (Gilbert-Norton et al. 2009, p. 1 of 9). Managers must continue to tackle invasive species and reduce the risks of catastrophic fires through hazardous fuels reduction because both strategies enhance landscape health and build ecosystem resilience.

The US must conserve diverse habitats and protect coastal wetlands and sea marshes to build resilience to storm intensity and storm surge. Consider the Louisiana coast. Each 4.35 linear kilometers of sea marsh reduces storm surge by 0.9 m (US Department of the Interior 2005). Louisiana already has lost ~160 km of sea marsh because the US has channeled the Mississippi River, so sediment that once continuously rebuilt coastal marsh is now thrust out to sea. Thus, wetlands restoration strategies, such as the Everglades restoration, have increased importance because these efforts can build resilience to sea level rises and saltwater intrusion into freshwater supplies.

New Directions for Land and Water Management

This portfolio of actions is not merely old wine in new bottles. Resource managers must broaden their management horizons to recognize the effects of a changing climate on landscapes and water management. This broadening requires that managers not simply look at historic data as they manage lands and waters. Managers need to peer into the future. A variety of analytic tools can help project future habitat ranges (Pearson and Dawson 2003, Araujo and New 2006, Dormann 2007). The Bureau of Reclamation already is re-evaluating its water models to take into account changed timing of snow melt and altered precipitation patterns as it develops its annual operating plans.

In the context of benthos, policy makers need to apply a much more concentrated focus on freshwater systems, water consumption, and instream flows. Even without climate change, water-use patterns are careering toward persistent shortages under current management patterns. The US already is experiencing major threats to some freshwater ecosystems through human-generated changes in water flows. Climate change might augment these threats. One conservation organization suggests that "a key to providing for human water needs is sustaining healthy, functioning freshwater ecosystems that tolerate changes in river flows and are resilient to drought, floods, and rising temperatures" (www.nature.org/initiatives/freshwater/strategies/climatechange). Brian Richter, who co-leads The Nature Conservancy's Freshwater Conservation Program, notes that: "Natural freshwater habitats such as floodplains and wetlands temporarily store flood waters and help reduce downstream damages" (www.nature.org/initiatives/freshwater/about/art25836). Thus, conservation and restoration of freshwater ecosystems is a central element of strategies for adaptation to climate change.

A common theme of many studies of climate and freshwater is that climate-induced changes must be assessed in the context of massive changes in water quantity and quality resulting from already-altered patterns of land use, water withdrawal, and species invasions. In some cases, these changes could dwarf or exacerbate climate-induced changes. Competition for water is likely to increase in the context of a changing climate. Climate changes might generate warmer water temperatures that alter lake mixing regimes and availability of habitat. Climate change also might change the magnitude and seasonality of runoff regimes that alter nutrient loading and limit habitat availability at low flow. Many changes in aquatic ecosystems are the consequence of climatic effects on terrestrial ecosystems, with shifts in riparian vegetation and hydrology especially critical.

All these possibilities underscore the interconnectedness of natural systems and give rise to important policy questions. Are currently protected lands and waters sufficiently diverse and interconnected to maintain genetically diverse populations across multiple locations? Does the US have wildlife corridors along north–south dimensions to facilitate relocation as animals migrate to more northerly latitudes, and are there interconnected waterways? The importance of interconnections underscores the continued relevance of partnerships, cooperative conservation, and collaborative forms of governance across multiple jurisdictions.

Big-Picture Questions

Resource managers face some big-picture questions that warrant some policy reflection. What conservation goals should shape decision making? In conservation, policy makers and managers have tended to use retrospective benchmarks, defining success as a return to some past condition. Yet retrospection in a rapidly changing environment might not be a relevant target. Take the example of endangered species and the designation of critical habitat. In the past, this designation has centered on identifying the historic ranges of species. Is that information relevant in the context of a changing climate? If not, do scientists and policy makers have sufficient information to project future habitat ranges that might be important to protect? Similar questions could be asked about efforts to refine in-stream flow requirements.

Climate change for resource managers puts a premium on ecosystem management options that enhance system resilience and on decision-making frameworks that provide some nimbleness with which managers can respond to change. Managers need monitoring, course corrections, and adaptive strategies in which scientists and managers jointly design a management option, implement that option (or options) along with targeted monitoring, assess and analyze over time the effects of the intervention, and use that evaluation to adjust management interventions if deemed necessary (Holling 1978, Walters 1986, Lee 1999). Adaptive management offers a construct that is potentially relevant for resource management in a climate change context. However, in practice, it has sometimes fallen short of expectations for a variety of both practical and contextual reasons.

In a review of adaptive management, the National Academy of Sciences reported that experience indicated limits to adaptive management (NRC 2009). The approach might be most feasible where 4 conditions are met: 1) temporal and spatial scales are relatively small, 2) dimensions of uncertainty are bounded so option experiments can yield clear results, 3) costs, benefits, and risks of experimentation are acceptable and course corrections are tolerated, and 4) institutional support exists for flexibility and adjustments.

These features might not apply to some climate effects issues and contexts or some landscape-scale initiatives. Some analysts suggest that a *deliberation with analysis* model might be more relevant (NRC 2009). This model refers to the iterative formulation of a problem, identification of interests and values relevant to addressing the problem, development of a shared understanding of risks, and crafting of responses using this shared knowledge. Climate change also puts a premium on holistic thinking; i.e., avoiding unintended consequences. Consider reforestation and C sequestration. C sequestration might be maximized by planting fast-growing monocultures, but that strategy would not be good for species diversity and ecosystem health.

The climate change context also reinforces the importance of what author Gretchen Daily (1997) has called "Nature's Capital," in which land managers explore the use of management strategies premised on bioengineering (Scarlett 2010). Can land managers enhance landscape resilience by maintaining permeable surfaces to reduce runoff and serve as natural contaminant filters in the built environment (Walsh et al. 2005)? Can land managers restore natural hydrology along the coasts to enhance sediment deposition where feasible? How can land managers use natural wetland systems to purify water and maintain buffers against coastal flooding?

Scientists need to help resource managers better assess the vulnerabilities of the lands and waters. Some scientists suggest that ecosystems are more sensitive to extremes than to changes in average conditions. Managers, working with scientists, have some tools to assess, in part, average changing conditions, but they also need tools to assess thresholds (what some have called tipping points), extreme changes that result in a series of domino effects. Scientists have made some progress in developing such tools (Anderson et al. 2009, Martin et al. 2009).

Perhaps it is fitting to conclude with one final observation: the parable of the petrel as told by Baer (2003). A common refrain of researchers referring to petrels was that: "We just don't know." The petrel is a seabird whose lifestyle has made it difficult to study. It emerges after dark and rarely hovers over boats. Historically, scientists had no good way to track them. Even simple analyses like counting them were tricky. Now scientists have new technologies, remote intelligent sensor networks, that have enabled scientists to generate more information about petrels in a short time than had been acquired cumulatively over centuries.

Take-Home Messages for the Scientific Community

Scientific inquiry has intrinsic value for enhancing understanding of how the world works. The results of that inquiry also have potentially significant value for natural resource managers. That value depends, in part, on how well science can help managers: 1) answer the questions they need to have answered in the timeframe available to decision makers, 2) evaluate resource management options and their likely resource outcomes, 3) develop relevant monitoring or other evaluation protocols and regimes, and 4) adjust resource management actions in response to new information and analysis.

At the nexus of science and resource management, several needs are especially relevant. The first is vulnerability assessments to help policy makers set priorities that will help ensure that scarce public resources are directed at highest-priority challenges. The second is adaptive management. The complexity of climate change details often translates into uncertainties about management regimes and their effects, leaving decision makers with discretion and underscoring the importance of adaptive management in which new information shapes and informs ongoing management choices, although as the National Academy of Sciences has noted, adaptive management might not offer a feasible framework for some climate change problems (NRC 2009). A corollary to the importance of adaptive management is the importance of diverse responses tailored to circumstance that apply a regional or integrated, cross-issue focus to reduce unintended and adverse consequences.

The third is dashboard indicators. Much scientific inquiry deepens knowledge about particular details of an individual species or stream temperature dynamics or soil moisture patterns. These inquiries are important and provide the building blocks of scientific understanding. However, in the context of natural resource management and, especially, for purposes of monitoring and evaluation of management actions, managers often want broader and clustered sets of indicators that, while imprecise about landscape particulars, might provide general information about land health trends. The concept of dashboard indicators is a performance management tool first used in the context of business management and the identification of critical success factors. This concept has been broadly adopted in other contexts, including environmental management, to provide managers with a relatively small set of indicators through which trends in the condition of key ecosystem and biological variables can be monitored and reported. Selection of such indicators can be difficult, especially if managers want to track ecological processes rather than trends in species populations at specific locations. Despite these difficulties, dashboard indicators for environmental management have been developed (Doren et al. 2009). Managers need scientists to help interpret these indicators. What do they mean? How do they relate to resource management options and next steps in a conservation or restoration project?

The last need is investments in science. One major lesson in this paper is that whatever the current state of knowledge, new tools and new methods will facilitate the continuous accumulation of scientific knowledge regardless of the subject. That knowledge, in turn, will help policy makers and managers make better decisions with fewer unintended consequences.

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