ISSUES IN ECOLOGY

Published by the Ecological Society of America

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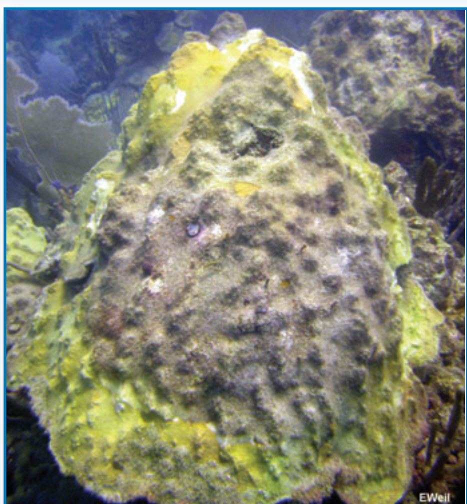

Fall 2013

Report Number 18

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SUMMARY

Climate change is affecting land, water, and biodiversity in a variety of ways. Higher temperatures, altered precipitation patterns, increasing extreme events (droughts and floods), and increasing disturbances are occurring across the United States, with detrimental effects on sensitive systems. These kinds of changes, combined with other ongoing stresses, such as landscape fragmentation, could dramatically hinder the ability of natural resource managers to maintain established goals for ecosystems and species now and in the future.

While managing ecosystems and resources by relying on an expected set of climate conditions may have worked in the past, a growing number of managers understand the need to develop new ways to manage ecosystems in the face of climate change. The purpose of this *Issue* is to provide a broad perspective on approaches for adapting to climate change impacts on national water and land resources and biodiversity. Using examples from different management settings, we explore ways to apply management options that allow natural and managed systems to adjust to the range of potential variations in future climate conditions.

Broad recommendations for managing the impacts of climate change on ecosystems and resources include:

- **Plan** – Conduct systematic adaptation planning based on vulnerability of management targets to climate change.
- **Address uncertainty** – Analyze the effects of primary sources of uncertainty on adaptation options with context-specific methods.
- **Leverage** – Adjust existing management tools to changes in temporal and spatial patterns of climate impacts and ecological responses.
- **Increase flexibility** – Cultivate institutional flexibility and cooperation to meet adaptation planning goals.
- **Expand and integrate** – Coordinate research and management efforts across jurisdictions to broaden available information and the scale at which management tools can be applied.
- **Monitor** – Enhance and augment existing monitoring networks to detect and measure climate change impacts and ecosystem responses to management actions.
- **Review** – Evaluate the effectiveness of management options; revise and improve adaptation plans accordingly.
- **Assess and reassess** – Conduct and update assessments frequently to identify changing priorities and conditions within systems of interest.

Coordinated research and strategic planning for climate change across government agencies is needed to increase the nation's capacity to adapt. The U.S. National Climate Assessment provides a platform to engage networks of local, regional, and national experts and decision makers to exchange information, lessons learned, and insights on impacts and adaptation to support adaptation decision making. Over time, and with concentrated effort, implementing these recommendations and changes at all levels of management will help prepare us to successfully address climate change.

Cover photos: *(clockwise starting on the upper left): a) Pine bark beetle damage to lodgepole pines in Colorado; b) Northern pintails in flight at Bear River Migratory Bird Refuge, Utah; c) Bark beetle; d) Coral bleaching caused by high water temperatures.*

Photos credits: *a) Flickr user vsmoothe; b) J. Kelly, U.S. Fish and Wildlife Service; c) Jeff Mitton, Department of Ecology and Evolutionary Biology, University of Colorado, Boulder; d) Ernesto Weil, University of Puerto Rico at Mayaguez.*

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Introduction

The Earth's climate is changing, affecting ecosystems and presenting resource managers with increased uncertainty and risk for achieving their goals. Some observations that support these trends include consistently higher temperatures and more extreme precipitation events, rising sea levels, and increasing ocean acidity. The United States has experienced an average increase in temperature of about 1.5°F since 1895, and is likely to see an additional rise of 2°F to 4°F over the next two or three decades (here and throughout this paper, when an event or outcome is described as "likely," that means that it has a greater than a 66% probability of occurring). Over the past century, the U.S. has also seen an increase in very heavy precipitation events in every region except the Southwest, Northwest, and Pacific islands including Hawai'i. Globally, sea level has risen by about 8 inches over the last century and is projected to rise by another 1 to 4 feet over this century. Ocean acidification has increased by 30% due to increases of carbon dioxide in the atmosphere. Other observed trends include more frequent or more intense floods and droughts in some regions of the country and glacier and arctic sea ice melt.

These kinds of climatic changes affect ecosystems and biodiversity, most often in adverse ways. Effects include degradation of air and water quality, reduced productivity of forests and arid lands, loss of iconic species and landscapes, and a decoupling of predator-prey relationships that leads to pest outbreaks and invasions by non-native nuisance species. Some species have responded by moving to higher elevations and latitudes in response to warmer temperatures, but many species may not be able to keep pace with climate change because of limitations in seed dispersal or mobility. In some places, these limitations will lead to local extinctions of plants and animals, causing large changes in species composition and creating new communities. Although it is possible that a warmer climate may increase biodiversity and productivity in some systems (e.g., higher spring temperatures can extend the growing season and, with adequate moisture, increase forest productivity), overall, ecosystem health is expected to decline.

Unfortunately, even if all greenhouse gas emissions were to cease today, the lifespan of those gases already emitted into the atmosphere (decades to centuries) means that temperatures will still increase for another few decades and sea levels will continue to rise for a number of centuries. In addition, it is unlikely that greenhouse gas emissions will be curbed soon. These two factors have led to the realization that adaptation to climate change is necessary.

Adaptation has been defined by the Intergovernmental Panel on Climate Change (IPCC) as the "adjustment in natural or human systems in response to actual or expected climatic stimuli or their effects, which moderates harm or exploits beneficial opportunities." Making such adjustments for successful adaptation will require enhanced understanding of climate-related transformations – how they will manifest and in what ways they will affect ecosystem components and processes. Also important will be understanding how management actions can be developed, refined, and employed in the context of a well-developed and flexible management system in order to increase our ability to cope with climate change and preserve ecosystem resilience.

By making adaptation investments in the present, managers can effectively expand their coping capacity in the future, giving them greater ability to accommodate a range of potential variations in future climate (Figure 1, panel c). An inflexible management system that makes no adaptation investments will have little capacity to protect ecosystems from future climate variability and change (Figure 1, panel b). A key concept is that in addition to taking actions that build ecological resilience, institutions themselves need to become more resilient by adopting flexible management structures and approaches that are prepared for changing conditions. Recognizing the importance of climate change adaptation in managing natural resources will require modifications to management plans and, in some cases, the development of new management tools, in addition to enhanced collaboration across and among institutions, agencies, and stakeholders.

In this *Issue*, we summarize important climate-related stresses on selected land and water resources and biodiversity and discuss adaptation options for management. Case studies are provided to demonstrate how some managers can approach climate-related management problems. We review a generalized scheme that is available for managers to use in adaptation planning, in which management goals are the starting point for identifying key actions that could be used to build ecosystem resilience in the face of climate-related stresses. The final section discusses critical research needs and provides recommendations for how adaptation and decision-making strategies might be improved.

Climate Change Impacts on Natural Resources and Potential Adaptation Responses

Climate change is a global phenomenon that affects ecosystems at local to regional scales. It can even create connections between remote regions by affecting the movement of organisms, nutrients, and pollutants, for example, through changes in species ranges, changes in connectivity of streams and rivers, and through changes in atmospheric transport of nutrients and pollutants. Meanwhile, resource managers often work at local scales in order to fulfill site-oriented obligations such as meeting pollution reduction targets or managing fish stocks, but may themselves be affected by (or affect) what is happening in distant systems. Natural- and human-generated non-climate stressors complicate the issue as they act separately and interactively with climatic changes to alter ecosystems. Among these are increased impacts from pest species, changes in cycling of nutrients such as nitrogen, point and non-point source pollution, wildfires, and land use change. Minimizing adverse effects of human-caused stresses to ecosystems will likely increase their ability to respond and adapt to climate change.

In this section we use forest and arid ecosystems as boundary examples of possible changes to terrestrial systems and freshwater ecosystems to illustrate a range of potential future changes in water resources. We also provide examples of biodiversity impacts and explore adaptation options for each of these areas from a resource manager's perspective. Management goals are the starting point for identifying key

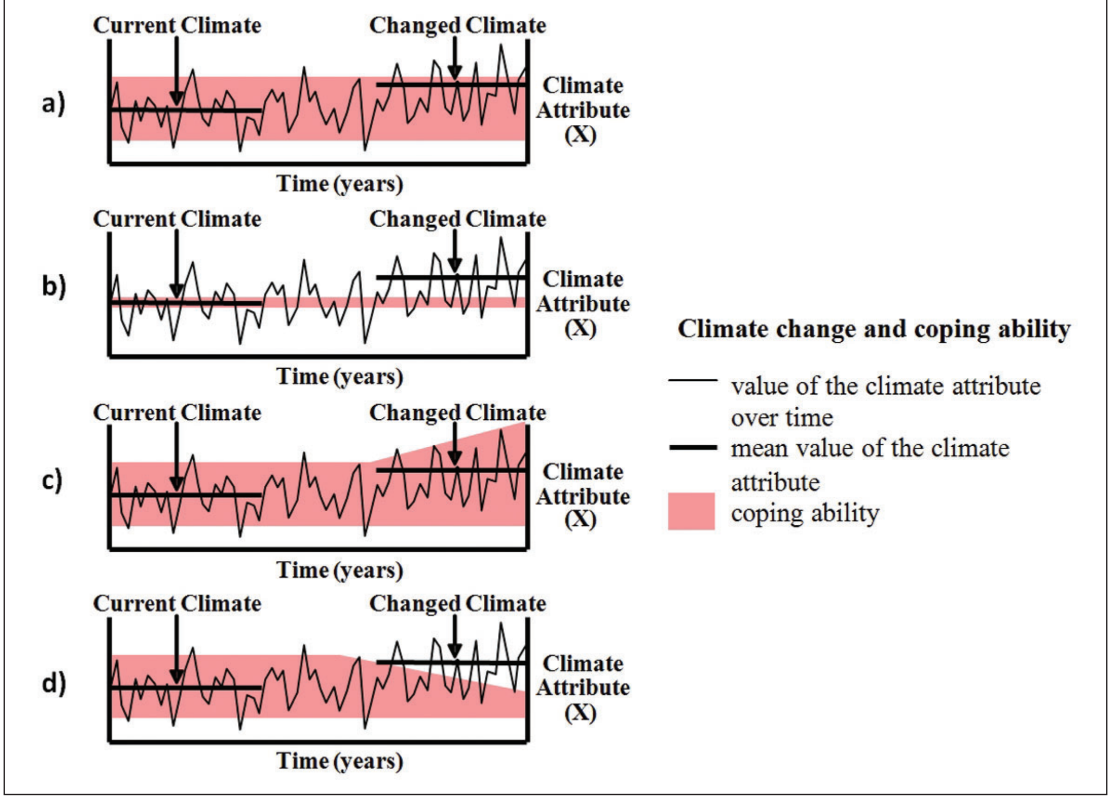

Figure 1. *Climate change and coping ability. a) A well-developed and flexible management system unadjusted for climate change. b) A rigid management system barely able to protect ecosystems under average climate, with little or no capacity to address climate variability. c) An increase in coping ability due to investments in adaptation, allowing management to deal with the effects on ecosystems of future climate variability and change. d) Decreasing coping capacity so that even future average climate poses threats. Adapted from: Grambsch and Menne, 2003.*

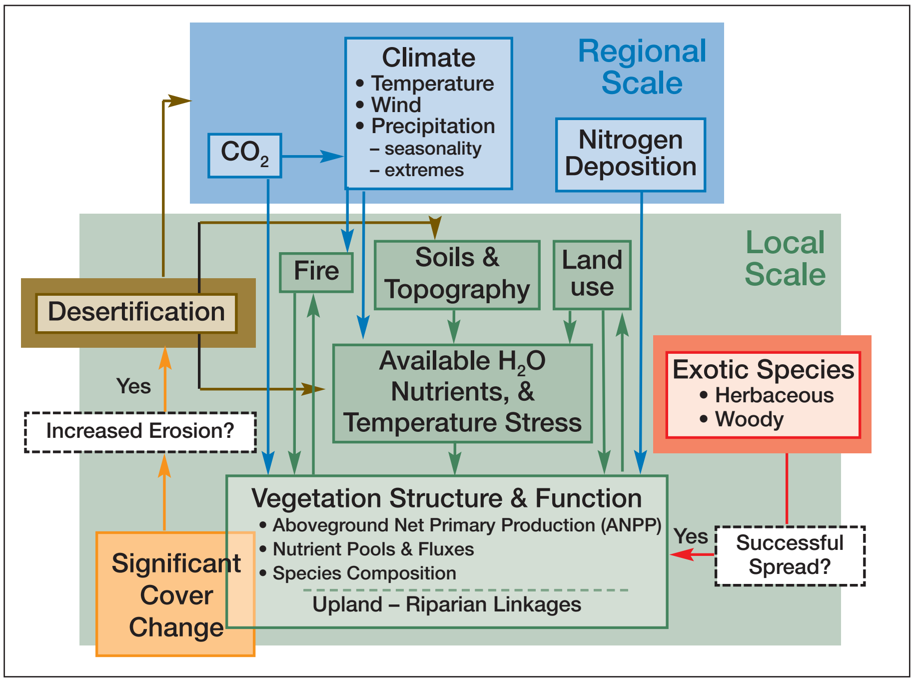

Figure 2. Conceptual framework illustrating the variety of climate and climate change feedbacks and effects on arid land ecosystems at the local scale from regional scale drivers such as climate and nutrient transport (blue box) on local scale processes (green box). Redrawn from CCSP, 2008a.

actions that could be used to build ecosystem resilience in the face of climate-related stresses.

Land Resources: Forests and Arid Lands

Forests and arid lands (i.e., subtropical hot deserts of the Southwest and temperate cold deserts of the Intermountain West) cover about 749 million acres, most of which are in the western U.S. There are five major arid land areas located in the Great Basin (Utah and Nevada), the Colorado Plateau (Utah, Colorado, Arizona, and New Mexico), the Mojave Desert (California, Nevada, Utah, and Arizona), the Sonoran Desert (California, Arizona, and northern Mexico), and the Chihuahuan Desert (New Mexico, Texas, Arizona, and northern Mexico). These lands present unique and integrated management challenges that are the focus of many state, federal, and nongovernmental organizations. Changing climate influences forest and arid land productivity, species composition, and the frequency and magnitude of disturbances, such as fires and insect outbreaks (Figure 2). Climate change drives the response of arid ecosystems to changes in land cover. Many plants and animals are near their physiological limits for temperature and water stress in these ecosystems, and even slight changes in temperature or the frequency and intensity of precipitation events will likely result in significant consequences for these organisms.

Climate change-related effects on forest and desert ecosystems include:

- Invasions by exotic grass species and more frequent wildfires in arid lands from higher temperatures, increased drought, and more intense thunderstorms.
- Greater susceptibility of U.S. forests to disturbance, including insect infestations, invasive species, wildfires, and damage from extreme events such as drought.
- Increased tree mortality in western U.S. forests from combined drought, higher temperatures, and pests and pathogens (see Box 1).
- Increased ecosystem carbon loss through weathering and erosion in arid lands from coupled land-use change and climate-induced disturbance (Figure 2).
- Increased photosynthesis for forests from rising atmospheric carbon dioxide (CO_2) levels; young forests on fertile soils will increase wood production.

Reducing local stresses can make land resources more resilient to climate change impacts. Example actions may include: (1) creating larger management units that reduce landscape fragmentation and provide migration corridors and (2) managing for a variety of species and genotypes with a range of tolerances to low soil moisture and higher temperatures. When large-scale disturbances or extreme events do occur, one option is to assist ecosystem adjustments by manipulating species mixes, increasing genetic variation, and diversifying age structures to support greater system resilience in the future.

Water Resources: Freshwater Systems

With both human and natural systems highly dependent upon water resources, even slight changes in climate can result in changes to water quality, storage, and biogeochemical fluxes that significantly impact water management and planning requirements. U.S. water resource management plans are often based on assumptions about past conditions and behaviors. Planning for future conditions will require an understanding that climate futures are, at present, uncertain. We provide a list of observed and projected climate change-related effects on U.S. water resources below.

- Most of the United States experienced increases in average precipitation and stream

Box 1. Bark Beetle Outbreaks

Management Context: Since 1990, native bark beetles have killed trees across millions of hectares of forest from Alaska to southern California, and east into the Rocky Mountains. Although bark beetle infestations are a natural phenomenon in forested ecosystems, current outbreaks, which have occurred simultaneously across the Western U.S., are the largest and most severe in recorded history. These outbreaks appear to be related to a combination of recent warming trends associated with climate change and forest age and condition. Consecutive warm winters in particular can increase the size and severity of outbreaks, as cold-induced mortality is reduced and growing season lengthens (see Figure 3). Shifts in precipitation patterns and associated droughts also favor bark beetle outbreaks by weakening trees and making them more susceptible to beetle attack.

Management Goal: Deal with invasive outbreaks during the early stages of invasion when outbreak patches are small and treatable.

Adaptation Strategies: To deal with invasive outbreaks and other ecosystem issues, managers of the Olympic National Forest in Olympia, Washington developed a land management plan that included an Early Detection/Rapid Response (EDRR) methodology. EDRR allows managers to coordinate rapid responses to extreme events, including insect outbreaks, with an eye toward management responses that may also be appropriate for other types of disturbances, such as those related to climate change. The plan includes actions for both post-disturbance management related to short-term restoration, e.g., thinning, as well as for long-term restoration under climate change, e.g., planting tree varieties that are adapted to the altered climatic conditions. Such large, system-resetting disturbances require an immediate plan of action, and they allow managers to influence future structure and ecosystem function through carefully designed management experiments in adapting to climatic change.

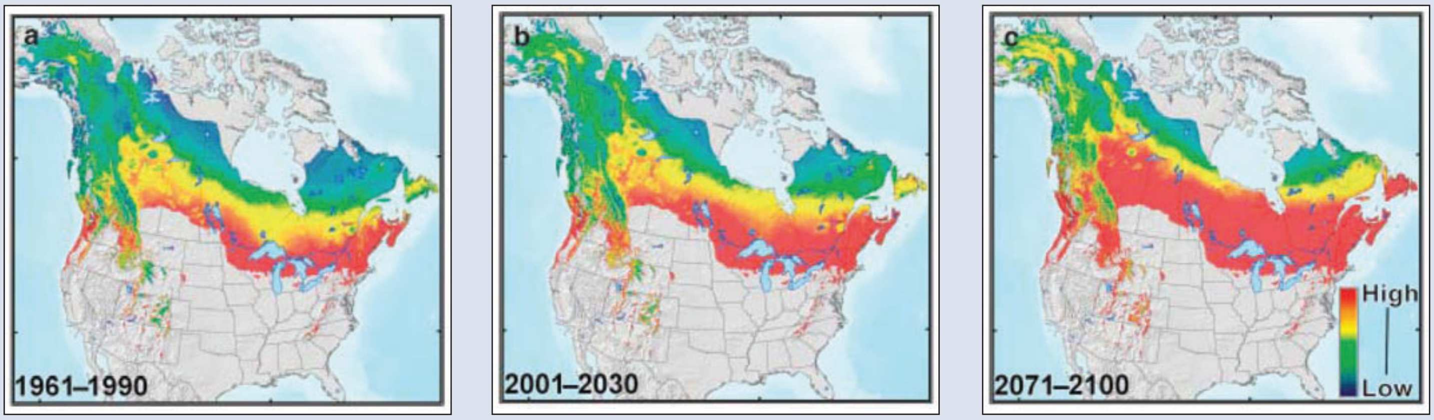

Figure 3. Probability of spruce beetle offspring developing in a single year. Panels a-c show predictions for spruce forests across the range of this insect in North America during three periods: (a) 1961–1990, (b) 2001–2030, and (c) 2071–2100. Higher probability of one-year life-cycle duration translates to higher probability of population outbreak and increased levels of spruce-beetle-caused tree mortality. Model results are shown only for areas estimated to be 20th-century spruce habitat. Source: Bentz et al. 2010.

flow and decreases in drought during the second half of the 20th century. These trends are likely due to a combination of decadal-scale variability and long-term climatic change.

- The timing of peak flows has changed across the Western U.S., with a consistent shift toward earlier seasonal snowmelt coupled with reduced summer and fall flows.
- Regional differences in runoff are predicted, with increased annual runoff in the Eastern U.S., little or no change in the Missouri and Mississippi Basins, and substantial decreases in the interior West (Figure 5).
- Stream temperatures are expected to increase as climate warms, affecting aquatic ecosystems and species directly and indirectly.
- Warming surface waters will likely increase stratification of water bodies, leading to declining oxygen concentrations in bottom waters and declining habitat quality (Box 2).
- Increasing export of carbon and nitrogen from watersheds is expected as enhanced weathering rates interact with land-use change and an increasing frequency of extreme events such as floods and droughts (Box 2).

To address potential ecosystem impacts from changes in water quality and availability, options include using drought-tolerant plant varieties to maintain riparian buffers, creating wetlands or off-channel storage basins to reduce erosion during high flow periods, purchasing or leasing water rights to enhance flow management options, managing water storage and withdrawals to smooth the supply of available water throughout the year, and developing effective storm water infrastructure

Box 2. Water Quality in the Chesapeake Bay

Management Context: Runoff from agricultural and urban development and discharge from sewage treatment plants have resulted in elevated levels of nitrogen and phosphorus in surface waters, causing increased growth of algae in the Chesapeake Bay watershed. In shallow waters, these organisms deprive seagrasses of sunlight, limiting plant health and in some cases bringing about death of grass beds; seagrass provides habitat to many aquatic species, such as sea bass and blue crab. In deeper waters, algal growth and subsequent die-off reduce oxygen concentrations in normally oxygen-rich waters. In summer, when mixing between surface water and low-oxygen bottom water decreases, bottom-dwelling creatures such as clams, oysters, and worms – food for fish and humans alike – are negatively affected. The range of climate change-related challenges to near coastal habitats includes increases in water temperature, sea level rise, fewer seagrasses due to temperature-related shifts in growing range, more precipitation, and larger dead zones caused by the oxygen depletion described above.

Goal: Bring together local, state, and federal stakeholders to clean up the severely degraded Chesapeake Bay watershed ecosystem under the aegis of the Clean Water Act.

Adaptation Strategies: To address the above issues, the Chesapeake Bay Program (CBP) engages a broad spectrum of stakeholders from Pennsylvania, Virginia, Maryland, Delaware, New York, West Virginia, and the District of Columbia, as well as representatives from federal agencies, and members of nongovernmental organizations. Bringing together a consortium of interests enhances accountability for efforts related to bay restoration and ongoing protection. Participants leverage scientific understanding – including information on climate change interactions that exacerbate existing stressors – to develop and implement plans for reducing the influx of pollutants and improving the Bay's aquatic ecosystems. Moreover, the program offers a framework for assessing success including consideration of needs and desires of stakeholders. This approach and framework has facilitated development of a strong cooperative partnership based on accountability. While ongoing rapid population growth and urban development are outpacing the ability of the CBP to get ahead of the problem, without the program and its participants, the Bay's problems could be far more serious. Some successes reported in the 2010 Bay Barometer include less nitrogen and phosphorus entering non-tidal creeks and rivers, stable and abundant populations of adult blue crabs, and a return of shad populations to the Potomac River. Over the same period of time, however, underwater bay grasses decreased, tidal waters meeting or exceeding guidelines for water clarity decreased, and less than half of stream health scores at monitoring sites were fair, good, or excellent.

Most recently, the Bay Program is focused on meeting a Bay-wide TMDL (Total Maximum Daily Load), established by the U.S. Environmental Protection Agency in 2010. This TMDL sets limits on nitrogen, phosphorus and sediment pollution necessary to meet water quality standards in the Bay and its tidal rivers. The purpose of the TMDL is to ensure that all pollution control measures that are needed to fully restore the Bay will be in place by 2025, with at least 60% of pollution reductions completed by 2017.

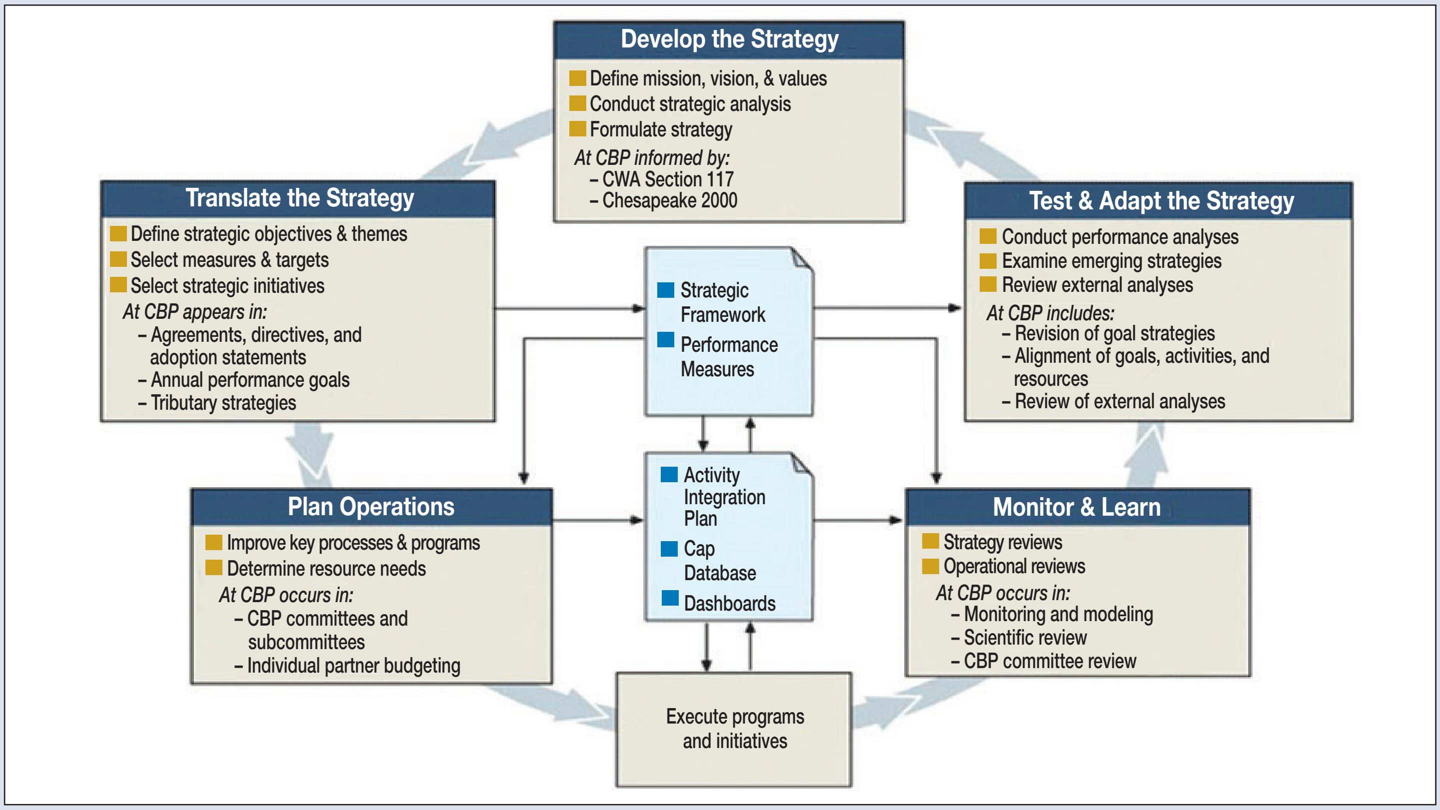

Figure 4. Chesapeake Bay Adaptive Management Model. The adaptive management process model above shows the cycle of strategy development, planning, implementation, monitoring, and evaluation applied to all areas of the Chesapeake Bay Program's activities, allowing the organization to more nimbly adapt and change strategies based on evolution of options and processes. Source: Chesapeake Bay Program, cap.chesapeakebay.net/managementmodel.htm.

that reduces future occurrences of severe erosion. Other strategies that enhance aquatic species' resilience to climate change include increasing physical habitat heterogeneity in channels to support diverse biotic assemblages and conducting river restoration to stabilize eroding banks and repair in-stream habitat.

Biodiversity

Once reduced or lost, biodiversity is difficult if not impossible to restore or replace. Although the impact of climate change on species variety is currently exceeded by other major drivers such as land-use change, it will likely become increasingly important in the coming decades. Already, changes in the climate system are affecting processes that control different aspects of biodiversity, such as the physiological processes that control where populations can thrive – which in turn determine plant and animal ranges. The major effects of climate change on aspects of biodiversity in the United States are listed below.

- The patterns of life cycle events for some plants have been affected by shorter, milder winters and earlier spring thaws, with some plant species flowering around a day or two earlier per decade in the northern hemisphere.
- Species distributions have shifted over the last few decades, with plants and animals moving to higher elevations and latitudes at median rates of 36 feet per decade and 10.5 miles per decade respectively (Figure 6). Greater shifts are expected to occur in the future.
- In higher latitudes, where temperature increases are relatively large, evidence indicates a significant lengthening of the growing season and higher net primary productivity, which has been shown to correlate with higher biodiversity.
- Water quality is anticipated to degrade due to temperature increases, higher amounts of nutrient export (due to increased precipitation), and increased acidification, resulting in a variety of changes in aquatic ecosystems including potential species losses (Box 3).
- Subtropical and tropical corals in shallow waters have already suffered mass mortalities from temperature-induced bleaching events (Box 3) and also face a growing problem of inhibited calcification rates due to increasing ocean acidification (a direct result of increases in atmospheric carbon dioxide levels).

One of the most effective options for increasing species' and ecosystems' resilience to climate change is to reduce other human sources of stress, such as development pressures that increase habitat fragmentation, activities that increase pollutant, nutrient, and sediment loadings, introduction of invasive species that

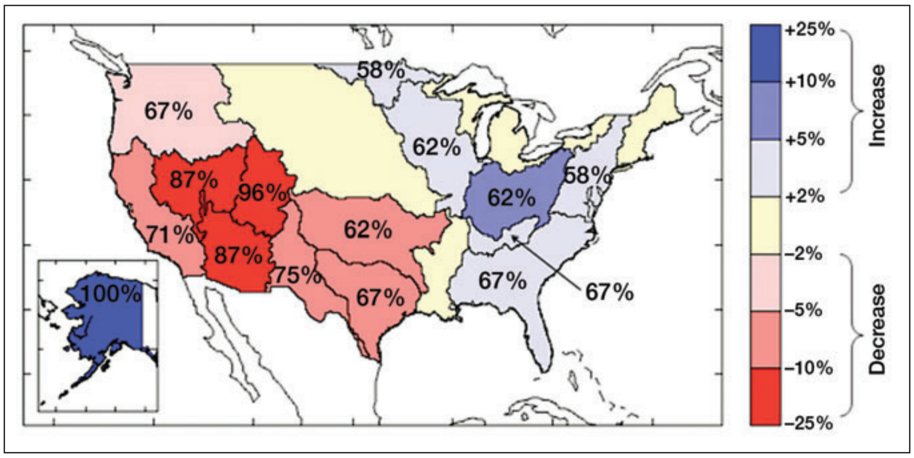

Figure 5. Median changes in runoff interpolated to USGS water resources regions from Milly et al. (2005) from 24 general circulation model simulations for 2041-2060 relative to 1901-1970. Numbers on the map show the percentage of the 24 runs for which change in runoff had the same sign as the 24-run median. Colors on the map show the median magnitude of change in runoff from historical runoff for that region. Source: CCSP, 2008a.

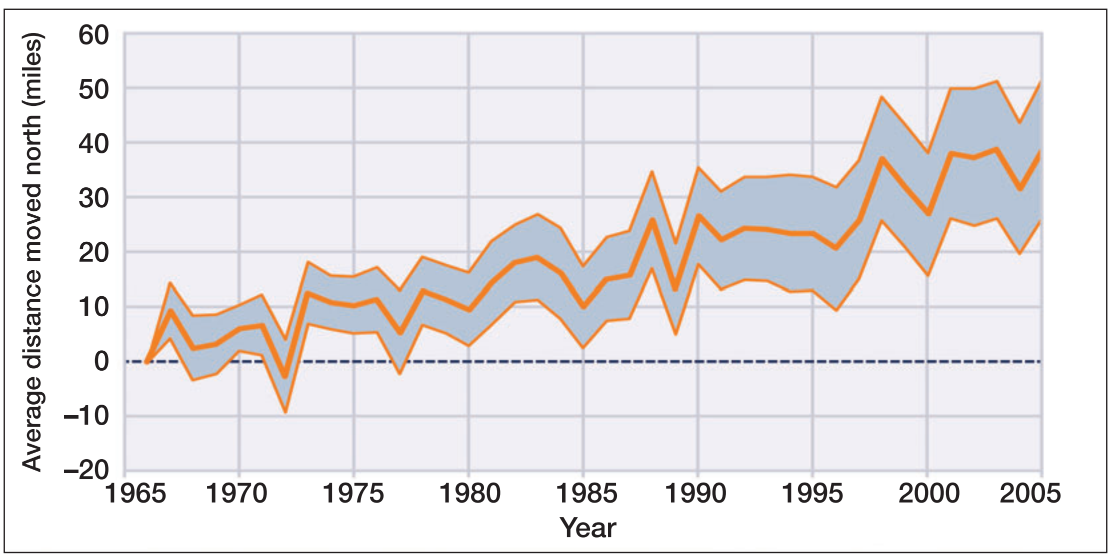

Figure 6. Annual change in latitude of center of abundance for 305 widespread bird species in North America, 1966-2005. The shaded band shows the likely range of values, based on the number of measurements collected and the precision of the methods used. Figure source: EPA. Bird Wintering Ranges. http://epa.gov/climatechange/science/indicators/society-eco/bird-ranges.html. Data source: National Audubon Society. 2009. Northward shifts in the abundance of North American birds in early winter: A response to warmer winter temperatures? Available online at: www.audubon.org/bird/bacc/techreport.html.

out-compete native species, overfishing, or other activities that deplete scarce or sensitive resources or species. Other options that more directly address climate change impacts are centered on identifying and protecting areas that appear to be resistant to climate change effects, that recover well from climate-induced disturbances, that are ecologically significant (such as nursery grounds, spawning grounds, and areas of high species diversity), or that have a full breadth of habitat types that maximize habitat heterogeneity.

Adaptation Planning

In previous sections we have presented some examples of how managers have responded to climate change-related impacts on sensitive systems thus far. Based on these and an ever-growing number of other efforts, the adaptation community has developed a set of principles for adaptation planning that can be arranged into a framework. In this section we discuss a generalized framework for systematic adaptation planning, followed by a discussion of how to accommodate the uncertainty that typically accompanies planning processes.

Example Framework for Adaptation Planning

A number of frameworks have been developed to address the need to systematically incorporate climate change adaptation into planning processes. Most of these frameworks have similar steps. We present one such representative

Box 3. Biodiversity in the Florida Keys National Marine Sanctuary

Management Context: Congress established the Florida Keys National Marine Sanctuary in November 1990 to protect the region's valuable and unique biodiversity. Mounting threats to the Keys' coral reef ecosystem prompted this designation. Environmental problems such as deteriorating water quality are being exacerbated by climate change, as are temperature-induced coral bleaching events and disease outbreaks (Figure 7). Coral species, communities, and locations are differentially affected by these impacts, with consequences for biodiversity at local and regional scales.

Goal: Maintain the chemical, physical, and biological integrity of the Sanctuary, including restoration and maintenance of a balanced indigenous population of corals.

Adaptation Strategies: Management actions to reduce anthropogenic stressors such as pollution and overfishing may also increase coral resilience in the face of climate change. For example, no-take zones have been shown to enhance heavily-fished populations, and this in turn supports resilience through re-establishment of important predators. Meanwhile, monitoring and research efforts are underway to identify bleaching-resistant sites that can be targeted for protection as refugia and as larval sources for recovery. Looking to the future, another strategy is to identify and protect sites where coral reefs flourished north of their current distributions in past geological periods. These locations could be used as destination sites for northward range migrations as climate change continues in the coming decades. Finally, restoration of adjacent systems, such as mangrove swamps, not only provides habitat and shoreline protection, but also a source of dissolved organic compounds that have been shown to provide protection from photo-oxidative stress in corals.

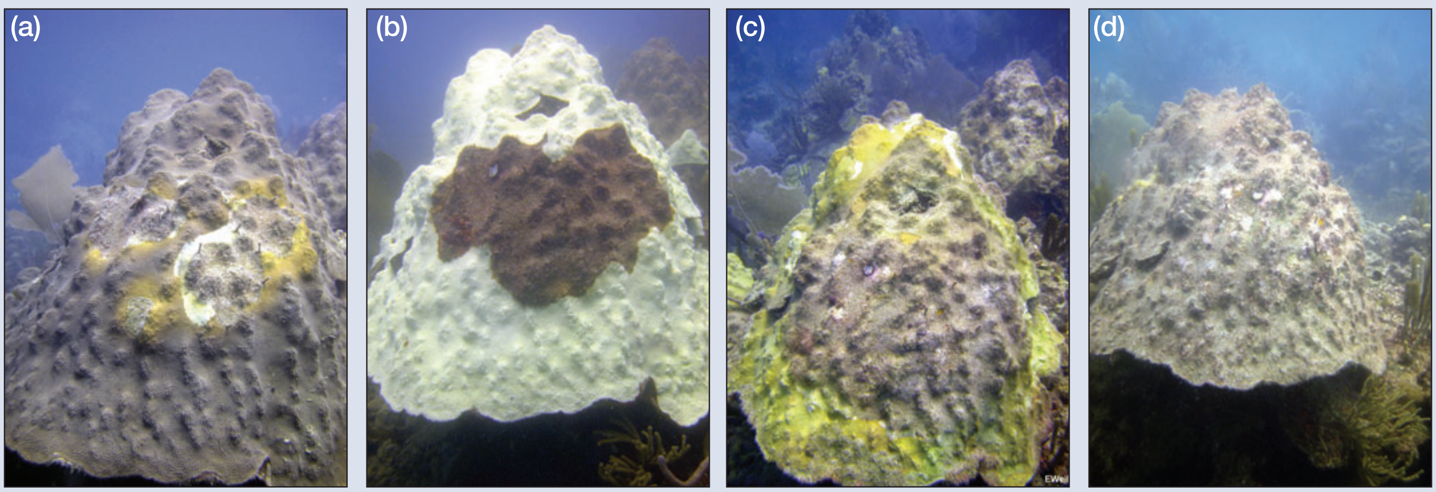

Figure 7. Combined effects of disease and bleaching due to rising water temperatures. This 500 year old star coral off the southwest coast of Puerto Rico illustrates the effect of rising water temperatures. An initial disease infection exacerbated by warming waters (a) was followed by such high temperatures that bleaching (loss of symbiotic micro-algae from the coral) occurred (b), followed by more disease (c) that finally killed the colony (d). Source: USGCRP, in press. Photo credit: Ernesto Weil, University of Puerto Rico at Mayaguez.

framework in Figure 8 below and discuss it.

Step 1 – Identify management targets (Figure 8) based on the overarching conservation goal(s). Since climate change effects on ecosystems and natural resources will vary from site to site, and adaptation responses will need to be individually tailored to the location of implementation, beginning with established goals and objectives places the targets of concern at the center of analysis and evaluation in order to develop adaptation plans that maintain desired goals. Conservation targets can be selected at multiple ecological levels, including species, habitats, ecosystems, or networks of protected areas.

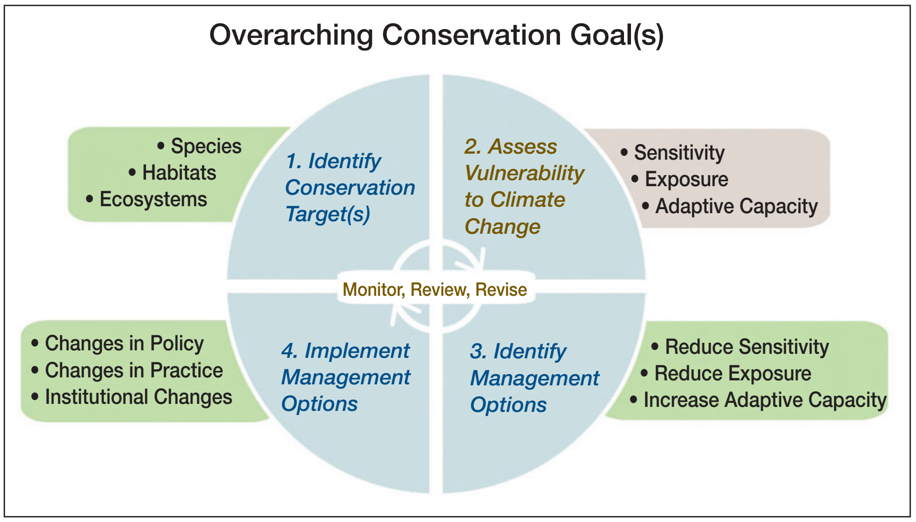

Figure 8. Framework for developing climate change adaptation strategies. Source: Glick et al. 2011.

Step 2 – Assess vulnerabilities of conservation targets to climate change. This includes developing relevant problem parameters for the targets of concern, creating conceptual models that link drivers to endpoints (targets) to capture the major processes that need to be assessed, choosing analytic methods/models based on the identified processes, gathering available data, and evaluating what is known about climate change and ecological processes to assess impacts and vulnerability. Once a qualitative or quantitative sense of a species' or system's vulnerability to climate change is better understood, management options that address the new information can be evaluated.

Step 3 – Identify management options. These can be categorized under seven general adaptation approaches for managing for resilience (Table 1). For each of these approaches there are many specific management options that can be considered – we have provided just a few illustrative examples in Table 1. Note that different options may employ different techniques and/or focus on different ecosystem types or elements, but in all cases their purpose is to address one or more of three key components of vulnerability to climate change: sensitivity, exposure, and adaptive capacity (Figure 8). In implementing these options, it is not sufficient to simply employ the same best practices; rather, their application should be considered through the "climate lens." Managers need to examine how the timing, location, and application of practices may need to be adjusted to account

Table 1. Adaptation approaches and example management options to address climate change impacts on ecosystems. See CCSP 2008b for more examples.

Adaptation approaches	Examples of specific adaptation options
Reduce local anthropogenic stresses	Reduce overfishing or correct altered hydrology to restore the ability of species or ecosystems to withstand a stressful climatic event.
Protect key ecosystem features for system resilience	Protect complexity of landscape features in order to preserve critical buffer zones and migration corridors.
Protect diverse habitats and biological communities	Increase genetic diversity in river systems and maintain habitat complexity to safeguard sources for recovery regardless of climate change.
Ensure redundancy in protection of ecosystem type or species	Protect redundant ecosystem types, such as cypress savannas, to reduce the risk that a disturbance (e.g., wildfire) will cause global species extinction.
Restore compromised or lost ecosystems	Restore tidal marshes, seagrass meadows, and mangroves, since together these stabilize estuary function by providing diverse vegetation structure.
Identify ecosystem refuges	Protect coral reefs on islands' shady side or near areas of ocean upwelling to use natural protection from heat and light during bleaching events.
Relocate organisms to new habitats	Transport fish populations with low thermal tolerances to cooler river reaches (e.g., at higher altitudes or in groundwater-fed systems).

for climate change in order to attain the desired result. Further, they should explore how the efficacy of these practices might be affected by climate change, and whether differences in effectiveness might affect prioritization of certain practices or options over others.

Step 4 – Implement management options. Implementation may be constrained by policies or cultural and institutional beliefs and behaviors. Successful implementation will depend on creative use of policies, practices, and institutional changes to empower action.

The central circle of Figure 8 depicts the cyclical nature of adaptation planning through an iterative process of monitoring, review, and revision of the adaptation plan. Monitoring is necessary to follow continuing ecosystem change and to measure whether the desired outcome was achieved. Periodically revisiting existing management plans is recommended to incorporate newly gained system knowledge or needs, and to make adjustments in response to expected or unexpected positive or negative outcomes. Review and revision can be repeated for every step in order to keep pace with changing ecological conditions, management targets, vulnerabilities, and other new scientific information. In some cases, a complete revision of management goals may be required when the goal of maintaining ecosystems, resources, or species compositions in an unchanged state is no longer feasible.

Dealing with Uncertainty

In assessing vulnerability and planning adaptation responses, it may be difficult for resource managers to know how to characterize the ranges of uncertainty in climate change impacts and translate these uncertainties into practical management actions. Fortunately, tools are being developed and tested that can help with such tasks. One such tool is scenario planning, which facilitates exploration of the breadth of projected impacts and potential responses. Scenario planning may be done in several ways. One way is to conduct sensitivity analyses of key management targets to a wide range of climate scenarios using realistic specified changes in climate drivers, such as incremental changes in temperature or precipitation, across a broader range of changes. Results may be used in the planning process to target for adaptation those processes that are most sensitive to climate change. Another method is to use specific models or climate-baseline scenarios to assess relevant and plausible alternative futures as points in a range of future conditions. Due to model and system uncertainties, there is no one model that can provide an accurate "prediction;" rather, by capturing a breadth of realistic outcomes, suitable adaptation responses can be selected that are effective across a range of potential climate scenarios. These approaches provide means to identify the greatest vulnerabilities and enable selection of targeted and robust adaptation approaches. These approaches are similar to engineering tolerances that are developed to ensure proper and safe functioning of equipment or processes under a wide and uncertain range of possible conditions, properties, imperfections, or stresses.

Two examples where uncertainty methods have been applied are (1) in British Columbia, to decisions related to managing the Mountain Pine Beetle; and (2) in the Metropolitan Water District of Southern California, to decisions related to meeting water demands under a variety of future hydrologic conditions induced by climate change. In the first example, management goals and objectives were established for British Columbia forests for the short- and long-term in light of potential near- and long-term pest infestations and damages. A number of climate change and land management scenarios were run and outcomes evaluated according to desired timber economic values, nontimber values, fire risk level, and ecological resilience. The strategies selected were those that, although the most costly, were most robust across the climate scenarios in meeting desired goals, allowed for flexibility in implementation, and provided long term benefits. In the second example, the Metropolitan District and RAND Corporation worked together to run hundreds of scenarios of future temperature and precipitation changes, demographic changes, condition of the San Francisco Bay Delta Yields from local resources, and timeliness of implementing actions articulated in the Metropolitan District's Integrated Resources Plan. The analysis helped identify the Metropolitan District's key vulnerabilities to climate change and other future uncertainties, and gave them markers to monitor that will provide early warnings that management actions in their plan might fail in meeting established goals. These markers will allow the Metropolitan

District the necessary lead-time to adapt their plans and actions accordingly.

Other approaches are also available for handling uncertainty in management and planning processes. These include:

- *Structured Decision Making*, a process that begins with problem framing, then elicits objectives, develops alternatives, evaluates the consequences of alternatives relative to the objectives, and identifies preferred actions using decision analytic tools;
- *Adaptive Management*, an approach used when a decision is recurrent, when uncertainty matters in terms of the decision to be made, and when monitoring can provide information to discriminate among alternative hypotheses or models in order to adjust management strategies in response to what is learned;
- *Robust Decision-Making*, an approach that uses robustness rather than optimality as the primary criterion for evaluation in identifying decisions that maximize the likelihood of some acceptable outcome across a range of scenarios; and
- *Expert Elicitation*, a systematic process for obtaining the judgments of experts to characterize uncertainty and fill data gaps where traditional scientific research is not feasible or adequate data are not yet available. Useful in situations where uncertainties are large, more than one conceptual model can explain available data, and technical judgments are required to assess assumptions.

All of these approaches are being tested and applied in planning processes for climate change adaptation and are worth exploring to understand which are most appropriate for specific management contexts.

Planning appropriately for climate change impacts will also require transitioning from "managing for resilience" to "managing for change" at appropriate times. In other words, when a system is pushed past the limits of its resilience such that there is no longer maintenance of ecosystem status or achievement of previously defined goals, those goals may have to be adjusted toward managing transitions to new ecosystem states. For example, in a case where management goals are focused on populations of cold water fish species, but stream temperatures exceed their thermal tolerances, goals may have to be adjusted to focus on warm water fish species. Many of the same tools mentioned in this section that provide a range of plausible alternative futures may be used to explore new ecosystem states and the potential management responses that might enable smooth transitions into more favorable states than may occur without management. The potential importance of shifting management targets and/or approaches underscores the importance of monitoring, reviewing, and revising adaptation plans at every step of plan development and implementation, as indicated in the center of Figure 8.

Advancing the Nation's Capability to Adapt to Changing Climate

It is certain that climate change will leave no system unaffected, but it is highly uncertain how those effects will be manifested. Thus it is imperative that we improve our knowledge, tools, and capabilities to respond in an adaptive way to future climate changes. Areas for improvement include (1) systems to detect climate changes and to monitor effectiveness of management options, (2) mechanisms to increase institutional flexibility and cooperation to enable more rapid management adjustments in scale and application, and (3) support for ongoing assessment of impacts and adaptation for continued improvement of adaptation practices, planning, and implementation. These needs are discussed in more detail in the next section.

Monitoring Systems

Observations of conditions and trends in ecological systems are essential for detecting and assessing responses to climate change; however, because land, water, and biodiversity monitoring systems were originally designed for other objectives, their utility for quantifying the effects of climate change is often limited. For example, state bioassessment programs have been established to assess the status and health of aquatic ecosystems by using monitoring results to compare high quality (or least impaired) sites with other sites to detect impairments. These programs have been shown to be inadequate for detecting climate change impacts because they are designed to detect differences among a population of streams rather than gradual, long term changes in the entire population. Meanwhile, climate observations are monitored largely independently of natural resource monitoring, and observations are often not collocated, resulting in the need to interpolate or downscale climate information for use in ecological studies. As an example, two types of observing systems are generally used to provide data on biological diversity: species or ecosystem-specific observing systems (such as the National Science Foundation's Long Term Ecological Research program that has established monitoring sites within specific ecosystem types such as grasslands, deserts, and forests) and spatially extensive observations derived from remotely-sensed data (such as the National Aeronautics and Space Administration's Moderate Resolution Imaging Spectroradiometer, or MODIS, that collects data on global dynamics and processes occurring on the land, in the oceans, and in the lower atmosphere). While multiple systems of both types exist, coverage has not been comprehensive across space, time, and species/ecosystems; furthermore, the capacity to maintain and expand these monitoring systems into the future is not assured. Continuous long-term data are needed to understand ecosystem responses to climate change.

In addition to detecting change, monitoring is also needed for adaptation planning and management. Availability of timely, accurate, and system-specific environmental data aids the ongoing process that is adaptive management, enlightening decision makers about responses of ecosystems and their components to management actions and enabling adjustments to those actions as necessary. Observing systems designed to detect climate-related changes support management assessments of key system sensitivities (or, as in Box 3, assessments of least sensitive, i.e., most resistant, areas). They can also be used to measure the efficacy of management actions by detecting, for example, whether climate-related sensitivities decrease after implementation of adaptation strategies (e.g., as called for in the "monitor and learn" step in Box 2). Observational programs to improve this type of monitoring could be achieved through a combination of overhauling and adjusting existing systems and creating new systems to effectively and accurately capture climate-related phenomena affecting ecosystems. More detailed observations at local scales could better detect subtle changes and would foster basic understanding of ecosystem health, as well as improved management insights and capabilities. Standard observations over large areas would complement these detailed observations and provide better knowledge of large-scale trends, information on spatial processes such as movement of invasive species, and insights into macroscale processes such as nutrient redistributions across systems. Efforts are underway at the U.S. Global Change Research Program to inventory established monitoring networks and assess the feasibility of adapting these networks to detect system responses to climate change.

Institutional Flexibility and Cooperation

In addition to effective observation systems, managers need their respective institutions to both support individual flexibility and cooperation, and be flexible and dynamic themselves. Ecosystem adaptation and mitigation strategies provide maximum benefit when managers and institutions coordinate different activities to address multiple impacts simultaneously, including climate impacts (see Box 1). In addition to institutional rigidity, another stumbling block to effective management can arise from incentive systems that reward the status quo while discouraging creative-but-risky ideas, which inhibits the development of innovative responses to emergent climate change risks. Organizational obstacles that delay or prevent implementation of adaptation actions can put valuable ecological resources at risk, rule out actions that require long lead times for implementation, and potentially trigger internal or external policy and regulatory actions to remedy inaction.

Many of these limitations can be overcome by, for example, building incentives that reward innovative ideas, creating guides for managers that outline strategies for climate change adaptation, and generating high-level priorities, policies, and planning procedures that encourage local-level strategies and management actions. Strengthening internal and external cooperation and cross-institutional ties is also crucial, as the ability of managers to preserve valued ecosystems and their services in the future may ultimately depend on flexibility in terms of setting priorities, managing for change, and managing simultaneously at various spatial and temporal scales. For example, as temperatures rise and climate impacts become more severe and potentially irreversible, enabling managers to re-examine priorities and shift to adaptation options that incorporate newly acquired information on thresholds and projected ecosystem changes will increase their ability to attain ecosystem management goals.

Expansion of interagency collaboration, integration, and lesson-sharing to support flexible decision making and agile management responses is more critical now than ever before. Fortunately, the U.S. has a history of achieving powerful responses to crises and national challenges. The nation's executive and congressional leadership have mandated new collaboration among agencies, extended existing authority for action, and successfully encouraged innovation to address climate change impacts. For example, the U.S. Fish and Wildlife Service hosts 22 Landscape Conservation Cooperatives (LCCs) that engage states, tribes, federal agencies, non-governmental organizations, universities, and other groups to develop the science and technical expertise to support conservation planning at landscape scales and to promote collaboration in defining and achieving conservation goals. Such collaborative responses will allow managers to address issues that extend beyond a single habitat, conservation area, or political/administrative unit, and beyond traditional agency-by-agency response mechanisms.

Need for Ongoing Assessment

Ongoing assessment of impacts, adaptation methods, and ecosystem responses is essential for continued improvement in adaptation planning and management to meet conservation goals. Existing management practices may not adequately address future anticipated ecosystem responses since the rate, type, direction, and extent of changes are highly uncertain. Through a process of ongoing distributed assessments, in contrast to centralized and periodic assessments, new observations and research findings may be rapidly incorporated to adjust existing management strategies, address unanticipated threats, and improve projections of future ecosystem responses.

In order for such ongoing assessments to produce useful information, models will need to be further refined and observational networks and experimentation capabilities will need to be expanded. With the establishment of a distributed assessment system – a network of experienced scientists, managers, and decision makers from across the country who participate in sustained and long-term interactions – integration of results from across sources can occur to inform research agendas and decision making.

Consideration and incorporation of results from ongoing assessments into adaptation planning processes may necessitate ongoing evaluations of organizational missions and strategic plans. For example, projected changes in ecosystem dynamics may alter current "optimal" allocation of resources embodied in existing strategic plans. Some federally managed systems already allow for strategic plans to change as new scientific information is considered. For example, the National Park Service (NPS) guidelines have historically provided flexibility regarding policy interpretation that has allowed advances in ecological knowledge to be incorporated into management guidelines. Over its 100-plus year history, the NPS has changed some practices based on this enhanced knowledge. One such practice, strict management of wildlife (e.g., species culling) has evolved over time based on consideration of new scientific information, resulting in some park managers opting to let natural processes control population numbers. Similarly, where active fire suppression was the norm in the Forest Service, consideration of new scientific results led to a shift to the current practice of prescriptive burns and natural fire management.

In support of furthering adaptation assessment at the national level, the White House Council on Environmental Quality initiated an Interagency Climate Change Adaptation Task Force, drawing on the expertise of more the 20 federal agencies. This group released an interim report recommending a variety of key components of a national strategy for climate change adaptation, including integration of science into adaptation decisions and policy, and coordination and communication across agencies and industry. The Task Force will be replaced with the Council on Climate Preparedness and Resilience (as per Executive Order 13653). This Council will continue the efforts of the Task force to address water resource management issues. It will also continue looking at ways to establish international cooperation on climate change adaptation schemes to build knowledge, harmonize efforts, and better support multilateral organizations and efforts around climate change mitigation, adaptation, and resilience building. While efforts to provide national-scale ecosystem management are under way and are essential to climate change adaptation efforts, administration of public lands and resources ultimately falls to local and regional authorities and requires specific local management and monitoring.

The U.S. Global Change Research Program has unveiled a strategic vision for ongoing assessment to increase our ability to adapt at all levels of management across the country (USGCRP, 2012). The program defines ongoing assessment as a commitment to a long-term, consistent, and ongoing process for evaluation of climate risks and opportunities to inform decision-making at multiple scales and for various systems. This will require the development of a sustained assessment capacity by the federal government in support of stakeholders and scientists across the country. It also requires increasing efficiency and leveraging existing federal science investments for impacts and adaptation research as well as distribution of lessons learned.

Conclusions

Climate change impacts are already being felt by the nation's ecosystems, and management adaptation is both needed and possible. Engaging in adaptation planning as early as possible will broaden the range of management options that can be employed, while waiting can result in foreclosure of options that require long lead times for organization or implementation, and could even increase adaptation costs. Fortunately, natural resource managers have a long history of dealing with extreme events and have well-developed tools that can be used for adaptation to new conditions. In addition, experimentation with new tools is also underway in the scientific and management communities.

For maximum benefit in the climate change context, traditional management tools may need to be applied in new ways. Climate change has spatial and temporal effects on environmental drivers of ecological systems, such as regional patterns of rainfall and temperature. Therefore managers may need to adjust their use of these tools in terms of when, where, and how they are applied, in order to maximize their effectiveness at maintaining management goals. For example, in using restoration as a management tool, it may not be enough to simply restore the same wetland to its previous condition, and in the same location. Rather, managers should consider whether there are other locations with features that will confer greater resistance to future climate change effects and whether there is a different composition of species that will be more tolerant of potential future conditions. The case studies that we have presented explore these types of ideas.

The case studies represent individual instances where early adopters, experimenting with adapting locally, have gone through a process of developing adaptation plans. Although no single case study reflects completion of every step of the generalized framework for adaptation planning presented in Figure 8 (as these were pioneer efforts), the combined wisdom generated by examining the efforts of many early adopters is leading toward convergence on similar supporting frameworks such as the one presented here. Managers can tailor the process to their particular management context, using existing information where available or new information generated when necessary. Despite the convergence of adaptation planning frameworks, uncertainty will always be an inherent part of making adaptation decisions. There is therefore a need to incorporate uncertainty and make robust choices, monitor to gauge the efficacy of those choices, adjust practices where necessary as new information comes in, and improve methods for addressing uncertainties.

Advancing the nation's capability to adapt to a changing climate will require overcoming numerous challenges. Climate change has brought renewed urgency to the already-acknowledged need for coherent and coordinated national-level ecological and climate monitoring systems. Consequently, there are a number of agencies and organizations striving to develop monitoring and observation systems that can detect climate changes and ecological responses. Improved monitoring networks will also be necessary to respond quickly to rapidly changing environmental conditions. Such unanticipated environmental outcomes in the face of climate change make flexible responses essential for both management and adaptation planning to maintain resilience of natural resources and ecosystems. Planning itself needs to occur at larger scales as well as local scales, making advances in cooperative planning and decision-making important. Currently, flexibility is somewhat limited at the national level because of the need to fulfill very specific mandates, but progress is being made as agencies are supported and encouraged to coordinate on research and strategic planning for climate change. Not only is such coordination increasingly occurring, but the federal government has made a commitment to provide the means to engage networks of local, regional, and national experts and decision makers to exchange information, lessons learned, and insights on impacts and adaptation. Information from such exchanges will provide the basis on which ongoing assessments are conducted to support adaptation decision making and inform national-level adaptation policies. Success will depend largely on the extent to which all of these efforts prepare us to address the formidable challenges posed by climate change, and the extent to which we continue to assess the success of adaptation planning efforts.

For Further Reading

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Acknowledgments

Funding for this project was provided by Purchase Order EP11H000073 from the U.S. Environmental Protection Agency to the Ecological Society of America. This article synthesizes information from the U.S. Climate Change Science Program (CCSP)'s Synthesis and Assessment Products 4.3 and 4.4, as well as the most recent 2013 External Review Draft National Climate Assessment. The views expressed in this report are those of the authors and do not necessarily reflect the views or policies of the U.S. Environmental Protection Agency.

About the Scientists

Susan H. Julius, Global Change Impacts and Adaptation Program (8601P), Office of Research and Development, U.S. Environmental Protection Agency, 1200 Pennsylvania Avenue NW, Washington, DC 20460

Jordan M. West, Global Change Impacts and Adaptation Program (8601P), Office of Research and Development, U.S. Environmental Protection Agency, 1200 Pennsylvania Avenue NW, Washington, DC 20460

Daniel Nover, AAAS Fellow, Global Change Impacts and Adaptation Program (8601P), Office of Research and Development, U.S. Environmental Protection Agency, 1200 Pennsylvania Avenue NW, Washington, DC 20460

Rachel Hauser, University Corporation for Atmospheric Research, P.O. Box 3000, 1850 Table Mesa Drive, Boulder, CO 80307

David S. Schimel, Jet Propulsion Laboratory M/S 233-300, 4800 Oak Grove Drive, Pasadena, CA 91109

Anthony C. Janetos, Pardee Center for the Study of the Longer-Range Future, Boston University, Boston University Pardee House, 67 Bay State Road, Boston, MA 02215

Margaret K. Walsh, Global Change Program Office, U.S. Department of Agriculture, 1400 Independence Avenue SW #4407, Washington, DC 20250

Peter Backlund, Integrated Science Program and External Relations, National Center for Atmospheric Research, PO Box 3000, Boulder, CO 80307

Layout

Bernie Taylor, Design and layout

About Issues in Ecology

Editor-in-Chief

Jill S. Baron, U.S. Geological Survey and Colorado State University, jill.baron@colostate.edu

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Ecological Society of America
1990 M Street NW, Suite 700
Washington, DC 20036
(202) 833-8773, esahq@esa.org