A New Era for Conservation:
Review of Climate Change Adaptation Literature

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EXECUTIVE SUMMARY

Natural resource managers and conservationists are coming to grips with the fact that rapid global warming and associated climate changes are already having a considerable impact on the world's ecological systems. More and larger shifts are expected, even in the best-case scenarios for greenhouse gas emissions reductions and future warming. These climate changes are ushering in a fundamental shift in natural resource management and conservation, to help natural systems withstand and adapt to new climate conditions.

This literature review summarizes recent science on climate change adaptation in the context of natural resource management and fish and wildlife conservation. The review was prepared as a background contribution to the *Adaptation 2009* conference being held February 2009 in Washington, DC, under the auspices of the National Council on Science and the Environment (NCSE) and National Wildlife Federation (NWF). The review starts with an overview of the concept of climate change adaptation, including overarching principles and barriers experienced to date in adaptation planning and implementation. We then provide specific examples of adaptation strategies for four broad habitat types: (1) forests; (2) grasslands and shrublands; (3) freshwater systems; and (4) coasts and estuaries.

The term "adaptation" has been used in the climate change community since the early 1990's, but no single definition has been generally adopted among conservation professionals. Most definitions offered in the literature in some way reflect that climate change adaptation involves "initiatives and measures designed to reduce the vulnerability of natural and human systems against actual or expected climate change effects." The term adaptation, however, is not yet well-understood by the general public in the context of climate change. In part the term has engendered confusion because the same word refers to the process by which organisms naturally adapt over time to survive in a new environment, even though the rapid rate of climate change is expected to outpace the capacity of many organisms to adapt in this classical sense.

U.S. natural resource managers and conservationists are accelerating their plans and actions for climate change adaptation, in large part because the magnitude and urgency of the problem has become increasingly apparent. Nonetheless, a number of factors continue to pose a challenge to adaptation planning and implementation. Among these are the limited availability of place-based information about future climate conditions, difficulty in planning in the face of uncertainty, and lack of credible management and policy options. In addition, inadequate funding and capacity combined with various institutional barriers remain as major challenges to moving forward. Progress is being made, however, as illustrated by the recent release of draft climate change adaptation strategies by the U.S. Department of the Interior and the U.S. Fish and Wildlife Service, as well as efforts underway in a number of states to explicitly address climate change in State Wildlife Action Plans.

Climate change adaptation measures identified in the literature generally address the following five overarching principles:

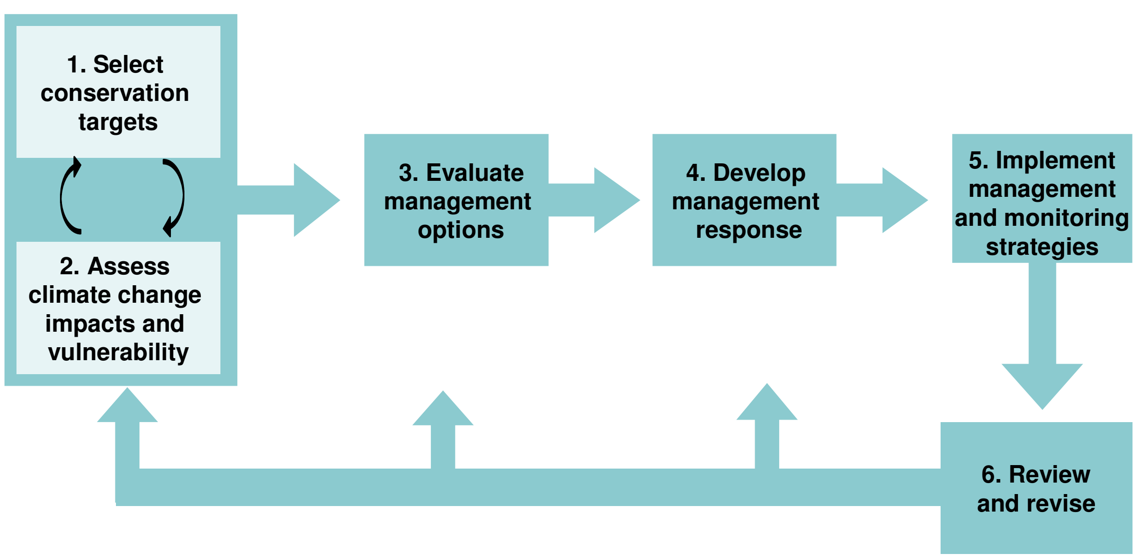
1. **Reduce other, non-climate stressors.** Addressing other conservation challenges—such as habitat destruction and fragmentation, pollution, and invasive species—will be critical

for improving the ability of natural systems to withstand or adapt to climate change. Reducing these stressors will increase the resilience of the systems, referring to the ability of a system to recover from a disturbance and return to a functional state.

2. **Manage for ecological function and protection of biological diversity.** Healthy, biologically diverse ecosystems will be better able to withstand some of the impacts of climate change. Ecosystem resilience can be enhanced by protecting biodiversity among different functional groups, among species within function groups, and variations within species and populations, in addition to species richness itself.
3. **Establish habitat buffer zones and wildlife corridors.** Improving habitat "connectivity" to facilitate species migration and range shifts in response to changing climate condition is an important adaptation strategy.
4. **Implement "proactive" management and restoration strategies.** Efforts that actively facilitate the ability of species, habitats and ecosystems to accommodate climate change—for example, beach renourishment, enhancing marsh accretion, planting climate-resistant species, and translocating species—may be necessary to protect highly valued species or ecosystems when other options are insufficient.
5. **Increase monitoring and facilitate management under uncertainty.** Because there will always be some uncertainty about future climate change impacts and the effectiveness of proposed management strategies, careful monitoring of ecosystem health coupled with management approaches that accommodate uncertainty will be required.

Putting these overarching principles into action will require that agencies identify conservation targets, consider their vulnerability, evaluate management options, and then develop and implement management and monitoring strategies. Based on our review of the literature, we offer the following conceptual framework for developing and implementing adaptation strategies (Figure 1). It is important to note that the development and implementation of a successful climate change adaptation strategy for natural resources will need to employ an iterative adaptive management approach, incorporate significant stakeholder engagement, and promote sharing of knowledge among conservation practitioners and other experts.

Figure 1. Framework for developing and implementing adaptations strategies



I. INTRODUCTION

Throughout the past century, we have made considerable investments in conservation. We have set aside lands as wilderness, parks, and refuges; worked to reduce air and water pollution; developed strategies to restore degraded forests, wetlands, and other habitats; and enacted measures to protect threatened and endangered species. To date, our approach to conservation has largely been from the perspective of restoring and protecting the natural systems we know (or have known) from problems associated with past or ongoing human activities – essentially, righting wrongs. Without these important efforts, many of our special places, fish, and wildlife species would likely be lost forever. Conservation traditionally has been about working to protect the existing condition of high quality places or restore degraded areas to some desired past condition. In the context of a changing climate, use of past condition as the benchmark and goal for conservation objectives is increasingly problematic.

For the most part, natural resources management has been implemented under the assumption that weather patterns, species and habitat ranges, and other environmental factors will (or should) remain consistent with historical trends. Today, however, this is no longer the case, with global warming looming as the greatest and most pervasive threat to the world's ecological systems. Given current trends, the environment in which the planet's living resources – humans, plants, and animals alike – will exist in the future will be vastly different from the one we have experienced over the past century during which our conservation traditions evolved.

Scientific evidence that our world is experiencing dramatic climate changes has been building at an astounding pace (IPCC, 2007a; CCSP, 2008b). In the United States, we are seeing a plethora of changes:

- Higher average air and water temperatures (both freshwater and marine);
- Increases in average annual precipitation in wetter regions (e.g., Northeast) and decreases in drier regions (e.g., Southwest), with an increasing proportion of precipitation falling in intense downpours;
- Lengthening of the frost-free season and earlier date of last-spring freeze;
- Declines in average Great Lakes ice cover and Arctic sea ice extent and thickness;
- More extreme heat waves;
- More extensive drought and wildfires, particularly in the West;
- Earlier spring snowmelt and a significant decline in average snowpack in the Rocky Mountains, Cascades, and Sierra Nevada ranges;
- Accelerating rate of sea-level rise and increased ocean acidity; and
- Increase in the intensity, duration, and destructiveness of hurricanes.

Furthermore, these physical changes associated with climate change are already having a significant biological impact across a broad range of natural systems. For example, across North America, plants are leafing out and blooming earlier; birds, butterflies, amphibians, and other wildlife are breeding or migrating earlier; and species are shifting ranges northward and to higher elevations (Parmesan and Galbraith, 2004; Parmesan and Yohe, 2003; Root, et al., 2003). Increased water temperatures in coral reefs in Southern Florida, the Caribbean, and Pacific Islands have contributed to unprecedented bleaching and disease outbreaks (Donner, Knutson, and Oppenheimer, 2006; Harvell, et al., 2007). Increased storm events, sea level rise, and saltwater intrusion have all led to a decline in coastal wetland habitats from the Atlantic Coast to the Gulf of Mexico (Janetos, et al., 2008; Kennedy, et al., 2002; Field, et al., 2001). Already-beleaguered salmon and steelhead from Northern California to the Pacific Northwest are now challenged by global warming induced alteration of habitat conditions throughout their complex life cycles (Glick and Martin, 2008; ISAB, 2007; Glick, 2005; Mantua and Francis, 2004). Forest and grassland systems throughout the West have been stressed by drought, catastrophic wildfires, insect outbreaks, and the expansion of invasive species (NSTC, 2008; Ryan, et al., 2008; Fischlin, et al., 2007).

These and other changes are bellwethers for what scientists project will be even more dramatic impacts in the decades to come, even if we achieve significant reductions in our emissions of heat-trapping greenhouse gases. Some studies suggest that parts of North America will experience complete biome shifts, whereby the composition and function of a region's ecological systems change (Fischlin, A., et al., 2007; Gonzalez, Neilson, and Drapek, 2005). For example, boreal forest vegetation is projected to continue its spread into Arctic tundra regions at northern latitudes and higher elevations, with its current southern range possibly converting to grassland or temperate forest. The southwestern U.S is expected to shift permanently to a more arid climate with even a modest amount of additional warming (Seager, et al., 2007; Solomon, et al., 2009)

Of particular concern is the potential for entire ecosystems to be disrupted. As diverse species respond to global warming in different ways, important inter-specific connections – such as between pollinators and the flowers they fertilize, or breeding birds and the insects on which they feed – will be broken (Root and Schneider, 2002). Decoupling of such relationships among species can have disastrous consequences. For example, research on the Edith's checkerspot butterfly (*Euphydryas editha*) in California revealed a climate-driven mismatch between caterpillar growth and the timing of its host plant drying up at the end of the season (Parmesan, 1996). Observations of the species in the southernmost portions of its range have shown that during periods of extreme drought, or in low snowpack years, caterpillar food plants were already half dry by the time the eggs hatched. This reduction in forage quality led to high extinction rates among those populations.

The ecological impacts associated with climate change do not exist in isolation, but combine with and exacerbate other stresses on our natural systems. Leading threats to biodiversity include habitat destruction, alteration of key ecological processes such as fire, the spread of harmful invasive species, and the emergence of new pathogens and diseases (Wilcove et al. 1998). The health and resilience of many of our natural systems are already seriously compromised by these "traditional" stressors and changes in climate will have the effect of increasing their impact, often in unpredictable ways. The loss and fragmentation of natural habitats due to the development of roads, buildings, and farms is especially worrisome because it hinders the ability of species to move across the landscape to track favorable climatic conditions (Ibañez, et al., 2006; Root and Schneider, 2002; Myers, 1992). The Intergovernmental Panel on Climate Change (IPCC) concluded in its most recent assessment of the science that as many as a million species of plants and animals around the world could be threatened with extinction between now and 2050 if we do not implement meaningful steps to address the problem (IPCC, 2007b).

II. CLIMATE CHANGE ADAPTATION: AN OVERVIEW

We must develop strategies *today* to help species and ecosystems cope with impacts that are already underway or are projected, as well as the potentially significant changes that may remain unforeseen. This will require looking at conservation through a different lens, one that acknowledges and addresses environmental problems of the past but also recognizes and prepares for those of the future. Waiting until the full brunt of climate change impacts is felt to act is not an effective option. Not only will such delay likely make our necessary responses more costly, but it may ultimately limit what options we might have to successfully meet our conservation goals (Easterling, Hurd, and Smith, 2004).

A. Definition

The application of climate change adaptation to conservation is still an emerging field, and as yet there is no universally accepted characterization for what it encompasses. Drawing on extensive scholarship within the climate change community, the fourth assessment of the IPPC (2007c) succinctly defines adaptation as “initiatives and measures designed to reduce the vulnerability of natural and human systems against actual or expected climate change effects,” and other reports on adaptation have adopted similar definitions (e.g., Perkins et al., 2007; CCSP, 2008a). Such actions may be intended to avoid, minimize, or even take advantage of current and projected climate changes and impacts. These actions may be anticipatory or reactive.

This general definition of climate change adaptation may need elaboration to better articulate its meaning in the context of conservation. Confusion arises in part because many management strategies that might be classified as part of adaptation are identical to well-established conservation approaches. Yet, it has long been recognized that “the threat of global warming calls for a new paradigm of resource planning, one which elaborates rather than replaces traditional planning approaches based on empirical analysis, economic efficiency, and environmental protection” (Riebsame, 1990).

The ecological meaning of the term adaptation also contributes to confusion over its application to climate change. From an ecological perspective, the term “adaptation,” refers to changes in an organism’s behavior, physiology, or other characteristics that enhance its survival in a new environment, while from an evolutionary perspective it refers to the development of novel traits and genetic changes that may result from natural selection. Certainly, changes in the timing of life cycle events (phenology) and shifts in range or habitat usage are evidence that at least some species are, indeed, already adapting to the changes underway. However, in an evolutionary context, the climate changes underway are occurring at an extraordinarily rapid pace, likely far outpacing the capacity of many organisms to adapt in the classic sense. In addition, many other human-induced stressors have reduced or eliminated their ability to do so. Consequently, as used in the climate change literature, the term perhaps more appropriately refers to “managed adaptation to climate change” (CCSP, 2008a; Adger, et al., 2007; Heinz Center, 2008).

In a recently completed survey of natural resource and conservation experts, participants were asked to articulate their definition of climate change adaptation for natural systems (Theoharides, et al., 2009). Although the responses varied, reflecting some of the confusion outlined here, there were common elements that led the authors to propose the following definition:

> ***Climate change adaptation for natural systems is a management strategy that involves identifying, preparing for, and responding to expected climate changes in order to promote ecological resilience, maintain ecological function, and provide the necessary elements to support biodiversity and sustainable ecosystem services.***

The term adaptation is still little understood by the broader public. As a result, a number of alternative terms are being used to refer to climate change adaptation, particularly in communicating with more general audiences. These include such phrases as "climate change safeguards," "coping mechanisms," "preparing for a warming world," and "protecting wildlife and natural resources from global warming."

B. Slow Progress on Developing Adaptation Strategies

The concept of managed adaptation to climate change is not new. Under the 1992 United Nations Framework Convention on Climate Change (UNFCCC), the founding international treaty to address global warming, both mitigation (i.e., the reduction of greenhouse gas emissions) and adaptation were considered to be priorities. In this context, adaptation measures focused particularly on funding strategies to address the impacts of climate change in developing countries. Peters (1992) suggested several concrete steps that natural resource managers could take to conserve biological diversity under climate change, from researching and monitoring species and community responses to climate change to developing regional plans for non-reserve habitat to accommodate changes in the location and abundance of critical habitat resources due to climate change. Even going back to 1989, the U.S. Environmental Protection Agency (EPA) offered policy recommendations to help the nation cope with the projected changes across a number of sectors, including forest management, agriculture, coastal management, biological diversity, water resources, electricity demand, air quality, human health, and urban infrastructure (EPA, 1989).

Over subsequent years there has been considerable attention to climate change adaptation in both scientific and popular publications. Heller and Zavaleta (2009) conducted a review of more than one hundred scientific papers focused on the issue of climate change in biodiversity management and identified 524 specific adaptation recommendations. Over the years much of the attention to climate change adaptation has been focused internationally, however, only in the past few years has the issue received significant consideration in U.S. natural resource conservation and management efforts. As recently as August 2007, the U.S. Government Accountability Office (GAO) concluded that, despite the overwhelming evidence that "U.S. federal resources within four principle ecosystem types are vulnerable to a wide range of effects from climate change," the federal agencies responsible for managing and protecting the nation's ecological resources [including the Bureau of Land Management (BLM), the U.S. Forest Service (USFS), the U.S. Fish and Wildlife Service (FWS), the National Oceanic and Atmospheric Administration (NOAA), and the National Park Service (NPS)] have not made climate change a priority, nor have they paid sufficient attention to addressing climate change in their management and planning efforts (GAO, 2007). Moreover, there are still few examples of specific, on-the-ground adaptation activities in practice (Heller and Zavaleta, 2009).

C. Overcoming Barriers to Climate Change Adaptation

Why have U.S. conservationists and natural resource managers been slow to embrace and plan for climate change adaptation? Perhaps most importantly, many sectors of U.S. society have been slow in recognizing the magnitude and severity of the threat posed by climate change. Although the scientific evidence for climate change and its ecological impacts has been growing over the past few decades, much of the public debate focused on whether global warming was real and if humans were responsible for it. Only recently has the focus shifted to how to respond to the threat. Furthermore, responses to climate change largely have been framed around efforts to reduce greenhouse gas emissions. Whatever complacency may have existed regarding society's ability to address the climate crisis through emission reductions alone was shattered by the Intergovernmental Panel on Climate Change's 2007 assessment, which concluded that even if greenhouse gas concentrations were to be stabilized, anthropogenic warming and sea-level rise would continue for centuries due to the timescales associated with climate processes and feedbacks (IPCC, 2007a). This report made clear that future conservation efforts will be taking place against the backdrop of a dramatically altered climate.

The relative lack of progress to date on climate change adaptation measures is also likely due to a number of informational, economic, institutional, and psychological barriers (Peters, 2008; CCSP, 2008b; CIG, 2007; Luers and Moser, 2006; Glick, et al., 2001). As resource managers and conservation practitioners grapple with how to plan for shifting climates, several issues in particular emerge as stumbling blocks: (1) lack of knowledge of climate change impacts at a scale relevant to decision making and difficulties envisioning "desired" future conditions; (2) difficulty in planning in the face of uncertainty; (3) lack of management and policy options for addressing vulnerabilities; (4) insufficient conservation resources; and (5) lack of political will.

One of the primary concerns that resource managers have expressed in terms of incorporating climate change into their respective activities is the perceived lack of sufficiently "downscaled" studies in terms of both localized projections of climatic changes and the potential responses of species and ecosystems to those changes. However, there have been considerable advances in model development in recent years including methods to downscale results from global climate models (GCMs) to a scale better suited for resource management decisions. Research on more regional and localized impacts of climate change is being conducted by the Regional Integrated Sciences and Assessments (RISA) program of NOAA, with the primary purpose of providing much-needed information on issues of concern to decision-makers and policy planners. There are currently nine funded RISA centers across the country, information for which can be found at http://www.climate.noaa.gov/cpo_pa/risa/. Some downscaled climate information is now accessible to relatively non-technical users. For example, The Nature Conservancy (TNC) has been working with scientists at the University of Washington and the University of Southern Mississippi to develop ClimateWizard, a web-based mapping tool that enables users to identify how climate is projected to change at specific geographic locations (http://faculty.washington.edu/girvetz/ClimateWizard/index.html).

Developing useful projections is related to another barrier for climate change adaptation in the context of conservation: identifying desired future conditions. Conservation traditionally has been based upon a paradigm of maintaining some existing desired condition, or restoring an area to a previous desired state. The prospect of rapid climate change upends this notion. Because species will respond in individualistic ways to changing climates, ecological communities will not migrate as intact units. Rather they will be subject to disaggregation and reassembly. In this process there will be biological winners and losers. Such considerations are causing conservationists and resource managers to grapple with disconcerting concepts such as triage or translocation of species. Managers responsible for particular places, such as individual National Wildlife Refuges, are faced with the prospect of the loss of the resources for which the area was originally established. Because most conservationists and wildlife managers are, by temperament or tradition, committed to preserving a semblance of past conditions, significant effort must be given to helping communities envision and work toward a new ecological future.

Planning in the face of uncertainty is always difficult, but managers attempting to develop appropriate and affective adaptation strategies are faced with multiple levels of uncertainty. Climate forecasts, ecological responses to those shifts in climate and often unpredictable synergistic effects with other stressors (e.g., human development patterns, emergence of new diseases and pests), and the effectiveness of proposed management responses all are associated with some uncertainty. Resource managers have always faced uncertainty in their work, and "adaptive management" (not to be confused with "managed adaptation to climate change" discussed above) is an extremely useful approach for operating in an uncertain environment. Nonetheless, the level of uncertainty related to the effects of climate change can be paralyzing for many practitioners. Work is needed to facilitate decision making based on climate projections despite the uncertainties.

Even if natural resource managers sincerely want to plan for climate change adaptation, they can be hindered by a lack of management options and a lack of resources for implementing those responses. Most currently available guidance is either at a very high-level strategy (e.g., maximize resilience), or can be characterized as calling for "more of the same." Although it is clear that adaptation will need to rely on many of our existing arsenal of conservation tools and approaches (including land acquisition and habitat restoration), there is also a very real need to determine how, where, and when these tools should be deployed – or redeployed – to respond to or anticipate projected climate change impacts. At the same time, the scope of the climate change adaptation challenge will likely require significant investments in capacity at federal, state, and local agencies.[1]

Finally, there are a number of institutional barriers, such as short planning horizons, reliance on historical trends to drive management decisions, as well as limited resources to meet

[1] Just how much it will cost to implement adaptation measures for natural resources is difficult to determine, as there are many factors at play (OECD, 2008). Estimates will vary considerably depending on the methodologies and assumptions used (e.g., how much future costs are discounted; whether and how non-market values are included; whether indirect or secondary effects are included; when specific actions are taken; and whether actions are proactive or reactive). In addition, there are likely to be wide variations among different sectors and within and across different regions.

our current conservation objectives, let alone tackle the growing challenges we face from climate change. Policies that serve as drivers for conservation and development will need to be reevaluated and revised to facilitate needed management responses.

While not insurmountable, many of these barriers continue to be a problem. Repetto (2008) cites several cases in the U.S. where institutional, informational, and political factors have prevented proactive measures to address climate-related problems, including hurricane damage, flood control, water supply management, and land and natural resource management. For example, following Hurricane Katrina, efforts of the U.S. Army Corps of Engineers (ACE) to build and rebuild levees still rely on historical data and the same construction standard that had failed. And despite the overwhelming scientific evidence that climate change will contribute to water scarcity in parts of the West, several key states have yet to consider climate change in their water management plans. The reasons include: "lack of consensus on impacts" (Arizona); a short (5-year) planning horizons (New Mexico); and a law requiring use of historical data in developing water forecasts (Texas). An important step in developing meaningful climate change adaptation plans must include efforts to identify and reduce these and other barriers (see Table 1).

Table 1. Overcoming Barriers to Climate Change Adaptation

Barriers	Solutions/Opportunities	Examples
Lack of knowledge of climate change impacts	• Organize workshops to engage scientists and managers on common issues; • Target research and monitoring programs to address climate change information needs; • Develop clearinghouses for sharing information.	• U.S. EPA's Climate Ready Estuaries Program: http://www.epa.gov/CRE/index.html. • FWS and USGS Coastal Management Workshop: http://www.fws.gov/pacific/climatechange/meetings/coastal.html. • Regional Integrated Sciences and Assessment centers:
Uncertainty	• Manage for uncertainty and change through adaptive management and scenario-based planning; • Focus on factors that promote resilience.	• NPS scenario planning (Welling, 2008). • TNC sea-level rise project in Albemarle-Pamlico Region of North Carolina (Pearsall and Poulter, 2005).
Limited conservation resources (funding and staff)	• Dedicate state and federal funding sources to climate change adaptation; • Train existing staff to tackle climate change issues within current job descriptions and management frameworks; • Re-evaluate priorities based on potential climate change impacts.	• Lieberman-Warner Climate Security Act of 2008: http://www.govtrack.us/congress/bill.xpd?bill=s110-3036&tab=related • NPS Climate Friendly Parks program: http://www.nps.gov/climatefriendlyparks/index.html.
Institutional barriers	• Lengthen planning horizons; • Encourage use of projections rather than reliance on historical trends; • Place greater emphasis on ecosystem services when	• CIG collaboration with Washington State's Watershed Planning Program: http://cses.washington.edu/cig/fpt/watershedplan.shtml. • Living Shorelines Stewardship Initiative, MD and VA (CSO, 2007).

	weighing decisions about structural vs. non-structural approaches; • Re-evaluate local, state, and federal environmental policies; • Expand inter-agency cooperation and public/private partnerships.	• Western Water Assessment evaluation of water law and water rights: http://wwa.colorado.edu/western_water_law/.
Political will	• Promote public education and grassroots mobilization; • Encourage leadership.	• National Wildlife Federation's hunter and angler outreach campaign: http://www.targetglobalwarming.org • Department of the Interior Task Force on Climate Change (DOI, 2008). • Governor of California Executive Order on sea-level rise adaptation: http://gov.ca.gov/executive-order/11036/
Primary Source: CCSP, 2008a.		

However, it does appear that the tide is turning, as both federal and state agencies responsible for the management and protection of the nation's natural resources, fish and wildlife have begun to develop more detailed strategies to incorporate climate change into their work. For example, a number of states are beginning to explicitly address climate change in their State Wildlife Action Plans (SWAP) (Joyce, Flather, and Koopman, 2008), and the U.S. Department of the Interior (DOI) and FWS have recently developed draft strategies to address climate change within their jurisdictions (DOI, 2008; FWS, 2008). Internationally, several countries have initiated climate change adaptation strategies specific to species and habitat conservation [e.g., the United Kingdom (Hossell, Briggs, and Hepburn, 2000), Italy (Carraro and Sgobbi, 2008), Australia (PMSEIC Independent Working Group, 2007) and Canada (Lemmen, et al., eds., 2008)]. A major impetus for this growing attention has most likely been the strength of the science and the compelling evidence that climate change is already affecting our natural systems, along with the groundswell of support for action among grassroots constituencies.

D. Overarching Principles

As the thinking about climate change adaptation for species and ecosystems has evolved over the past two decades, several overarching principles have emerged. In particular, scientists are increasingly emphasizing the concepts of maintaining or improving ecosystem *resistance* (the ability for a system to withstand a disturbance without significant loss of function) and *resilience* (the ability of a system to bounce back from a disturbance and return to a functional state) (Peters, 2008; Heinz, 2008; CCSP, 2008; Easterling, Hurd, and Smith, 2004; Hansen and Biringer, 2003). Of course, appropriate adaptation measures to maximize resistance and resilience to climate change will depend on how we define that "functional state" – in other words, it will depend on our particular conservation goal or goals. For example, our objective may be to restore and protect populations of a particular species or group of species. Or, we may want to ensure that a given ecosystem will continue to support sustainable levels of a natural resource such as timber or provide certain ecosystems services, such as clean water. These goals are not necessarily mutually exclusive, but they may require different strategies to achieve.

It will also be important to develop strategies that actually enable or facilitate the ability of a species or ecosystem to change in response to global warming, not just avoid or bounce back from the impacts. In all likelihood, measures to manage for change are going to be an increasingly significant part of our conservation agenda. Meeting conservation objectives in the face of climate change will require both the development of novel techniques and approaches, as well as the strategic use of our existing arsenal of conservation tools and techniques, such as creating buffers and wildlife corridors, conducting "proactive" restoration and management practices, and perhaps translocating species. Ultimately, the development of specific climate change adaptation strategies will require collaborative efforts across a multitude of fields and among numerous stakeholders.[2] While such strategies will vary considerably on a case-by-case basis, there are some general principles that will likely apply across the board:

1. **Reduce Other, Non-climate Stressors.**

Certainly, global climate change has emerged as our ultimate conservation challenge. However, its existence does not mean that we should downplay or ignore the many other major anthropogenic stressors we face (Inkley, et al., 2004; Hansen and Biringer, 2003; Root and Schneider, 2002). In fact, it is the combined effects of climate change and problems such as habitat fragmentation that ultimately pose the greatest threat to the world's natural systems and the fish, wildlife, and people that they support (Root and Schneider, 2002).

In some cases, dealing with existing, non-climate problems may well be our best conservation option in the near term. For example, for species that are already highly endangered, failure to reduce or eliminate immediate threats such as habitat destruction may lead to extinction before climate change becomes a significant factor. If our goal is to restore and protect these species for current and future generations, it may be necessary to continue to invest in remedial conservation measures such as captive breeding and maintenance of critical habitat reserves. That said, we must be mindful of the costs involved as well as the potential for climate change to reduce or eliminate the ability of these species to exist in their historic or current habitat range or conditions down the road. Ultimately, the threat of climate change may require us to re-prioritize which problems to address (Heinz, 2008).

The importance of reducing non-climate stressors to improve species and ecosystem resilience applies in other ways as well, especially given the fact that our ability to ameliorate some of the more direct impacts of climate change (such as higher air and water temperatures) may be exceedingly difficult, if not impossible. For example, while it may not be possible to prevent coral bleaching due to higher sea surface temperatures, many coral reef managers are working to enhance the resilience of coral reefs to major bleaching events by implementing measures to reduce other problems, such as land-based sources of pollution and harmful fishing

[2] It is important to note that, although in this report we do not go into extensive detail about adaptation measures directly related to human society (e.g., human health, urban infrastructure, and agriculture), it should not be viewed as a tradeoff. Rather, adaptation to climate change must take into consideration the important interconnections among humans and the natural world (Heinz, 2008). Failure to consider these interconnections can lead to perverse decisions, or what some call "maladaptation" (Easterling, Hurd, and Smith, 2004). Ultimately, we should place much greater emphasis on the multiple benefits of natural systems (including ecosystem services) that all too often are underplayed or ignored.

practices (Marshall and Schuttenberg, 2006; Grimsditch and Salm, 2005; Westmacott, et al., 2000).

2. Manage for Ecological Function and Protection of Biological Diversity.

Another common recommendation to improve ecosystem resilience to climate change is to place a greater emphasis on managing for ecological function and protection of biological diversity on multiple fronts. There is clear scientific evidence that "healthy," biologically diverse ecosystems will be better able to withstand some of the impacts of climate change (Kareiva, et al., 2008; Peters, 2008; Worm, et al., 2006; Folke, et al., 2004; Luck, Daily, and Ehrlich, 2003; Elmqvist, et al., 2003; Naeem, et al., 1999; Peterson, Allen, and Holling, 1998; Chapin, et al., 1997).

Kareiva, et al. (2008), cite several studies that show that diversity at many levels (i.e., among different functional groups, species within functional groups, and within species and populations of those species, in addition to species richness itself) is what is particularly critical for ecosystem resilience. For example, Luck, Daily, and Ehrlich (2003) suggest that the traditional measure of biodiversity loss, which is based on species extinction rates, understates the severity of the problem in that it fails to adequately reflect the importance of those species to the functioning of ecosystems. Rather, they recommend resource managers and conservationists expand the focus of efforts to protect biodiversity to include changes in the size, number, distribution, and genetic composition of populations and the implications of those changes for the functioning of ecosystems. This will prove a more effective tool to ensure that these systems will be as resilient as possible under climate change. Elmqvist, et al. (2003) expand on this by emphasizing the importance of maintaining "response diversity," defined as "the range of reactions to environmental change among species contributing to the same ecosystem function," to promote ecosystem resilience. An example of how consideration of ecosystem function among species can inform management decisions to deal with climate change can be found in the case of coral bleaching. Nyström, Folke, and Moberg (2000) have found, for example, that the presence of algae-grazing species of fish and invertebrates can help limit the overgrowth of harmful, opportunistic algae on reefs damaged by coral bleaching, facilitating their ability to recover. In a sense, managing for ecological function and biological diversity is like buying "natural climate insurance" (Mantua and Francis, 2004). Additional examples of this approach are given in the sector-specific discussions, below.

3. Establish Habitat Buffer Zones and Wildlife Corridors.

Improving habitat "connectivity" to facilitate species migration and range shifts in response to changing climate conditions is also considered to be an important adaptation strategy. A number of studies recommend the establishment of habitat buffers (i.e., restoring or protecting areas adjacent to current habitats) and wildlife corridors to reduce or prevent barriers such as urban development, roads, sea walls, and levees that might otherwise limit a species' ability to inhabit new areas. In addition, creating habitat buffers around current protected areas will help reduce the impacts of external stressors such as pollution, invasive species, and encroaching development. There are a number of tools that could be used, including expansion of protected areas, establishment of conservation easements, restoration of degraded habitat, and other measures.

Some of the earliest attention to the importance of creating habitat buffers and corridors as a response to climate change has occurred in the context of managing the nation's protected areas. In particular, there is significant concern that as species and habitats change, our existing portfolio of protected areas such as parks, wildlife refuges, and reserves will no longer be able to support many of the services for which they had originally been intended, especially the protection of fish and wildlife species (Peters, 1992). Several studies have assessed the likely effectiveness of protected areas to support given species under scenarios of climate change, largely based on model projections of whether and how far the species range is projected to shift.

For example, a study by Hannah, et al. (2007), looked at projected range changes for a number of plant and animal species, combined with an assessment of existing and potential suitable habitat areas (based on land use projections) in parts of Mexico, South Africa, and Western Europe. The results of their analysis suggest that, at least in the study areas, fixed protected areas alone will not be sufficient to protect biodiversity from the impacts of climate change. However, the likelihood of species conservation will be substantially improved with the creation of new protected areas, particularly if designed as a series of "networks" (Hannah, 2008). It is important to note, however, that not all species will be able to move, nor will those that can move do so at a comparable pace or distance (Hannah, 2008). As a result, the "new" protected areas are likely to be significantly different in both species and habitat composition.

The Western Governors' Association (WGA) recently established a Wildlife Corridors Initiative to help to protect the region's fish and wildlife from the impacts of climate change (in addition to those from energy development, land use and growth, and transportation and roads) (WGA, 2008a). The objectives of the initiative are to identify and map those areas across the West that represent "crucial wildlife habitat" (defined as "those lands and waters needed to conserve the broad array of wildlife that make the West unique") and "important wildlife corridors" (defined as "crucial habitats that provide connectivity over different time scales, including seasonal or longer, among areas used by animal and plant species"). An initial step in this effort is the establishment of a Western Wildlife Habitat Council (WWHC), which is charged with assessing the effects of climate change on wildlife and habitat throughout the region, and a Wildlife Adaptation Advisory Council (WAAC), which will help identify regional habitat priorities and assist decision makers in building a well-connected network of lands that includes consideration of climate change impacts in order to protect wildlife into the future.

As greater emphasis is placed on corridors as a possible climate change adaptation strategy, however, it will be important for managers to consider many factors that could determine whether or not they will be effective in achieving the desired conservation outcome, including the size of the landscape, the location, size, and habitat composition of the corridor, and the behaviors of the targeted species. In a review of recent studies of wildlife corridors, Haddad (2008) notes that there is still relatively little science to guide managers on how to design, implement, and assess corridors, underscoring the need to additional research and monitoring.

4. Implement Proactive Management and Restoration Strategies.

By "proactive" management and restoration, we refer to actions that resource managers and others can take to *actively* facilitate the ability of species, habitats, and ecosystems to accommodate climate change impacts. Examples include beach renourishment; placement of organic and/or inorganic materials to enhance marsh accretion; planting more climate-resistant plant species in forests, grasslands, shrublands, and wetlands that have been affected by major disturbances such as wildfires and coastal storms; and translocating species to new environments. Such strategies are likely to be applied in cases where the species and/or ecosystems are highly important from an ecological, economic, and/or cultural perspective, and where other options are not likely to offer sufficient protection against climate change.

Arguably, one of the most controversial issues regarding proactive management in response to climate change is the application of translocation and assisted colonization of species, whereby humans physically move a species from one location to another based on the likelihood that the latter location is likely to provide more optimal habitat conditions due to climate change (CCSP, 2008; Heinz, 2008; Hannah, 2008).[3] In principle, translocation of a species (such as through the dispersal of seeds) might be appropriate if the rate of climate change exceeds the rate at which a given species might naturally respond, or where problems such habitat fragmentation prevent its ability to move (Hunter, 2007; McLachlan, Hellmann, and Schwartz, 2007). In these cases, it might simply be a matter of helping nature along.

Translocating a species to a new area is likely to be a particularly important consideration in cases where the species in its current habitat range is highly vulnerable to extinction due to climate change (Hoegh-Guldberg, et al., 2008). This approach is already being implemented in the Southeastern U.S., where conservationists are planting seedlings of endangered Florida torreya (*Torreya taxifolia*), a conifer native to its namesake state, in areas of North Carolina (Marris, 2008). Another endangered species currently under consideration for translocation is the Quino checkerspot butterfly (*Euphydryas editha quino*), whose native habitat in California has been heavily fragmented by development. Research suggests that climate change will make the current habitat range increasingly unfavorable for the species, likely dooming it to extinction unless it is able to move to cooler areas (Parmesan, 1996; Biello, 2008). The likelihood that these types of projects will be successful will depend not only on whether the climatic variables in the target area will be favorable, but on whether the other habitat needs of the particular species can be met (e.g., food, shelter, existence of predators, etc.) (Fischer and Lindenmayer, 2000). Identifying these potential interactions will require significant research and monitoring.

The primary controversy surrounding translocation and assisted colonization stems largely from the risk that the newly relocated species will cause problems for the existing ecosystems, such as by out-competing native species for food and habitat (i.e., becoming "invasive") or by introducing new diseases or parasites (Hoegh-Guldberg, et al., 2008; Hunter,

[3] This has also been referred to as "assisted migration" in much of the literature, although Hunter (2007) suggests that this is a misleading term given that many ecologists use the term migration to mean seasonal, round-trip movements of animals. The purpose of translocation is to facilitate a permanent range shift outside of the historic range of the species, while assisted colonization refers to management efforts to help the species thrive in its new location.

2007). As has been the case with numerous exotic species that have been introduced into North America by human activities (either intentionally or unintentionally), it is difficult to know in advance how a species will ultimately interact with its new environment. While not all exotic species are invasive, those that are can cause tremendous problems for native fish and wildlife. It is important to note, however, that the majority of the most harmful invasive species have been introduced from far away places (e.g., from a different continent or isolated island) (Hoegh-Guldberg, et al., 2008). The relatively smaller scale at which translocation is being considered in response to climate change may reduce that risk, at least somewhat. That said, a secondary concern is the high rate of failure in existing translocation efforts, which makes the prospects for assisted colonization as a significant adaptation strategy somewhat dubious (Fischer and Lindenmayer, 2000).

5. Increase Monitoring and Facilitate Management Under Uncertainty.

As mentioned earlier, one of the primary barriers to climate change adaptation in the conservation arena has been concern about *uncertainty* in terms of both how our climate will change and how those changes will affect fish and wildlife species and their habitats (Repetto, 2008; GAO, 2007). Certainly, resource managers and other relevant decision makers need information about the more regional and localized consequences of climate change, as well as the vulnerability of species and ecosystems, in order to develop effective solutions.

As the science of climate change has progressed over the past few decades, our understanding of climate change as well as its impacts (both those that have already occurred as well as those that are projected for the future) has increased considerably. Significant improvements in downscaled climate models and research on impacts to natural systems and species already offer a tremendous amount of useful information, and investments in additional research will ensure that our body of knowledge will continue to grow.

However, by its very nature, there will always be some degree of uncertainty about how, when, and where climate change will affect natural systems. Increased monitoring and research on the known and potential impacts on species and habitats will help close the gap in knowledge, but we will never know exactly when and where we will experience the impacts. This does not mean we shouldn't act. Rather, the very fact that there is risk – and the potential for climate change to lead to irreversible damages, such as the extinction of species – necessitates precautionary action. It is prudent to consider actions we can take now that can reduce our vulnerability as well as how to incorporate useful measures of uncertainty into our decision making. Two tools that can help resource managers make decisions under uncertainty are adaptive management and scenario planning.

DOI defines adaptive management as "a systematic approach for improving resource management by learning from management outcomes," based on principles laid out by the National Research Council (Williams, Szaro, and Shapiro, 2007; NRC, 2004).[4] In principle, its purpose is to enable natural resource managers and other relevant decision-makers deal with uncertainty about future conditions by supporting the development of conservation projects

[4] It is important to recognize that "adaptive management" is not the same as "adaptation" to climate change. The former is just one management tool to achieve the latter.

based on available information and then providing the flexibility to modify their management activities to improve their effectiveness as new information becomes available. It is a concept that has been around for many years, and it has often been identified as a priority in resource management plans. However, it has seldom been effectively applied to date, due to factors such as insufficient long-term monitoring resources, unclear or conflicting conservation and management goals, political and institutional resistance to changing management practices, and/or inability to control a particular outcome through management (Johnson, 1999). With the growing attention to adaptive management as a tool to address climate change, resource managers will need to be mindful of its potential shortcomings (Brennan, 2008; Inkley, et al., 2004; Easterling, Hurd, and Smith, 2004).

Another approach to managing under uncertainty is scenario planning, a concept developed by Peterson, Cumming, and Carpenter (2003). They define scenario planning as "a systematic method for thinking creatively about possible complex and uncertain futures. The central idea of scenario planning is to consider a variety of possible futures that include many of the important uncertainties in the system rather than to focus on the accurate prediction of a single outcome." In this context, the scenarios are not predictions or forecasts but, rather, a set of *plausible* alternative future conditions. The approach entails several steps:

1. Identify a particular conservation issue or goal through a collaborative process (such as a series of workshops) among stakeholders;
2. Assess the issue in the broader ecological and social context, including likely external drivers (e.g., climate change, invasive species, likelihood of funding, etc.);
3. Identify alternative ways in which the system could evolve, focusing in particular on potential factors that are "uncontrollably uncertain" (e.g., changes in rainfall, as opposed to "controllable" factors such as development in floodplains);
4. Develop and test 3-4 plausible scenarios of future conditions (which could be based on modeled projections as well as expert opinion); and
5. Identify and test potential management or policy measures to see how they would fare under the different scenarios.

The National Park Service (NPS) has been conducting scenario planning to identify potential adaptation strategies for several of its parks (Welling, 2008). In November 2007, the agency held a Climate Change Scenario Planning Workshop for the Joshua Tree National Park. They chose three different climate scenarios from the IPCC and identified potential impacts to variables such as extent of native and non-native vegetation, the fire regime, and native animal species. For example, under a potential scenario of persistent and extensive drought, workshop participants identified the likely impacts to be loss of woody species, increased erosion, loss of vegetative cover, and dune formation. Based on this, several management options could be considered, such as relocation of high priority species to higher elevations. Welling (2008) suggests that the ultimate value of this tool may be in the process of engaging the stakeholders in substantive discussion of the issues.

E. Guidelines for Developing Adaptation Strategies

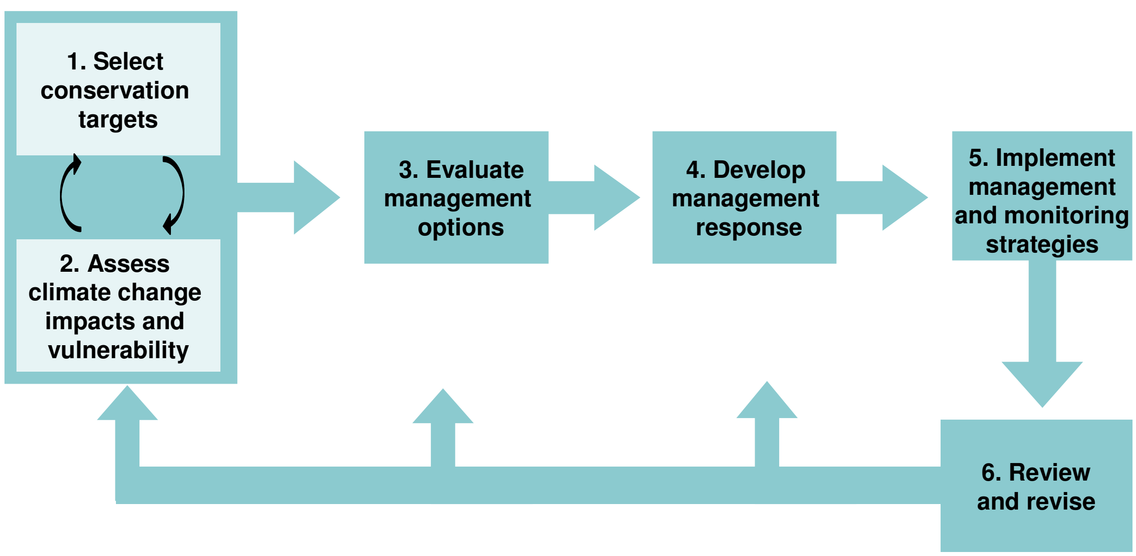
The definitive guidebook for developing adaptation strategies for natural resources management has yet to be written. Nonetheless, there are several resources to draw upon.

Significant thought has been given to developing adaptation strategies for urban areas and various sorts of infrastructure. Several of these strategies have been summarized in Perkins et al. (2008). Many of these are quite practical in terms of engaging the right experts, specific tools to use, and building stakeholder support (e.g., CIG, 2007; Bedsworth and Hanak, 2008; European Environment Agency, 2007). The conservation community also has a long history of engaging in systematic planning to meet defined conservation goals (e.g., Pressey et al. 1993; Groves 2003).

A few frameworks for merging adaptation strategies and conservation planning have been proposed recently. The Heinz Center presented a decision tree for natural resource managers that maps the process from selection of a conservation target through modeling potential climate impacts and finally the choice of appropriate adaptation strategies (Heinz, 2008). CCSP (2008a) compares conceptual models proposed by the climate community for adaptation generally with those already in use for managing natural resources. While the two approaches include similar elements—assessing impacts, determining vulnerability and the capacity to respond, evaluating response options, and developing management responses—they differ in the order of the steps. Heller and Zavaleta (2009) present the key steps in climate change adaptation planning for conserving biodiversity and how the steps relate to each other.

Here we propose a simple framework for merging the strategies developed from a climate adaptation perspective with those adaptive management strategies developed for natural resource conservation. A schematic is presented in Figure 1 and each step is discussed in more detail below. This framework draws on other previously proposed versions (e.g., CIG, 2007; Bedsworth and Hanak, 2008; European Environment Agency, 2007; Heinz, 2008; Groves 2003; Heller and Zavaleta, 2009). There are several elements that will feed into each step: an iterative approach, stakeholder engagement, and knowledge sharing.

Figure 1. Framework for developing and implementing adaptations strategies



Any successful natural resources adaptation strategy will need to be iterative, incorporating monitoring of indicators and progress toward conservation targets with opportunities to learn and adjust strategies as necessary. Given the uncertainties inherent when it comes to climate trends, such an adaptive management strategy will be more important than ever because of the inability to perfectly predict future climate conditions and the significant potential for unanticipated changes in the interactions among species.

At the same time, stakeholder engagement will play an even more important role in managing natural resources as climate changes. The conservation community will need to be prepared to make difficult choices among multiple competing conservation objectives that can not all be met given new climate realities. The input of stakeholders will be critical for making trade-offs that require consideration of moral considerations, cultural traditions, and local history in addition to the scientific and feasibility factors that typically inform such decisions.

Knowledge sharing among conservation practitioners as they develop new management strategies and between the conservation and climate change science communities will be essential if we are to meet the challenge of managing natural resources in the face of global warming. With so much new information available about how the climate is changing and options for conservation responses, networking and tools will be needed to facilitate information exchange among experts working in discrete locations.

1. Select Conservation Targets

Conservation efforts have historically begun with identifying a target or set of targets, such as the protection of a species, ecosystem, or specific location. This step will still be critical for conservation strategies in the face of climate change. The difference, however, will be that the conservation targets will need to account for climate trends. Some targets may no longer be achievable while other targets may become appropriate given new climate realities. As an example, restoration of submerged aquatic vegetation is a major conservation objective in the Chesapeake Bay region. This target will need to be re-evaluated as sea-level rise is expected to inundate some current areas of submerged aquatic vegetation and create other suitable areas.

The selection of the conservation targets will need to proceed in tandem with efforts to assess climate impacts and vulnerability. On one hand, information about climate trends and impacts will need to inform the identification of conservation targets. On the other, the choice of conservation targets and acceptable ranges of variation will define the scope of vulnerability assessments and the climate impact information required. Similarly, the outcome of vulnerability assessments will help to determine which species or habitats should be priority conservation targets. The range of possible targets includes species – rare and endangered, game, and non-game – as well as particular habitat types or ecological communities. Because many ecological assemblages will likely undergo disassembly under future climate scenarios as their component species differentially respond to changes, a combined strategy of targeting both species and habitats may be desirable.

2. Assess Climate Change Impacts and Vulnerability of Conservation Targets

For each conservation target, it will be necessary to use the best available information about current and projected climate impacts to assess vulnerability. Ideally, this exercise will consider a range of future climate scenarios, based on different assumptions about how much global warming pollution will be emitted over the coming decades as well as exploring the range of uncertainty about how the climate system and habitats will respond to warming. The vulnerability assessment should identify both critical threats to the conservation target and measurable indicators of the health of the species or ecosystem in question.

Vulnerability assessment is an active field of research, and a number of different approaches are in the process of being tested. The IPCC (2007b) has defined vulnerability as the degree to which a system is susceptible to, and unable to cope with, adverse effects of climate change, including climate variability and extremes. Vulnerability is a function of the character, magnitude, and rate of climate change, and variation to which a system is exposed, its sensitivity, and its adaptive capacity. In turn, adaptive capacity encompasses the ability of a system to adjust to climate change to moderate potential damages, to take advantage of opportunities, or to cope with the consequences.

3. Evaluate Management Options

Once the conservation target and its vulnerability to climate change have been identified, the various management options available should be evaluated. These options will include existing conservation tools, programs, and laws, as well as adaptation-specific options necessary to supplement where the available tools are insufficient. Several examples of potential adaptation strategies for four key ecosystems are provided in Section V. The evaluation of management options will need to consider the technical feasibility of potential solutions and the capacity to respond, along with the social, economic, political and cultural factors contributing to threats or representing opportunities.

4. Develop Management Responses

Drawing upon the evaluation of management options, a management response should be developed that modifies existing program and policies, supplementing with new strategies where needed. Risk management approaches and tools may be necessary because of the inherent uncertainty in climate projections and in the understanding of how effective various conservation strategies may be. It is important that uncertainty not be used as an excuse for inaction, but rather informs the necessary action.

5. Implement Management and Monitoring Strategies

Implementation of the management strategies will need to be accompanied by appropriate monitoring strategies to help determine the effectiveness of the conservation actions and track the status of key indicators. Education and outreach to key stakeholders will also be an important aspect of the implementation phase. In addition to management actions specifically designed to address climate adaptation, it will be important to incorporate climate change considerations into operational decision making.

6. Review and Revise

The regular review of each step that informed the development of the management strategy and appropriate revisions will be critical to success. Such an adaptive management approach is already common in conservation efforts, and will need to be even more central given that the underlying climate conditions are shifting. It is important to review the measured indicators, updates to climate projections, and the selection of the conservation target, as well as the effectiveness of the management strategies themselves.

III. SECTOR-SPECIFIC ADAPTATION STRATEGIES

A. Forests

Climate Change Impacts and Vulnerability Assessment Approaches

Climate change is already affecting forest systems across North America, and scientists project significant changes in forest composition, productivity, and extent (Shugart, Sedjo, and Sohngen, 2003). There have been a number of assessments to date on the impacts of climate change to forests, ranging from studies of past and projected changes across broad biogeographical ranges to more detailed studies of specific species and ecosystems. The U.S. Climate Change Science Program (CCSP) provides a summary of the literature in its recently-published report, *The Effects of Climate Change on Agriculture, Land Resources, Water Resources, and Biodiversity in the United States* (Ryan, et al., 2008).[5] The National Science and Technology Council (NSTC) also compiled a summary of the latest science, including forest impacts, in the *Scientific Assessment of the Effects of Global Change on the United States* (2008). And the National Assessment Synthesis Team report, *Climate Change Impacts on the United States*, provides a comprehensive overview of recent science on the impacts of climate change in the U.S., including a chapter on forests (Joyce, et al., 2001).

In general, the primary impacts of climate change on the nation's forests include the following:

- Higher average temperatures and shifts in precipitation patterns will contribute to a shift in the range of forest vegetation; ranges of tree species favoring cool climates, such as sugar maple, birch, and some sub-alpine conifers, are likely to shift north or to higher elevations, while oaks, hickory, pines in the east and ponderosa pine and arid woodlands in the west are projected to expand.
- Warmer average winter temperatures and a longer frost-free season are likely to contribute to an increase in the rate, intensity, and extent of invasive species, pest and disease outbreaks.
- Warmer springs and summer dry periods will contribute to an increase in the incidence and severity of wildfires.
- An increase in atmospheric concentrations of CO_2 may contribute to a general increase in forest productivity in the short term, likely to be outweighed by declines in water and mineral nutrients.

Significant changes to forest systems are already underway. A recent study of long-term data from unmanaged old growth forests in western North America has found that the rate of tree mortality across the region has increased considerably over the past few decades (van Mantgem, et al., 2009). This increase in death rates is attributed largely to regional warming and increased drought stress, rather than other factors such altered fire regimes and general aging of trees, as the changes are occurring across multiple elevations, tree sizes, species, and fire histories. Because new seedlings are not keeping pace, the authors suggest that many of the region's forests are likely to become sparser over time as these trends continue.

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[5] U.S. Climate Change Science Program (CCSP) reports are available at http://www.climatescience.gov.

There are many modeling and assessment tools and resources that can assist forest managers and other stakeholders in conducting vulnerability studies. Some of the most commonly-used models to project shifts in the range of vegetation (or other organisms) due to changes in climatic variables at relatively large regional or continental scales are the bioclimatic envelope models (also called niche-based models or biome models) (Botkin, et al., 2007). These models range in levels of complexity. Some of the more basic are static models that project vegetation changes under steady-state conditions (e.g., they relate the current distribution of a species to current climate conditions such as temperature and precipitation and then project a potential future range based on future climate conditions projected under climate change models). Basic bioclimatic models can be run using relatively little data and can provide useful as first approximations, but they do not capture important additional factors that will affect species' range and/or behavior under climate change (such as dispersal rates, interactions with other species, or the impacts of dynamic processes such) and thus are often considered to be overly simplistic (Botkin, et al., 2007).

There are also more complex dynamic global vegetation models (DGVM) available that can simulate more complex ecosystem processes (such as carbon dioxide uptake) and project potential changes in ecosystem structure and function. One such model is MC1, which is able to assess changes in the distribution pattern of vegetation as well as associated changes in carbon and nutrients (Bechelet, et al., 2001). Additional models that can project changes to individual species (e.g., forest gap models) and biodiversity of given areas (e.g., species richness prediction) are also in varying levels of development and use (Ibañez, et al., 2006; Hannah, Midgley, and Millar, 2002). The use of any of these models can assist forest managers in assessing vulnerability as well as identifying or prioritizing potential management approaches.

Potential Adaptation Strategies

Given the considerable diversity of the nation's forest systems as well as the multitude of services they provide, relevant adaptation strategies will necessarily vary significantly by region, type of forest, and the respective conservation goals (e.g., management for timber, species protection, provision of ecological services such as clean water, and even promoting carbon sequestration). In general, the actions recommended in the literature are consistent with the overarching principles discussed above, including the emphasis on promoting ecosystem resistance and resilience, as well as strategies to accommodate or facilitate change (Joyce, et al., 2008; Millar, Stephenson, and Stephens, 2007; Biringer, 2003).

1. Reduce Existing Stressors.

Efforts to reduce existing stressors are likely to lessen the vulnerability of forest ecosystems to more frequent and extreme disturbances such as droughts, wildfires, pests, and diseases. A number of problems plaguing the nation's forests, including habitat fragmentation, pollution, invasive species, and altered fire regimes, are likely to make it much more difficult for forest systems to withstand or recover from extreme events, and in some cases they may significantly exacerbate the impacts of climate change (Noss, 2001).

Wildfire management, in particular, is likely to warrant considerable attention as climate change contributes to longer fire seasons and an increase in the frequency and intensity of large wildfires. Fire is a natural and beneficial element of many forest ecosystems, but decades of fire suppression and harmful forest management practices such as clearcutting have made many of our forests unnaturally susceptible to catastrophic wildfires, particularly in the West (Kaufmann, Shlisky, and Marchand, 2005; Keane, et al., 2002). On top of the existing problems, wildfire frequency and severity are increasing because of rising temperatures, drying conditions, and more lightning brought by global warming. As a result, unnaturally intense wildfires have been occurring in systems that are not adapted to such disturbances (McKenzie, et al., 2004). A recent study of wildfire in the Western U.S., for example, found that there has been a four-fold increase in the number of major fires each year and a six-fold increase in the area of forest burned since 1986 compared to the period between 1970 and 1986 (Westerling, et al., 2006). These recent trends have occurred during a period when land use practices had not changed significantly from the period prior to the shift, which underscores the role that climate-related variables are playing in wildfire activity in the region. In addition, warmer average temperatures and drier conditions are projected to exacerbate outbreaks of harmful forest pests, including the mountain pine beetle (*Dendroctonus ponderosae*), which have already plagued many parts of western North America in recent years (Breshears, et al., 2005; Williams and Liebhold, 2002; Logan and Powell, 2001).

While the solutions are not cut-and-dry and will need to be customized for the given situation, scientists suggest that forest managers implement measures to reduce susceptibility to severe wildfires as well as develop new strategies to manage forests for altered fire regimes (Joyce, et al., 2008; CIG, 2007; Biringer, 2003). Noss (2001) recommends that forest managers take a mixed approach, including allowing many natural fires to burn, protecting old growth from stand-replacing fires, and managing other stands by prescribed burning and understory thinning. For National Forest system, Joyce, et al. (2008) recommend that the USFS incorporate climate change into the National Fire Plan to ensure that the agency can effectively achieve important conservation goals in an era of increased disturbances. Similarly, active strategies to address severe pest outbreaks (such as through prescribed burning or use of non-chemical pesticides) may be warranted (Biringer, 2003).

2. Promote Ecological Function and Biological Diversity.

Promoting ecological function and species diversity will be important for improving forest resiliency as well as ensuring the greatest opportunity for success in efforts to accommodate changes in forests due to climate change. Two well-established conservation approaches that are likely to be a useful tool for climate change adaptation in forest management are efforts focused on *representation* of all ecosystem types within a reserve, and *redundancy* of given ecosystem types across a broad geological range. Promoting representation is particularly useful given uncertainty about how specific forest types will respond to climate change, as some species or systems are likely to be more resistant or resilient to change than others (Biringer, 2003; Noss, 2001).

In addition, ensuring that there are multiple examples of similar (redundant) forest ecosystem types across a region will help reduce the risk of losing the ecological function those forests offer if some forest is altered or lost due to major disturbances or longer-term shifts in composition or range (Joyce, et al., 2008). It will also be important to identify and protect important keystone species within a forest ecosystem, to the best extent possible, to help maintain ecosystem function (Noss, 2001). These approaches can be considered in efforts to protect existing forests as well as efforts to restore or relocate forests through selected planting, etc.

Forest managers should also place greater attention to genetic diversity among replanted or newly planted species in forest restoration efforts (Joyce, et al., 2008; CIG, 2007; Noss, 2001). Traditional guidelines for reforestation have emphasized the use of local seed sources, primarily to reduce the risk of "contamination" of the forest with genotypes that are not adapted to that specific location's environment. While this is considered an appropriate approach under stable climatic conditions, the significant changes that we are now facing warrant a different strategy, including using seeds from multiple areas as well as placing added attention to genetic diversity of any give replanted species. Similarly, ensuring that there is diversity in age composition, the mix of forest species, and stand types should be a priority in both forest protection and restoration efforts (Biringer, 2003).

3. Establish Buffers and Corridors

Given the likelihood that many forest species (plants and animals) will shift their ranges in response to climate change, it is important to focus on increased habitat connectivity and establishment of buffer zones around protected areas to enable species movement. One of the first steps will be to identify those lands that are likely to be the best possible candidates to support new forest communities. As we highlighted above, there is a growing body of scientific studies as well as a suite of modeling tools to determine where and how forest species and ecosystems might change under different climate scenarios. Such studies can certainly help inform decisions about possible locations for protection. However, it will also be important to identify existing and proposed land use practices to determine potential barriers and/or opportunities. Successful strategies will require considerable cooperation across a multitude of stakeholders. Emphasis should be placed on developing public/private partnerships and providing incentives for landowners, particularly given the extent of land that may be necessary to support healthy forest ecosystems (Shugart, Sedjo, and Sohngen, 2003).

4. Implement Proactive Management and Restoration Strategies.

With the shifts in the ranges of forest species likely to be a major response to climate change, it might be possible to proactively assist such movements through restoration efforts. For example, forest managers may consider re-planting forests that have been damaged by extreme events such as a major wildfire with tree species that are more likely to thrive in projected climate change conditions. This may be especially valuable for cases where some forest species may not easily be able to naturally move to new areas due to habitat fragmentation or factors such as slow growth rates, inability to disperse seeds, etc. The modeling efforts discussed above can help identify some possible candidate species and locations.

The most extreme example of this approach is translocation of species to entirely new areas (e.g., the Florida torreya project). As mentioned previously, the identification of appropriate sites will need to consider multiple variables in the target area, including projected climate conditions, soil types, and potential interactions with other species. The optimal size of the new habitat area will also be an important factor to consider, since many forest systems require relatively large, intact areas to thrive (Noss, 2001). And since many tree species are slow growing, it might take considerable resources over a long period of time to achieve successful colonization.

5. Increase Monitoring and Facilitate Management Under Uncertainty

Ongoing monitoring of forest systems across the country will be critical to informing scientists, resource managers, and other stakeholders about the impacts of climate change, not just in terms of major disturbances such as wildfires and insect outbreaks, but also for more subtle, longer-term changes, including the sensitivity and response of forest species and ecosystems to climatic variability (Mote, et al., 2003). In addition, it will be important for forest managers to include both seasonal and long-term forecasts rather than rely on historic trends. In some cases, this may require institutional changes. For example, participants at the November 2006 *Climate Change and Federal Lands Workshop*, which was convened by the GAO in collaboration with the National Academies' Board on Atmospheric Sciences and Climate, identified current legislation that regulates the day-to-day management of the USFS as binding them to "backward-looking viewpoints" rather than allowing them to be proactive in addressing future threats (GAO, 2007).

Effectively dealing with climate change in forest management and protection will also require better incorporation of uncertainty and the potential for surprises. Joyce, et al., (2008) suggest that the development of management alternatives for adapting to climate change will require experiments or demonstration projects to explore their impact. Essentially, they recommend and adaptive management approach whereby new strategies such as translocating species should be established as small-scale pilot efforts to start.

Table 2. Summary of Potential Adaptation Strategies for Forests

Impacts	Examples of Adaptation Options
Shifts in composition and range of vegetation, associated species	• Reduce non-climate stressors such as habitat fragmentation to facilitate species movements; • Promote ecological function and diversity within and among species in forest protection and restoration efforts; • Consider translocation of species to new areas and replanting disturbed areas with less climate-sensitive species; • Expand monitoring to consider longer-term changes; • Promote forward-looking management and longer planning horizons.
Expansion of invasive species, pest and disease outbreaks	• Establish habitat buffers between known sources of invasive species and forest habitats; • Implement active strategies to address severe pest or disease outbreaks, such as prescribed burning and use of non-chemical pesticides.

Increased incidence and severity of wildfires	• Reform wildfire management to restore more natural fire regimes, such as through selective thinning, prescribed burning, protecting old-growth stands. • Consider future climate in selection of species for use in post-fire restoration
Changes in plant productivity due to higher CO_2 concentrations	• Research and monitor changes among different species; • Promote ecological function and diversity with and among species in forest protection and restoration efforts.

Case study: *Rogue River Basin, Southwest Oregon*

In 2008, researchers from the University of Oregon's Climate Leadership Initiative collaborated with the National Center for Conservation Science & Policy and the Mapped Atmosphere-Plant-Soil Study (MAPSS) Team of the USFS to identify the potential impacts of climate change on natural systems in the Rogue River Basin of Oregon as well as develop a targeted adaptation strategy (Doppelt, et al., 2008). Given that forest systems represent a significant area of the Rogue River Basin, much of this research and subsequent adaptation recommendations are applicable to forest management. The project was implemented in several stages:

1. Downscaled climate change and vegetation modeling.

Researchers downscaled three climate models and applied the global vegetation change model MC1 to project changes in temperature; precipitation and snowpack; storms, flooding, and drought; and wildfire across the entire Rogue Basin. The model results predicted how future conditions would affect the amount of carbon stored in vegetation as well as the amount of biomass consumed by fire. Results differ depending on the particular model used. Two models showing increased fires and biomass loss in the first half of this century followed by declining fire and increased vegetation carbon, while the third model shows increased fire early and late in the century, with increased carbon in mid-century. Model results also generally showed a dramatic shift in areas with climatic conditions suitable for various represented vegetation types (including forest species, grassland, and shrubland). With respect to forest species, two models project increasingly favorable conditions for warm maritime needleleaf and temperate deciduous broadleaf. All three models project significant declines in conditions for maritime evergreen needleleaf.

2. Expert-based assessment of impacts to aquatic and terrestrial species.

Based on the climate change projections, a panel of scientists and land managers identified the likely consequences for aquatic and terrestrial species in the Basin (based on expert opinion rather quantitative ecosystem assessments) and developed a suite of recommendations to prepare the region's natural systems for climate change. For example, the panel suggested that the projected increase in the intensity of wildfires fire and the length of the fire season is likely to be the primary driver of vegetation change across the region. In addition, if the region becomes hotter and drier, as projected, there is likely to be a decline in coniferous forest species and a possible expansion of deciduous forest, grassland, and shrubland species.

Several adaptation strategies were recommended to deal with the impacts of climate change to terrestrial species and systems, including:

- Reduce current stressors.
- Maintain forest resistance and resilience through strategic use of fire and fuels reduction.
- Protect remaining intact ecosystems.
- Maintain existing riparian forest connectivity.
- Identify and protect ecosystem services.
- Maintain biological diversity.
- Adjust timber harvest strategies.
- Adjust land use planning policy.
- Increase data collection, monitoring, flexibility and scientific integrity of land, water, and wildlife management.

3. Expert-based assessment of impacts to built, human, and economic systems.

In turn, a panel of policy experts identified the risks to built, human, and economic systems and recommended adaptation strategies for those systems. Forestry is an important sector for the regional economy. As reduced snowpack, rising temperatures, and the occurrence of drought dry out soils and make forests more susceptible to wildfires, the panelists expect forest product production to decline. The local industry is already undergoing transition, with greater attention to small diameter logs and fewer milling operations. The panel suggested that research efforts should focus on evaluating on how climate-induced changes in vegetation might impact this ongoing transition. The following adaptation strategies were recommended:

- Adjust forestry management practices.
- Carefully examine post-fire logging activities.
- Policies should integrate fuel reduction efforts with small scale biomass energy production.

The results of this project are considered to be just a first step. Ultimately, it will be up to organizations such as The Rogue Valley Council of Governments, municipal and county governments, federal and state agencies, and other relevant stakeholders will move forward with a more detailed strategy to help the region's forest systems (and other important resources) adapt to climate change.

B. Grasslands and Shrublands

Climate Change Impacts and Vulnerability Assessment Approaches

Native grasslands and shrublands across North America will be affected by climate change in multiple ways. Given the considerable diversity of ecosystem types and species represented by these lands (which range from chaparral shrublands in southern California, sagebrush shrublands and shrub-steppe habitats in the Northern Rocky Mountains and Pacific Northwest, and tundra in Alaska to the prairies of the Great Plains and scrublands in Florida) the impacts of climate change will be highly varied (NSTC, 2008). Several synopses of the recent scientific studies of climate change on grasslands and shrublands are available, including NSTC (2008) and Fischlin, et al.(2007). The following is a summary of some of the primary impacts noted in the literature:

- Changes in average temperatures and precipitation patterns, including increase in drought frequency in some areas and heavier precipitation in others, will contribute to natural shifts in the composition and range of vegetation;
- Warmer dryer conditions across the West will increase the frequency and severity of wildfires, which is likely to exacerbate the conversion of native grassland and shrubland habitats into monocultures of invasive, non-native plants.
- The impacts of increased atmospheric CO_2 on productivity in these systems is likely to be uncertain and non-linear given the significant differences in the response among diverse plant species.

The impacts of climate change are already apparent in some areas. In northern Alaska, for example, there has been a northward expansion of shrub tundra at the expense of sedge tundra, a change that scientists believe could significantly alter the regional energy balance (Hinzman, et al., 2005). Of particular concern is the potential for "feedback" effects as the greater area of shrub habitat in the region reduces the area of winter snowcover and enhances regional warming (i.e., a reduction in albedo). In addition, Archer, Schimel, and Holland (2004) found that the encroachment of trees and shrubs into grassland and savanna habitats in the Southwest are likely due to the interactions among several factors, including climate, higher atmospheric CO_2, altered fire regimes, and livestock grazing. Ultimately, it will be the combination of climate change and the many other stressors that are affecting grasslands and shrublands that will pose the greatest conservation challenge for these systems.

Many of the same modeling tools used to project changes to forest systems can be used for grassland and shrubland systems. However, given the significant concerns about multiple stressors, Galbraith, Smith, and Jones (2006) suggest that it will be especially important to take an approach that integrates the intersecting effects of all the important stressors. In a recent study for California, the authors combined estimations of changes in the spatial extents and distributions of vegetation community types (including rare coastal sage scrub) due to climate change with projections of future urban development patterns. They then analyzed the combined data sets to identify and quantify future vegetation community changes that could result from climate change, urbanization, or the combination of the two. They found that the relative influence of climate change and urbanization impacts varied among different community types. Climate change was likely to have a relatively greater impact than urbanization on some major communities such as chaparral, while future urbanization poses a particular threat to the now rare coastal sage scrub. For the latter habitat, however, the additional impact of climate change significantly increases the potential loss of these habitats in the study area. "Hybrid" studies such as this can help resource managers prioritize their conservation efforts.

Potential Adaptation Strategies

While the literature on climate change adaptation strategies specific to grasslands and shrublands has been relatively limited to date, some of the same overarching principles for forest systems are likely to apply for these systems as well.

1. Reduce Existing Stressors.

Many of the conservation efforts to reduce the non-climate stressors to grasslands and shrublands will be important to continue under a changing climate. What may differ in terms of adapting to climate change, however, is the prioritization of actions. As with forests, the diversity of the nation's grassland and shrubland habitats and the many services they provide mean that relevant adaptation strategies will vary significantly by region, type of habitat, and the particular conservation goals.

On public lands that are managed as rangeland, several recent studies suggest that management practices may need to change considerably not only to reduce the stress of grazing on systems weakened by drought or other disturbances, but also to optimize the ability of the rangeland to support livestock given likely changes in forage quality. For example, Chambers and Pellant (2008) propose that significant changes to Northwestern and Intermountain rangelands due to climate change warrant the need for increased flexibility in local and regional management plans and actions as well as more options for ranchers and land owners to make economically sound decisions. Similarly, a recent study by Morgan, et al (2008) of climate change impacts on Great Plains rangelands found that changes in the composition of plant species and altered fire regimes are likely to alter the abundance and quality of important forage plants. Accordingly, rangeland managers in the region may need to focus less on strategies that are based on past ecological knowledge and increase the use of tools such as "state-and-transition" models that enable agencies to prioritize areas that have the greatest degradation risk and recovery potential (Herrick, et al., 2004).

There is also a growing need to minimize and, more importantly, prevent the expansion of invasive species, as increased disturbances, higher average temperatures, and increased atmospheric CO_2 all are likely to exacerbate the problem (Gelbard, 2003). Prioritization will be important given the extent of the problem and the scarcity of resources to deal with it. Use of vegetation models and other tools can aid in the identification of areas that are likely to be at greatest risk of invasions (Aldridge, 2008). In addition, there are a number of studies that have identified invasive species that are likely to benefit from climate change (Zavaleta and Royval, 2002). In some areas, managers should implement targeted response plans to help prevent the expansion of invasive species after events such as major wildfires. This is likely to be particularly important for sagebrush-dominated habitats in the Great Basin, where significant wildfires in recent years have facilitated the invasion of non-native cheatgrass (*Bromus* *tectorum*), which germinates before native species. This has been a self-fulfilling prophesy, as the highly flammable cheatgrass communities contribute to even more severe wildfires (Young and Blank, 1995). This is not to say that wildfires are all bad. A number of grassland and shrubland systems have evolved to rely on "natural" fire regimes and have suffered from our history of fire suppression. For some systems, efforts to restore disturbances to a more natural pattern, such as through controlled burns, are likely to remain an important management strategy (Gelbard, 2003).

2. Promote Ecological Function and Biological Diversity.

Restoring and protecting the natural diversity of species and functional groups in grassland and shrubland systems will be important to maintaining their resilience to multiple stressors (Elmqvist, et al., 2003; Gelbard, 2003). For example, several experimental studies of grasslands systems have found that a decrease in grassland plant species richness increased ecosystem vulnerability to plant species invasions and fungal diseases and altered the abundance and diversity of associated insects (Mitchell, Tilman, and Groth, 2002; Knops, et al., 1999). Similarly, Dukes (2002) found that an increase on CO_2 concentrations contributed to much more rapid growth of the invasive species yellow starthistle (*Centaurea solstitialis*) in sites with monoculture grassland species than in sites higher grassland species richness. These studies suggest that efforts to protect or restore species richness of grassland systems may increase their resistance to invasive species and disease.

Research suggests that restoring heterogeneity to rangelands such as the tallgrass prairie of the Great Plains is likely to be an important strategy to improve the resilience of these systems to climate change. Fuhlendorf and Engle (2001) define heterogeneity in this context as variability in vegetation structure, composition, density, and biomass. In turn, this type of heterogeneity influences species diversity, habitat diversity, and ecosystem function. While many rangeland systems in the Great Plains evolved with disturbances such as fire and bison grazing, traditional rangeland management has been focused livestock production and promoting a few key forage species, which has led to much more homogeneous systems. This homogeneity, in turn, has made these systems much more vulnerable to disturbances such as widespread wildfires, which are different from the more patchwork-type burn patterns and associated grazing patterns that were typical of a more natural tallgrass prairie system. Increased droughts and wildfires due to climate change will exacerbate the problem. Active measures to restore habitat heterogeneity, such as through more selective livestock grazing practices prescribed burning, and even the reintroduction of native bison, have been offered as a possible strategy to improve the resiliency of these systems (Hamilton, 2008; Fuhlendorf and Engle, 2001; National Science Foundation, 1998).

3. Establish Habitat Buffers and Corridors.

As with other natural systems, protecting habitat buffers, enhancing habitat connectivity, and perhaps establishing wildlife corridors may be useful tools for climate change adaptation strategies in grassland and shrubland systems. For example, given the likelihood that climate change will increase the vulnerability of grasslands and shrublands to invasive species, creating buffers between these habitats known sources of invasives may provide some additional protection (Gelbard, 2003).

Many of the sagebrush habitats in Northern Rocky Mountains and Pacific Northwest have already been altered by habitat fragmentation, energy development, and other problems, making them particularly vulnerable to climate change. Researchers at Oregon State University (OSU) predict that climate change could reduce sagebrush lands in the Great Basin region to just 20 percent of its current area (Stauth, Neilson, and Bachelet, 2005). Only a few areas of sagebrush habitat in southern Wyoming, the northern edge of the Snake River plateau, and parts of Washington, Oregon, and Nevada are projected to remain. To protect important species such as greater sage-grouse (*Centrocercus urophasianus*) from the additional stressors associated with climate change, Aldridge, et al. (2008) suggest that it will be important to enhance the number and quality of sagebrush habitats and increase connectivity among those habitats through restoration efforts, while at the same time limit habitat fragmentation due to roads and other development. This might be particularly challenging in areas with a mosaic of public and private lands. Moreover, as climate change contributes to changing conditions, resource managers will need to be mindful that some areas that currently support native grassland and shrubland species may not be suitable over the long term. Accordingly, some of the habitats identified by the OSU study as likely to remain under projected climate conditions, so-called “refugia,” could be considered as priority areas for protection.

4. Implement Proactive Management and Restoration Activities.

Taking projected climate change impacts into consideration in grassland and shrubland management and restoration efforts may warrant proactive measures in anticipation of those changes. Some of the strategies are likely to be similar to those that forest managers may adopt. For example, after extreme events such as a major wildfire, resource managers might consider re-planting the disturbed grasslands or shrublands with plants that are more likely to thrive in projected climate change conditions. In the short-term, it may be sufficient to restore native species in the same area but at a life stage that is likely to be more resilient to extreme events. Suttle and Thomsen (2007) conducted a study of potential restoration strategies for California grasslands under different precipitation patterns that could occur with climate change. Specifically, they looked at how three different scenarios (including increased winter rainfall, increased spring rainfall, and ambient rainfall) affected the performance of three native perennial bunchgrass species in exotic-dominated stands. Results showed that the responses varied widely by the age class and species and depended heavily on the seasonal timing of the increase. In particular, they found that while establishment from seed was rare for all three native species under all scenarios, survival was high for transplanted plugs and tussocks in all scenarios, even with an increase in the production of the exotic species. These results suggest that the plants in these life stages are more likely to survive a range of climatic conditions and high densities of exotic annual grasses, and that restoration approaches focused on these life stages may be most robust to climate change.

Another potential option is translocation of species (which may involve relocating the grassland or shrubland vegetation itself or a specific wildlife species or group of species that those habitats support). Translocation has already been implemented as a management tool for greater sage-grouse, although the success rates to date have been low (Rowland, 2004; Reese and Connelly, 1997). While the reasons for the lack of success are not fully known, it is likely that, at least in some cases, unfavorable climate conditions may have been a contributing factor given the sensitivity of sage-grouse to severe droughts (Aldridge, et al., 2008). Ultimately, success of any translocation measure requires suitable habitat conditions (both short-term and long-term) in the target area, including climate. Use of climate change models to project future conditions will be an important tool for identifying appropriate sites.

5. Increase Monitoring and Facilitate Management Under Uncertainty.

As is the case with other ecosystems, increased monitoring and efforts to facilitate management under uncertainty will be critical elements of climate change adaptation for grasslands and shrublands. Specific attention to climate change impacts should be an explicit part of monitoring programs for these systems. Experts at the USDA-ARS Jornada Experimental Range in Las Cruces, New Mexico, have developed the *Monitoring Manual for Grassland, Shrubland, and Savanna Ecosystems*, which includes specific recommendations for monitoring climate-related factors (Herrick, et al., 2005). In addition, DOI has proposed the development of regional partnerships with other agencies and non-governmental organizations to build on existing biodiversity monitoring programs and adaptive management practices (DOI, 2008).

Table 3. Summary of Potential Adaptation Strategies for Grasslands and Shrublands

Impacts	Examples of Adaptation Options
Shifts in composition and range of vegetation, associated species	• Revise rangeland management to reduce stress of grazing on systems weakened by drought or disturbance; • Reduce non-climate stressors such as habitat fragmentation; • Restore and protect ecological function and diversity of grassland and shrubland systems; • Consider translocation of species to new areas and replanting disturbed areas with less climate-sensitive species;; • Identify and protect refugia.
Expansion of invasive species	• Establish habitat buffers between known sources of invasive species and grassland/shrubland habitats; • Implement more aggressive invasive species controls such as use of herbicides and controlled burns.
Increased incidence and severity of wildfires	• Reform wildfire management to restore more natural fire regimes. • Take future climate into consideration in selection of plant materials for post-fire restoration.
Changes in plant productivity due to higher CO_2 concentrations	• Research and monitor changes among different species; • Promote ecological function and diversity with and among species in forest protection and restoration efforts.

Case Study: ***Idaho Sage-grouse Conservation Plan***

The 2006 *Conservation Plan for the Greater Sage-grouse in Idaho* specifically identifies climate change as one of the 19 major threats to sage-grouse and their habitats and offers several specific conservation measures to address the problem (Idaho Sage-grouse Advisory Committee, 2006). In addition to recommending greater attention to long-term impacts and trends in current management actions, the plan emphasizes the importance of maintaining the resilience of sagebrush steppe vegetation as key to long-term success given the added stressors associated with climate change. Elements of the plan include the following:

Issue Addressed: Increase awareness of expected impacts of climate change.
Conservation Measures:
1. Support efforts by the Society for Range Management, and others to inform constituents of the seriousness of global climate change expectations.
2. Factor climate change needs and philosophy into current management of arid and semi-arid rangelands.

Issue Addressed: Maintenance of ecosystem resiliency.
Conservation Measures:
1. Avoid degradation of current vegetation communities.
2. Reduce pressure on the resource in periods of unusual climatic events such as drought.
3. Focus management of rangelands on restoration and resiliency of the vegetative resource.

Issue Addressed: Control exotic invasive species.
Conservation Measures:
1. Increase knowledge and awareness of invasive species problems on native ecosystems.
2. Reduce impacts of land uses that increase the rate of spread of invasive species.
3. Manage native plant communities to maintain biotic soil crusts (where appropriate), improve or maintain high vigor of native vegetation, and reduce use during periods when use favors invasive species ecologically.
4. Increase the pace of active control/elimination of invasive species in situations where other management is not capable of reducing the competition. Work closely with Cooperative Weed Management Areas/programs to control noxious and invasive weeds.

Issue Addressed: Restoration with suitable plant materials.
Conservation Measures:
1. Include seed from the warmer part of a species' range in mixes that are used to restore degraded sites.

C. Rivers, Streams, and Floodplains[6]

Climate Change Impacts and Vulnerability Assessment Approaches

Climate change will affect the nation's river and stream ecosystems in multiple ways, with significant implications for people, fish, and wildlife alike. Not only are our rivers and streams a critical source of freshwater to meet growing human demands, but they also support a diverse array of ecological processes, systems, and species. Accordingly, considerable scientific attention has been placed on determining the potential consequences of climate change on river and stream ecosystems across the country. Many of these studies have been summarized in broader overview reports, including Lettenmaier, et al. (2008); Poff, Brinson, and Day (2002); Jacobs, Adams, and Gleick (2001). While the specific impacts and responses will vary considerably among the diverse river and stream systems and species, in general, the primary impacts will include the following:

- Higher average air temperatures will translate into higher water temperatures in some areas, with multiple effects on temperature-dependent species.
- Changes in precipitation patterns, including more extreme weather events such as droughts and heavy downpours, will alter streamflows and flooding cycles.
- A reduction in average snowpack and earlier snowmelt runoff in many parts of the West will alter the timing of peak spring streamflows and reduce average streamflows in the summer.
- Changes in both temperatures and precipitation patterns will contribute to the expansion of invasive species in aquatic and riparian habitats.

Anticipating these changes today by taking climate change into consideration in long-term water resource management plans and other relevant decisions will enhance our ability to protect our river and stream ecosystems and the many benefits they provide.

Wider availability of spatially and temporally downscaled climate models have allowed for more localized projections on likely changes in temperatures and precipitation to a scale relevant for hydrological impact studies. However, the results can vary considerably depending on the particular models used, method of downscaling, quality of data, and other factors (Wilby, et al., 1997). In addition, the ability of GCMs to predict changes in precipitation patterns remains relatively uncertain compared to temperatures, making downscaled projections themselves more uncertain. For example, a study of potential climate change impacts on flood frequency by Prudhomme, Reynard, and Crooks (2002) found that uncertainties in rainfall projections from current generation of GCMs led to the development of less reliable rainfall scenarios for use in flood assessments. Nevertheless, the use of hydrological assessments based on downscaled climate projections is already proving to be an important tool for watershed planning under climate change. Scientists with the Climate Impacts Group (CIG) at the University of Washington, which is one of the national RISAs, are working with Washington State's

[6] In the interest of keeping the scope of this report relatively manageable, the conference organizers chose to focus specifically on rivers, streams, and floodplains (including riparian areas) rather than the more complete category of freshwater habitats that would also include lakes and wetlands. That said, we fully recognize that all of these systems are inextricably linked, and that climate change will affect them in numerous interrelated ways. Ultimately, the climate change impacts and adaptation approaches highlighted here should be viewed with that broader context in mind.

Watershed Planning Program to help locally-based watershed managers incorporate the effects of climate change, such as projected shifts in annual streamflow patterns, into their plans (http://cses.washington.edu/cig/fpt/watershedplan.shtml).

Potential Adaptation Strategies

The impacts of climate change on river and stream ecosystems are of particular concern in regions where water resources are already scarce and likely to become increasingly so due to higher demands associated with a growing human population (Palmer, et al., 2008). In addition, human alterations of river and stream ecosystems due to a number of factors, including the construction of dams, levees, and other structures; water diversions for agriculture; development in floodplains; destruction of riparian vegetation; and pollution, have significantly reduced their resistance and resilience to the impacts of climate change.

The multiple challenges facing our river and stream ecosystems call for a more holistic, long-term approach to managing and protecting our water resources. In particular, it will be necessary for water resource managers, watershed planners, conservationists, and other relevant stakeholders to incorporate future climate change projections into their decisions rather than continue to rely largely on historic trends assuming they will remain the same in the future (sometimes referred to as climate "stationarity") (Milly, et al., 2008). Wherever possible, we also should steer away from structural approaches to water resource and flood management and place greater attention on the ecosystem services provided by natural systems. Strategies such as promoting water conservation, restoring and protecting riparian vegetation and other habitat buffers, and replacing intensive agricultural practices in flood and drought prone areas with pasture and forests will provide a more intelligent, flexible approach to managing our rivers and streams under climate change (Glick, Inkley, and Tufts, 2001).

Several states across the country have started to incorporate climate change into their water plans. As one example, the California Department of Water Resources (DWR) recently completed an initial plan to develop a number of specific climate change adaptation strategies for water resource and flood management across the state (DWR, 2008). Specifically, the agency plans to develop and support collaborative actions to:

- Provide Sustainable Funding for Statewide and Integrated Regional Water Management;
- Fully Develop the Potential of Integrated Regional Water Management;
- Aggressively Increase Water Use Efficiency;
- Practice and Promote Integrated Flood Management;
- Enhance and Sustain Ecosystems;
- Expand Water Storage and Conjunctive Management of Surface and Groundwater Resources;
- Fix Delta Water Supply, Quality and Ecosystem Conditions;
- Preserve, Upgrade, and Increase Monitoring, Data Analysis and Management;
- Plan for and Adapt to Sea Level Rise; and
- Identify and Fund Focused Climate Change Impacts and Adaptation Research and Analysis.

In addition, the numerous state-driven climate change working groups across the country have included specific recommendations for climate change adaptation measures in water resources management within their respective states. The Florida Governor's Action Team on Energy & Climate Change, for example, has identified 15 specific goals for local, state, and regional actions to address climate change impacts related to water supply, water quality, flood protection, and natural systems protection (Center for Climate Studies, 2008). Similarly, the Colorado Climate Action Panel established 14 policy recommendations for water adaptation in that state (Colorado Climate Project, 2007). At the national level, the EPA has developed a strategy to respond to climate change in its National Water Program activities to meet clean water and wetland protection goals (EPA, 2008). FWS, as well, is in the process of developing strategies to help ensure that the needs of fish and wildlife are met as the nation moves forward with climate change adaptation strategies (FWS, 2008 Draft). Some of the strategies they are considering include acquiring key water rights and working with water management authorities to ensure instream flows.

While these and many other efforts across the country have laid an important foundation for the significant changes to water resource management that are necessary in an era of climate change, numerous institutional and political barriers exist that will likely make at least some of these changes difficult to achieve unless they are addressed. Perhaps the most notable barriers are ingrained in the long-standing paradigms of water law and water rights in the West. Partners with the Western Water Assessment have developed a project to explore and address some of the key challenges (http://wwa.colorado.edu/western_water_law/).

As with the other habitat categories covered in this report, we have organized the discussion of potential adaptation strategies for rivers, streams, and floodplains around the five overarching principles highlighted in section II.

1. Reduce Existing Stressors.

One of the primary challenges to protecting healthy river and stream ecosystems under climate change will be balancing the need to provide sufficient water resources for human activities and the need to maintain streamflows and protect water quality for fish and wildlife. For areas where water resources are already scarce, this challenge is not new – but the increasing enormity of the problem is. A major concern for much of the western U.S. is declining snowpack, which is the primary source of water supply for the region's rivers. Warmer winter temperatures have already contributed to substantial decline in snow accumulation across the West in recent decades (Pierce, et al., 2008). Further declines due to climate change could be devastating. For example, one study projects that climate change could lead to a 74 percent decline in average snowpack in the Sierra Nevada, a 51-percent decline in the Southern Rocky Mountains, and a 44-percent decline in the Pacific Northwest by 2025-2034, and as much as double those percentages by the end of this century (McCabe and Wolock, 1999). Barnett, et al. (2004) suggest that, "even with a conservative climate model, current demands on water resources in many parts of the West will not be met under plausible future climate conditions, much less the demands of a larger population and a larger economy." Some of the areas hardest hit will include the lower Colorado River Basin states, the Central Valley of California, the Columbia River system of the Pacific Northwest, and the Yakima River in Washington. Clearly, getting a better handle on human water consumption will be paramount. This should include actions to increase water-use efficiency and conservation among major users such as cities and farms and encourage greater use of seasonal and long-term projections for streamflows in water management decisions to more proactively protect and restore instream flows for fish habitat (Glick, 2005).

The concept of “integrated resource planning/management” (IRP/IRM) [e.g., Integrated Water Resource Management (IWRM), Integrated River Basin Management (IRBM), and Integrated Regional Water Management (IRWM)] has been suggested as a potentially useful climate change adaptation tool for water resources (DWR, 2008; Ray, et al., 2008; Bates, et al., 2008). The IPCC suggests several strategies necessary for successful IWRM: capturing society’s views; reshaping planning processes; coordinating land and water resources management; recognizing water quantity and quality linkages; conjunctive use of surface water and groundwater; protecting and restoring natural systems; and including consideration of climate change (Bates, et al., 2008). The proposed climate change adaptation strategies for water resources for both California and Colorado recommend placing greater attention to integrated resource planning as a long-term approach to address multiple stressors and achieve a variety of goals under uncertain conditions (DWR, 2008; Ray, Barsugli, and Averyt, 2008).

2. Promote Ecological Function and Biological Diversity.

In principle, a key element of IRP/IRM for water is the importance of restoring and protecting the ecological function of aquatic habitats at the watershed level, including placing greater attention on protecting habitat heterogeneity and biodiversity and restoring natural flow regimes (Combes, 2003; (Poff, et al., 1997). Ensuring that ecosystem and biodiversity protection is maintained as a priority in the development of climate change adaptation strategies will be necessary to reduce the likelihood of maladaptations such as erection of new dams for water storage.

This approach is likely to be increasingly important for the restoration and protection of threatened and endangered salmonids in the Pacific Northwest (Spence, 1996). Historically, the region’s salmonids have been incredibly resilient to environmental variability and change (Mantua and Francis, 2004). As different species, and populations within species, evolved over time, they acquired diverse spawning and migratory behaviors to take advantage of almost countless variations in temperatures, streamflow, ocean conditions, and other habitat features. This diversity provided a buffer against extreme events - if one population was devastated, behavioral and spatial diversity ensured other populations would be less at risk (Natural Research Council, 1996). Historic salmon abundance within populations also helped, making recovery from short-term damage more likely. Further, the natural habitats to which they have adapted offer physical features such as cool water pools, well-connected tributaries, and riparian shading (often called “refugia”), which help salmon survive periodic heat waves and other extremes.

As human activities over the past century have altered and destroyed habitat and led to declines in population abundances and species, we have significantly reduced that natural resilience. With the impacts of climate change likely to affect salmonids throughout their life cycles, restoring that resilience is all the more important. While the loss of wild salmonids has bolstered a significant management and recovery effort in the region, in general, strategies to protect the fish have been reactive rather than proactive, focusing on discrete problems once they have become critical and developing technological "fixes" such as building fish ladders and barging fish around dams, rather than looking at the problems from an ecosystem-based perspective (Lichatowich, 1999). Instead, we need to work to restore healthy habitat and healthy ecosystems by restoring and protecting the region's rivers to ensure a consistent supply of cold, clean water; ensuring reliable streamflows and obstacle-free passageways to allow adult fish to swim up rivers to spawn and help young fish make it to the ocean. It also means preserving genetic diversity, which maximizes species' ability to adapt to and survive in varying environments.

3. Establish Habitat Buffers and Corridors.

Also following on the concept of IRP/IRM is the need to restore and protect habitat buffers around rivers and streams, including riparian areas as well as natural floodplains. As many regions face the likelihood of heavier rainfall events, increased runoff and flooding will become even greater challenges to protecting river and stream habitats for fish and wildlife and the health and safety of people alike. In many areas where there is considerable urban and suburban development, improving stormwater management will be critical to meeting important goals to reduce eutrophication and other pollution problems as rivers carry excess nutrients and toxins downstream into lakes and coastal waters. For new developments and redevelopment projects, for example, greater emphasis should be placed on preventive measures employed through land-use planning, such as placing limits on areas of impervious surfaces, and requiring restoration and protection of natural buffers such as wetlands and riparian vegetation that can capture pollutants. These low-impact development (LID) measures are coming into widespread use in states and municipalities around the country, and are encouraged by the EPA as a cost-effective stormwater management approach (EPA, 2007).

Another important strategy that is gaining attention as climate change leads to greater extremes in precipitation is the need to revise flood management practices. Natural floodplains play an important role in river and stream ecosystems. Numerous species of plants and animals are adapted to the natural "pulses" of floodplain rivers – the regular annual or seasonal ebb and flow of floods. In addition, floodplains can trap sediments and pollutants, and natural floods can help build habitats such as sandbars and gravel beds. Unfortunately, human activities have vastly reduced the natural ecological services of our floodplain rivers. We have sought to control floods through levees and dams and used the newly acquired "dry land" for agriculture and urban development. Indeed, we have even encouraged development in areas at risk of flooding through incentives such as flood insurance via the NFIP of the Federal Emergency Management Agency (FEMA). Consequently, we are all too often left to fight nature rather than embrace it, to the detriment of human and natural communities. As the frequency and intensity of heavy downpours has increased due to climate change, the risk of major flooding events has grown (CCSP, 2008c). So, too, has the recognition that the nation's river and flood management needs to change. A seminal example is the recent National Marine Fisheries Service's Biological Opinion on the effects the NFIP on listed Puget Sound salmonids and Southern Resident killer whales (*Orcinus orca*) (NMFS, 2008). In the biological opinion, NMFS concluded that NFIP encourages harmful development and associated activities in floodplain habitats important to the listed salmonids, jeopardizing these species as well as the listed orcas that depend on them for food. An alternative approach laid out by NMFS would require development within floodplain and riparian buffer area be either prohibited or its impacts be completely mitigated, including requiring the use of LID.

4. Implement Proactive Management and Restoration Activities.

In some cases, protecting river and stream systems will require proactive management and restoration activities directly targeted to climate change impacts. For example, there are several strategies that may help lower water temperatures in an effort to protect cold-water fish such as salmon, steelhead, and trout. Across the U.S., higher average temperatures due to climate change are likely to translate directly warmer water temperatures for most rivers and streams (Eaton and Scheller, 1996). A number of non-climate stressors have already contributed to higher-than-normal river temperatures in some areas, such as the Columbia River and Snake River basins of the Pacific Northwest. Surface waters in reservoirs behind dams can get too warm when air temperatures rise (EPA, 2001). Deposition of sediments from logging, agricultural activities, and development has made some reaches wider and shallower, leading them to heat up more easily. Warm wastewater discharges from industrial sources along rivers have increased temperatures downstream. In addition, clearing of vegetation from riparian areas has eliminated shade that helps keep streams cooler. As a result, scientists already have identified human-caused warming of river temperatures as a key factor in the decline of salmonids populations in the region (Independent Scientific Advisory Board, 2007).

With many rivers already close to the upper thermal limit for salmon (very generally, about 70˚ Fahrenheit), additional warming due to climate change could be devastating. For example, Miles, et al. (2007) looked at a number of water quality stations in Washington and found that from 2001-2006, 15 percent of the stations studied registered a weekly maximum average temperature greater than 70˚ F. Under a climate change scenario of an additional 5˚ F increase in average regional air temperature, nearly half of those stations are projected to exceed this 70˚ F threshold, including all stations in the Columbia River basin.

Paradoxically, in already highly-managed river systems, management of reservoirs behind some dams may ultimately offer one of the few direct strategies to lower water temperatures downstream. A study by Yates, et al. (2008), for example, suggests that reservoirs such as that behind the Shasta Dam in the Sacramento River may provide a cold water supply to release downstream in an effort to counter the effects of climate change, at least at the lower range of projected temperature increase. However, this would require changes in operation that may be politically difficult to achieve given the alternative management objectives of flood control and meeting downstream demands. Some active restoration efforts, such as planting new vegetation and silvicultural options in riparian areas (as opposed to passive restoration, which entails allowing an area to recover naturally after removing factors causing degradation), also may offer opportunities to moderate water temperatures. Watanabe, et al. (2005), applied a state-of-the-art temperature model, WET-temp, to estimate the water temperature under various configurations of riparian vegetation in the Upper Grande Ronde River basin of northeastern Oregon. They found that the temperature benefits of passive restoration would be most appropriate when the time span considered is long and/or the magnitude of desired temperature reductions is small. The share of active restoration should be increased as the time span considered decreases and as the magnitude of desired temperature reduction increases.

5. Increase Monitoring and Facilitate Management Under Uncertainty.

According to Lettenmaier, et al. (2008), essentially no aspect of the current hydrologic observing system in the U.S. was designed for purposes of detecting climate change or its effects on the hydrologic cycle. Rather, they are either technologically obsolete, have non-compatible management accounting goals, or allow for significant data gaps, which make the current observation system insufficient to meet the management challenges brought by climate change. There also needs to be more monitoring of the climate sensitivity of species and ecosystems (Combes, 2003). In its recent assessment of climate change and water issues, the Western Governors' Association (WGA) recommends that the U.S. Geological Survey (USGS), in cooperation with states, significantly improve monitoring and data collection that a) focus on critical or vulnerable systems; b) deliver real-time data; c) improve data access, storage, and retrieval; d) allow for real-time smart analysis; and e) provide feedback and evaluation (WGA, 2008). Increased monitoring of both hydrological and ecological systems will be absolutely critical for effective, adaptive management of river and stream systems in an era of climate change. In addition, WGA recommends that states examine their existing water laws and institutions with an eye on increasing flexibility to deal with climate change impacts.

Table 4. Summary of Potential Adaptation Strategies for Rivers, Streams, and Floodplains

Impacts	Examples of Adaptation Options
Higher water temperatures	• Restore and protect natural streamflows and cold-water refugia; • Restore riparian vegetation; • Promote ecological function and diversity in species recovery and protection efforts; • Manage reservoirs to provide timely releases of cold water downstream; • Enhance temperature monitoring.
Altered streamflows and flooding; Reduced snowpack	• Incorporate climate change into water resource management, including ensuring that ecosystem and biodiversity protection is a priority; • Incorporate forward-looking assessments and longer time horizons in water resource planning. • Aggressively increase water use efficiency and conservation. • Discourage new development in natural floodplains, restore natural flood regimes. • Improve stormwater management, including increasing use of LID measures.
Expansion of invasive species	• Implement more aggressive invasive species controls, increase monitoring.

Case Study: ***Town Brook Restoration Project, Massachusetts***

The Massachusetts Department of Fish & Game (DFG) has become actively engaged in the development of climate change adaptation strategies for protecting the state's fish and wildlife species and their habitats. The agency is currently working with the Manomet Center for Conservation Sciences to integrate climate change into its Wildlife Action Plan (http://www.mass.gov/dfwele/climatechange.htm). The specific objectives of the Manomet project are to:

- Identify vulnerabilities of Massachusetts wildlife and wildlife habitats to climate change;
- Create an addendum to the action plan that updates its conservation strategies in the face of climate change scenarios;
- Develop a methodology for rapid assessment of climate change vulnerabilities of wildlife and habitat; and
- Establish a process and methodology that can be easily transferable to other states in New England and beyond.

At the same time, the state has embraced several general principles of climate change adaptation in its ongoing activities: preserving and expanding habitat connectivity; improving modeling, mapping, and data collection; and promoting sustainable water and stormwater management. One such activity is the Town Brook Restoration Project, which the agency cites as an example of Climate-Smart Restoration. The project is a public/private partnership between local, state, and federal agencies and non-governmental organizations to restore habitat and connectivity for both resident and anadromous cold water fish on Town Brook in Plymouth. The project entails a combination of selected dam removal, restoration of areas of natural stream bank, altering a culvert, and rebuilding a fish ladder. The goal of the project is to provide the fish with more natural flow regimes as well as cold-water refugia.

D. Coasts and Estuaries

Climate Change Impacts and Vulnerability Assessment Approaches

Coasts and estuaries are among the most vulnerable ecosystems in the nation to the impacts of climate change. There has been a considerable amount of research on the known and potential effects of sea-level rise, more-intense storm events, increased ocean temperatures, and altered freshwater flows into estuarine waters. Much of the scientific literature has been summarized in recent reports by the CCSP (Janetos, et al., 2008), the National Assessment Synthesis Team (Field, et al., 2001), the Pew Center on Global Climate Change (Kennedy, et al., 2002), and other major sources. A review of existing literature on impacts is an important first step in identifying the vulnerability of coasts and estuaries to climate change. In general, the impacts of climate change to coastal and estuarine systems include the following:

- Rising sea levels will increase erosion of beaches, cause saltwater intrusion into water supplies, inundate coastal marshes and other important habitats, and make coastal property more vulnerable to storms.
- More-extreme weather events, including intense rainfall, floods, droughts, and tropical storms, will alter freshwater flows into estuaries, exacerbate polluted runoff and water supply problems, and damage coastal habitats and property.
- Higher ocean temperatures will cause extensive coral bleaching, enhance marine diseases, alter species' ranges and population abundances, and harm fisheries.
- Higher ocean acidity will inhibit the ability of corals and other marine organisms to build up calcium carbonate, the substance that forms their protective skeletons.

Numerous modeling and assessment tools and resources also exist to assist coastal managers and other stakeholders in vulnerability studies. For example, there are a number of accessible tools to identify the potential impacts of sea level rise at multiple levels of complexity. Some of the most straightforward tools are the so-called "bathtub" models, which assess which coastal areas are likely to be inundated under various sea level rise scenarios based on coastal elevation. Researchers at the University of Arizona have developed an interactive website that provides users with an opportunity to view dynamic maps depicting inundation under multiple scenarios of sea level rise (available at: http://www.geo.arizona.edu/dgesl/research/other/climate_change_and_sea_level/sea_level_rise/sea_level_rise.htm). There are also a number of more complex statistical models that can identify some of the dynamic responses of coastal habitats such as wetlands in response to sea level rise (e.g., the Sea Level Affecting Marshes Model, or SLAMM, which is described at: http://www.warrenpinnacle.com/prof/SLAMM/index.html). Finally, several multidisciplinary support tools have been developed that can provide information on potential physical, ecological, and socio-economic impacts, typically at relatively large scales (e.g., the Dynamic Interactive Vulnerability Assessment Tool, or DIVA, at http://diva.demis.nl/). Models that identify current and potential land use changes, for example, will be especially useful to help identify those areas that might warrant specific protection to promote habitat/species migration, etc.

BOX 2. How Much Sea-Level Rise Should We Plan For?

This is a common question among coastal managers. Certainly, there are a lot of sea-level rise scenarios "out there." Some of the most widely used scenarios are from the IPCC, whose most recent estimates range from an additional 7 to 23 inch rise in global average sea level by the 2090s (IPCC, 2007a). There is compelling new evidence, however, that because these figures ignore the recent dynamic changes in Greenland and Antarctica ice flow, they significantly underestimate the rate of sea-level rise that we are likely to experience during this century (Otto-Bliesner, et al., 2006; Overpeck, et al., 2006; and Rignot and Kanagaratnam, 2006). Taking at least some of this accelerated melting into account, Rahmstorf (2007) suggests that a feasible range by 2100 might be 20 inches to 4.5 feet with a 9˚ F warming relative to 1990 levels. And a recent study by Grinsted, Moore, and Jevrejeva (2009) using a model based on the relationship of 2000 years of global temperatures and sea level suggests that the IPCC projections of sea-level rise by 2090-2099 are underestimated by a factor of three.

Ultimately, choosing which scenarios upon which to base climate change adaptation strategies will depend on how much risk we are willing to accept. When relatively little is at stake in the way of infrastructure investment or public inconvenience, we could choose to design for a conservative or low-end sea-level rise scenario. Where more is at stake, such as the decimation of habitats critical to a region's ecological and economic well-being, we should design for a mid-range or aggressive sea-level rise scenario. The bottom line, however, is that we may never know with certainty how much or how fast sea level will rise. This is where consideration of strategies to hedge against significant losses, such as by creating coastal habitat buffers, might be the optimal approach.

All of the available modeling and assessment tools have their own pluses and minuses. For example, bathtub-type assessments are relatively straight forward and low cost, and they can provide an excellent overall sense of the vulnerability of a coastal area to inundation and storm surges. They can be particularly useful as a public education tool. However, they are of limited use for more detailed assessments of impacts to specific habitats, species, and ecosystems. Some of the more sophisticated models, on the other hand, can provide coastal managers with important and useful information about vulnerability of specific habitats or ecosystems at relatively fine scales and levels of detail. For example, they may provide a more accurate projection of impacts by incorporating factors that affect *relative* rates of sea-level rise (the actual amount of sea-level change at a localized level based on both natural and human-influenced factors that affect land elevation, such as subsidence due groundwater withdrawals, sedimentation loss or gain, and rates of marsh accretion). They may also enable incorporation of projected land use changes that would influence the ability of habitats to migrate upland in response to rising sea levels (Li, et al., 2004). However, highly detailed assessments can require extensive amounts of data and computer capabilities and can be more costly and time consuming. In all cases, the levels of uncertainty in the results will depend on the resolution and quality of digital elevation data (CCSP, 2009).

Whether and how these tools might be used in the development of coastal adaptation strategies will vary for individual projects and programs based on already existing information, data availability, technical expertise, budget constraints, etc. Some areas will have more detailed information than others, and it will be important to invest in research and monitoring. It is also important to recognize that we cannot and need not wait until we have perfect information before develop strategies to cope with the impacts of climate change.

Potential Adaptation Strategies

Adaptation to sea level rise and other climate change impacts on coasts and estuaries has received considerable attention in the scientific literature as well as in practice. One of the reasons for this attention is the fact that an accelerating rate of sea-level rise is one of the most direct and certain effects of climate change, so it is relatively straightforward for stakeholders to understand. In addition, given the importance of coastal regions for human settlements and economic activities, risks to coastal property and to the services that coastal and estuarine ecosystems provide are of significant concern for people.

Recommendations to reduce the threat that sea-level rise, in particular, poses to both human and natural systems have been in development for two decades (e.g., Titus, et al., 1991, and others at http://yosemite.epa.gov/oar/GlobalWarming.nsf/content/ResourceCenterPublicationsSeaLevelRiseIndex.html). A number of coastal states have developed management strategies to directly and/or indirectly address the impacts of sea-level rise and coastal storms. Rubinoff, Vinhateiro, and Piecuch (2008) provide a detailed overview of specific state actions to date. What is striking about their findings is the fact that some of the most vulnerable coastal states only implicitly deal with the threat, primarily through hazard mitigation initiatives that are based in large part on historical trends. For example, while Louisiana's Coastal Program has long been dealing with a shrinking coastline (due to both sea-level rise and other anthropogenic stressors such as disruption of sedimentation and oil and gas development), there are currently no policies or initiatives specific to climate change. The same is true for Alabama, Alaska, Georgia, Hawaii, and Mississippi and it has only been in the past year that the State of Florida has officially begun to proactively address the problem. Nevertheless, a growing number of states have initiated or already developed coastal management strategies that specifically acknowledge and address the growing risks to coastal systems due to climate change. In 2008, the EPA established a new program called *Climate Ready Estuaries*, which is intended to build local ability to adapt to a number of impacts due to climate change. The program includes a web-accessible Coastal Toolkit that provides useful links to reports, coastal vulnerability and adaptation tools, data sources, and examples of on-the-ground adaptation activities in many coastal areas across the country (available at http://www.epa.gov/cre/toolkit.html).

As with other sectors, the identification of appropriate and effective adaptation measures will depend in large part on the relevant conservation goals. Given the extensive use of coastal areas for human settlements and activities, there will be tradeoffs between strategies aimed specifically at protecting coastal property and infrastructure and those aimed at protecting natural systems (Hanak and Moreno, 2008). However, it is important for coastal managers and other stakeholders to recognize that efforts to protect human uses of our coastal systems and those that will help maintain the important habitats they provide for fish and wildlife need not be mutually exclusive. The best approaches will be those that strive for multiple benefits, including ecosystem services, to avoid maladaptation (as described above).

A good example of the need to consider potential maladaptations is in the case of coastal protection from sea-level rise, whereby erection of armoring structures such as sea walls and bulkheads can protect property but is likely to lead to the destruction of coastal wetlands and other habitats by "sqeezing them" between rising seas and the hard structures (Titus, 2000). From a cost perspective, comparing the short-term construction cost of the sea walls with the potential loss of real estate value may make the armoring option seem like the economically optimal strategy (Adger, et al., 2007). Yet, there is evidence that coastal wetlands have considerable economic value in terms of hurricane protection, pollution control, and habitat for economically-important fish and wildlife species (Costanza, et al., 2008; Schuyt and Brander, 2004; Kazmierczak, 2001; Titus, et al., 1991). For example, a study by Costanza, et al. (2008), found that coastal wetlands in the U.S. provide $23.2 billion per year in storm protection services. Incorporating values for those and other quantifiable (and non-quantifiable) ecosystem services will likely point to alternative adaptation strategies such as managed retreat of coastal infrastructure in some areas as the optimal strategy for both people and wildlife (Sugiyama, Nicholls, and Vafeidis, 2008).

The following sections discuss potential adaptation strategies, with an emphasis on protecting coastal and estuarine habitats, fish, and wildlife species. Again, we have organized the potential strategies in the context of the overarching principles of adaptation.

1. Reduce Existing Stressors.

Numerous existing anthropogenic stressors, including coastal development, polluted runoff, groundwater withdrawal, altered river flows, and other problems, have significantly reduced the resilience and increased the vulnerability of coastal and estuarine systems to climate change. Identifying and prioritizing efforts to address these stressors should be an important part of coastal adaptation strategies.

For example, there are several activities that can contribute to higher relative sea-level rise in some areas by causing unnatural land subsidence or reducing sediment loads from upriver or other coastal sources (Twilley, 2007). Perhaps the most well-known region facing this problem is coastal Louisiana, where drainage of wetlands for agricultural use and development have contributed to subsidence of soils and reduced land elevations in some areas to below current sea level. In addition, the construction of dredged canals and levees for flood control, facilitation of oil and gas development, and boat navigation have starved the delta region of natural sediments from the Mississippi River and enabled saltwater to intrude into brackish and freshwater wetlands (USGS, http://pubs.usgs.gov/fs/la-wetlands/). These problems have made coastal wetlands and other important habitats all the more vulnerable to the impacts of storm events and sea-level rise. Efforts to restore more natural hydrological and geomorphic processes may enable coastal wetlands in the region accommodate some sea level rise by building soils (a process called "accretion") (DOI, 2008; Twilley, 2007).[7] Given the potentially significant cost of

[7] Wetlands may naturally be able to keep pace with sea-level rise through accretion (the build-up of organic and/or inorganic matter). Studies have shown that, in general, if the elevation of a marsh is low relative to sea-level rise,

the large-scale restoration measures required, however, it will be prudent for coastal managers to consider projected sea-level rise and other climate and non-climate stressors in the development of relevant projects.

For many of the nation's major estuaries, reduced water quality due to polluted runoff from rivers into coastal waters has been a longstanding problem. In the Chesapeake Bay, for example, runoff of excess nitrogen and phosphorus from sources such as agricultural fertilizers, sewage discharges, and septic tanks has contributed to excessive algae growth that contributes to depletion of oxygen in affected waters, conditions called hypoxia (low-oxygen events) and anoxia (when all oxygen in an area is depleted). Unless greater efforts are made in the region to reduce these excess nutrients, such as through improved stormwater management and LID, the problem is likely to significantly worsen with global warming (CCSP, 2008a; Hanak and Mareno, 2008; DOI, 2008). Heavier runoff associated with more extreme storm events flush greater amounts of pollutants into the estuary (Hayhoe, 2007; Howarth, 2006; Hayhoe, 2007). Excess freshwater flow may also decrease water mixing as less dense fresher water rides over the top of the denser saltier water, inhibiting the mixing of water and inhibiting the replenishment of oxygen in deep waters. In addition, higher water temperatures will affect oxygen levels because warm water holds less dissolved oxygen than cooler water does. For each degree Fahrenheit in temperature increase, the water's ability to dissolve oxygen decreases by about one percent (Najjar, et al., 2000).

2. Promote Ecological Function and Biological Diversity.

Managing coastal and estuarine systems to promote ecological function as well as biological diversity have been identified as critical approaches to improving the resiliency of these systems to climate change (Peterson, et al., 2008). Worm, et al. (2006) conducted an extensive analysis of coastal and marine ecosystems to determine whether and how the continuing decline in fish and wildlife species and populations associated with human activities might be affecting ocean ecosystem functions and services. They found, overall, that the loss of marine biodiversity is significantly reducing the ability of marine systems to recover from disturbances such as storms and thermal stress. Conversely, areas in which native species richness has been maintained or improved (through measures such as marine reserves, sustainable fisheries management, and critical habitat protection) show a significant increase in productivity and a reduction in variability. The growing emphasis on habitat protection and ecosystem-based approaches to managing fisheries and other coastal resources in the U.S. over the past decade has set an important foundation on which to deal with the multitude of stressors that are affecting them (Fluharty, 2005). To be successful, however, such efforts must explicitly take climate change into consideration (Peterson, et al. 2008). One strategy that is likely to be increasingly important is the establishment of marine protected areas (MPAs), with an emphasis on protecting species diversity and connectivity within and between designated areas.

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frequent inundation by tides can provide sediments and nutrients that facilitate accretion. Conversely, when a marsh is high relative to sea-level, the tidal influence and sedimentation rate declines (Working Group on Sea-Level Rise and Wetland Systems; Nyman, et al., 1993). A number of external factors can alter this dynamic, including changes in freshwater flows, restrictions to natural sedimentation, invasive species, etc. In addition, there is concern that, as the rate of sea-level rise accelerates due to global warming, even wetlands whose accretion ability has not been altered by these other factors may not be able to keep pace (Morris, et al., 2002).

In addition, studies show that natural systems such as coastal wetlands, barrier islands, dunes, and reefs are often more effective (and reliable) at supporting important ecosystem services such as protecting coasts from erosion and flooding than the engineered systems (e.g., dikes, levees, and sea walls) that have characterized much of the nation's coastal management to date (Costanza, et al., 2008; Hanak and Moreno, 2008; NRC, 2006). The devastating destruction in New Orleans that resulted from broken levees during Hurricane Katrina in 2005 is a striking (and tragic) example that such structures are not fail-proof in protecting coastal communities. Where possible, efforts to re-establish protective habitats, such as re-vegetating dunes, should be a priority in coastal restoration projects. One strategy that receiving growing attention is the development of "living shorelines," which involve the use of natural elements such as wetlands and riparian vegetation to provide wave protection, as an alternative to hard structures (Hanak and Moreno, 2008). The states of Maryland and Virginia, for example, are promoting the approach among coastal property owners through the Living Shorelines Stewardship Initiative, a public private partnership that provides technical and financial assistance, demonstration projects, training, and outreach (CSO, 2007).

3. Establish Coastal Buffers and Corridors.

One of the most frequently recommended strategies for protecting coastal habitats and ecosystems from sea-level rise, storms, and other climate change impacts is the establishment of coastal habitat buffers – upland areas into which coastal habitats and associated species can move. For example, studies have shown that come coastal wetlands may be able to accommodate moderate changes in sea level by migrating inland if conditions in the newly established areas are favorable (e.g., soil type, frequency of inundation, and salinity) and there are no physical barriers due to development (Walker, Smith, and Whelan, 2003; Ross, et al., 2000).

The primary tools for establishing buffers are associated with land-use planning. In particular, governments at the local, state, and federal levels must develop and implement adaptation policies and strategies that discourage development in vulnerable areas and support efforts to site structures farther inland of shorelines. This is essential not only to help reduce the serious risks to human safety and well being of communities, but also to ensure the preservation of beaches, dunes, and other natural coastal habitats that are important to our nation's economy and quality of life. A number of strategies are possible, including: rolling easements; targeted coastal land acquisition; tax incentives for landward relocation of development; transfer of development rights; conservation easements; buyouts; stricter setbacks; restrictions on rebuilding after storm destruction; revisions to the National Flood Insurance Program (NFIP); and other policies. The concept of a "rolling easement," for example, has been developed to allow private landowners to develop shorefront property but prohibit them from constructing bulkheads or other armoring against coastal erosion (Titus, 1998). Ownership of portions of the property would then revert to the easement purchaser (i.e., it would "roll" landward) if those areas become inundated by sea-level rise. The Texas Open Beaches Act is essentially a rolling easement, whereby the owners of property within in the easement must remove any structures that end up seaward of a defined "vegetation line" after a major storm event or erosion (Levina, et al., 2007). The cost of purchasing such easements is likely to be significantly lower than outright land purchases or acquisition of development rights (Titus, 1998). Rubinoff, Vinhateiro, and Piecuch

(2008) provide a summary of this ane a number of other actions being implemented in coastal states across the country.

4. Implement Proactive Management and Restoration

In some cases, the best option to protect important coastal and estuarine species and ecosystems from climate change will be to implement proactive management and restoration activities. In many coastal areas where beaches are highly valued for recreation and tourism, a long-standing approach to dealing with erosion has been beach re-nourishment, which involves the repeated use of dredged materials to replace lost sand. While such projects can help maintain some of the economic benefits of beaches, including recreational use and protection of coastal property, there is considerable evidence that it can diminish important fish and wildlife habitat by burying shallow reefs, temporarily depressing sea turtle nesting, and reducing densities of invertebrate prey for shorebirds, surf fishes, and crabs (Peterson and Bishop, 2005). Accordingly, it will be important to establish and enforce rigorous environmental standards to ensure that the projects are ecologically sound. In addition, it is becoming increasingly difficult to find sources of beach-quality sand in some areas, and the costs of re-nourishment and locating distant sand sources are rising substantially. As erosion continues to increase due to sea-level rise and more extreme storm events, the demand for beach re-nourishment is likely to increase as well – as will its cost. One early study published by the EPA estimated that it would cost the U.S. more than $14.5 billion to replenish sand beaches lost to a ½ meter (19.7 inch) rise in sea level and $58 billion for a 2 meter (78.7 inch) rise (Leatherman, 1989).

The use of dredged materials is also being used in some areas to help restore coastal marshes lost to sea level rise and other problems – an approach sometimes referred to as "assisted accretion" (Glick, Clough, and Nunley, 2008). The state of Texas, for example, has been working to restore coastal wetlands by placing fill and planting wetland vegetation, although to date only five percent of previously lost wetlands have been restored (Levina, et al., 2007). A more dramatic example of this approach is the restoration of Poplar Island in the Chesapeake Bay. This and a number of other islands in the bay, which supported an important cultural heritage as well as provided habitat for many migratory birds and other fish and wildlife, have essentially disappeared due to a combination of land subsidence and sea-level rise. In the interest of finding a "beneficial use" of excess dredged material from navigation channels in the region, ACE initiated the Poplar Island Environmental Restoration Project, which began in 1998. Restoration efforts are still underway, but recent monitoring at the site indicated that a number of waterbirds have returned (Erwin, Miller, and Reese, 2007). The downside of a project of this scale, however, is the expense. The initial project cost more than $425 million dollars, and plans for expansion indicate the need for at least $250 million additional funds (ACE, 2005).

5. Increase Monitoring and Facilitate Management Under Uncertainty**.**

Increased attention to monitoring as well as the use of adaptive management practices will be critical to improving knowledge about the impacts of climate change on coasts and estuaries and building effective adaptation strategies. For example, there is a considerable need for increased monitoring to better understand complex localized impacts of sea level rise on species and habitats – factors such as marsh accretion rates, species range changes, and interactions among species (Peterson, et al., 2008). Given the long-term nature of the threat, such monitoring programs need to be maintained over time, which will require committed staff time and funding.

It will also be important to develop meaningful adaptation strategies today, even if the specific impacts of climate change remain uncertain, which underscores the need for an adaptive management approach. There has been an ongoing effort to integrate adaptive management into the multi-decade, multi-billion dollar Comprehensive Everglades Restoration Plan, in part due to the recognition that new stressors like sea-level rise may warrant revisions to the plan to ensure that it is still able to meet its goals and objectives (http://www.evergladesplan.org/pm/recover/recover_docs/am/rec_am_stategy_brochure.pdf).

Table 5. Summary of Potential Adaptation Strategies for Coasts and Estuaries

Impacts	Examples of Adaptation Options
Erosion of beaches and inundation of coastal marshes	• Reduce non-climate stressors such as structures or activities that reduce natural sedimentation; • Remove or prevent coastal armoring to allow for inland habitat migration and natural littoral processes; • Establish coastal buffers by protecting upland areas from development through rolling easements, land acquisitions, and other means; • Restore protective habitats such as dunes and consider ecosystem function and diversity in restoration efforts; • Conduct ecologically-sound "assisted accretion" and beach re-nourishment.
Saltwater intrusion into water supplies	• Reduce non-climate stressors such as groundwater withdrawals; • Move freshwater intakes farther inland.
Altered freshwater flows into estuaries	• Reduce non-climate stressors such as nutrient pollution; • Restore riparian habitat buffers to capture pollutants; • Improve stormwater management, including increasing use of LID measures.
Coral bleaching/diseases and shifts in species' ranges due to higher ocean temperatures	• Reduce non-climate stressors such as land-based pollution. • Promote ecological function and diversity within and among species in coral reef systems, including expanding marine protected areas; • Incorporate climate change into fisheries management.
Ocean acidification	• Unknown

Case study: *Albemarle-Pamlico Region, North Carolina*.

In response to and anticipation of a significant loss of lowland wetlands due to a combination of land subsidence and sea-level rise in the Albemarle-Pamlico region of North Carolina, The Nature Conservancy (TNC) is piloting and researching several adaptation strategies to protect important habitats and ecosystems supported by conservation lands (Pearsall and Poulter, 2005; www.nature.org).

What is particularly notable about this project is its emphasis on an adaptive management approach. While researchers have been able to model which land areas of the region are likely to be inundated under various scenarios of sea-level rise, scientists working on the project fully acknowledge that uncertainty is the rule rather than the exception. In fact, given that sea-level rise is just one of the ways in which climate change will affect the region's coastal ecosystems and that the region's species and ecosystems will respond in unpredictable ways, the full brunt of the impacts will likely remain unknown. Despite the uncertainty, the project managers recognize that there are many actions that can be taken now, based on already available information. The approach Pearsall and Poulter (2005) recommended is classic adaptive management:

- Identify plausible steps, based on literature review, modeling, and expert opinion, to reduce the likelihood of catastrophic transformations;
- Formulate testable hypotheses about the best ways to mitigate against catastrophic change;
- Implement these hypotheses in many places and monitor each replicate to detect local failures;
- Adapt management as necessary to minimize the likelihood of catastrophic transformation across the region.

TNC currently has four pilot projects underway:

1. Conducting hydrologic modeling of the Alligator River refuge and adjoining areas to improve understanding of how numerous drainage ditches and canals that have been installed in the region over the past two centuries affect water flow. This will help project managers identify ditches and canals that could either be filled or managed with tide gates to reduce saltwater intrusion into sensitive peat areas.
2. Installing water control structures to manage water levels for wetland restoration, with a particular focus on enhancing marsh accretion.
3. Identifying areas that are likely to be submerged in the short-term and planting flood- and salt-tolerant plant species such as native bald cypress.
4. Constructing native oyster reefs along the shorelines to reduce wave energy and create new shallow-water habitats.

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