Preparing for and managing change: climate adaptation for biodiversity and ecosystems

Bruce A Stein1*, Amanda Staudt2, Molly S Cross3, Natalie S Dubois4, Carolyn Enquist5, Roger Griffis6, Lara J Hansen7, Jessica J Hellmann8, Joshua J Lawler9, Erik J Nelson10, and Amber Pairis11

The emerging field of climate-change adaptation has experienced a dramatic increase in attention as the impacts of climate change on biodiversity and ecosystems have become more evident. Preparing for and addressing these changes are now prominent themes in conservation and natural resource policy and practice. Adaptation increasingly is viewed as a way of managing change, rather than just maintaining existing conditions. There is also increasing recognition of the need not only to adjust management strategies in light of climate shifts, but to reassess and, as needed, modify underlying conservation goals. Major advances in the development of climate-adaptation principles, strategies, and planning processes have occurred over the past few years, although implementation of adaptation plans continues to lag. With ecosystems expected to undergo continuing climate-mediated changes for years to come, adaptation can best be thought of as an ongoing process, rather than as a fixed endpoint.

Climate-change adaptation has been discussed in the scientific community for nearly three decades, but over much of that time policy makers and climate activists largely regarded it as a taboo subject out of concern it would divert attention from addressing the underlying causes of climate change (Pielke et al. 2007). It has become increasingly clear that no matter how vigorously greenhouse-gas emissions are reduced, major shifts in climate will occur over at least the next century, necessitating serious action on adaptation in addition to climate mitigation (NRC 2010). Consequently, in recent years the topic of climate adaptation has received greater attention and has become an important theme in biodiversity conservation and natural resource management.

The increased focus on adaptation can be tracked through growth in media coverage (Moser 2009), scientific literature (Glick et al. 2011a), and government activities (Bierbaum et al. 2013). Indicative of this heightened attention is a 2009 Presidential Executive Order (EO 13514) requiring all federal agencies to develop and implement adaptation plans; the establishment of a federal interagency climate adaptation task force; the release of a national fish, wildlife, and plants climate adaptation strategy; the incorporation of climate change into state wildlife action plans; and the development of adaptation plans by states, cities, and Native American tribes.

Through geological time, climatic shifts have exerted a powerful influence on biotic evolution and the development of ecosystem structure and function. The current pace of climate change, coupled with other anthropogenic stresses, such as habitat loss and fragmentation, invasive species, and altered ecological processes, is expected to exceed the innate capacity of many species and ecosystems to adjust to and accommodate such changes. The rapid transitions in climate currently underway are already affecting species and ecosystems in varied and complex ways (Staudinger et al. 2013; Grimm et al. 2013), posing considerable challenges for biodiversity conservation and natural resource management.

In a nutshell:

- Climate adaptation focuses on addressing the impacts of climate change on natural and human systems, and is an essential complement to climate mitigation, which focuses on atmospheric greenhouse-gas concentrations;
- Conservation and natural resource managers and policy makers are increasingly incorporating climate considerations into their planning and management, taking advantage of an emerging body of adaptation principles, strategies, and planning processes;
- Given directional shifts in many climatic variables, adaptation efforts will need to emphasize managing for inevitable ecological changes, not just for the persistence of existing conditions;
- Depending on the rate, magnitude, and character of future climatic change, even the most aggressive adaptation actions may be unable to prevent losses of biodiversity or serious degradation of ecosystems and their services.

1National Wildlife Federation, Washington, DC *(steinb@nwf.org);
2National Wildlife Federation, Reston, VA; 3Wildlife Conservation Society, Bozeman, MT; 4Defenders of Wildlife, Washington, DC; 5USA National Phenology Network and Wildlife Society, Tucson, AZ; 6National Oceanic and Atmospheric Administration, Silver Spring, MD; 7EcoAdapt, Bainbridge Island, WA; 8University of Notre Dame, South Bend, IN; 9University of Washington, Seattle, WA; 10Bowdoin College, Brunswick, ME; 11California Department of Fish and Wildlife, Sacramento, CA
These climatic changes and their attendant impacts are affecting both wild and managed systems – from nature reserves and wilderness areas, to farms and ranchland, to urban parks and suburban backyards. Adaptation efforts will be relevant to each of these landscape types and land uses, and will have implications not only for the species they harbor but also for the continued provision of ecosystem services that are of benefit to human society.

There have been major advances in the development of principles, strategies, and planning processes for biodiversity and ecosystem adaptation over the past 5 years, and these advances are the focus of this review. Which adaptation strategies and actions are appropriate in any particular place or landscape will vary, depending on such considerations as societal values, conservation goals, technical feasibility, and cost, among others. Successful adaptation, however, will depend not only on the selection and implementation of appropriate strategies but also on the rate, magnitude, and character of climatic changes, highlighting the importance of continued action and progress on climate mitigation as well as adaptation.

**What is climate adaptation?**

Climate-change adaptation is an emerging field that focuses on preparing for, coping with, and responding to the impacts of current and future climate change. More formally, climate adaptation has been defined as “initiatives and measures to reduce the vulnerability of natural and human systems against actual or expected climate change effects” (IPCC 2007a) and “adjustment in natural or human systems in response to actual or expected climatic stimuli or their effects, which moderates harm or exploits beneficial opportunities” (IPCC 2007b). As these definitions suggest, climate adaptation focuses primarily on human responses to climate change (either active or passive), as distinct from use of the term “adaptation” in the traditional evolutionary biology sense, which focuses on genetic changes over time in response to selective pressures. Although they are different concepts, evolutionary adaptation plays an important role in climate adaptation, particularly in terms of the capacity of species and populations to naturally adjust to changing conditions through genotypic shifts or phenotypic plasticity (Hoffman and Sgrò 2011). Unless otherwise noted, however, here “adaptation” refers specifically to climate adaptation.

Effective climate adaptation stems from a structured process that considers the effects of climate change on valued resources so that appropriate management responses can be identified and implemented. Because adaptation is fundamentally about managing change, it can best be thought of as a continuing process rather than a fixed endpoint. Actions undertaken to prepare for anticipated climate-change impacts can be referred to as proactive or anticipatory adaptation, whereas actions in response to climate-related impacts can be referred to as reactive adaptation (Adger et al. 2005). For example, adaptation strategies in response to increasingly severe drought and forest fires might include such anticipatory actions as prescribed burns or selective forest thinning to reduce the intensity of future fires, while reactive adaptation actions might include broadening the genetic composition of plant materials used in post-fire restoration, with the goal of establishing species or strains better suited to future climatic conditions.

Adaptation actions can be targeted at different levels of biological organization (eg species, habitats, ecosystems) and designed to benefit various attributes of natural systems, such as the components of biodiversity (eg species diversity, ecological patterns), particular ecosystem processes (eg disturbance regimes, nutrient cycles, hydrological cycles), specific ecosystem services (eg water production, carbon sequestration, coastal protection), or specific locations (eg parks, wildlife refuges, cities). Adaptation strategies focusing on different biological levels or system attributes may be mutually beneficial or might work at cross-purposes. Simply put, what is viewed as adaptive for one conservation purpose might be detrimental (or “maladaptive”) for another.

Adaptation can focus on either human systems or natural systems, and “ecosystem-based adaptation” (EBA) is emerging as a framework for linking these perspectives (Vignola et al. 2009; Jones et al. 2012). Despite its ecologically oriented name, however, EBA is targeted primarily toward assisting people in adapting to climate change, as reflected in the Secretariat of the Convention on Biological Diversity’s (2009) definition of EBA as “the use of biodiversity and ecosystem services as part of an overall adaptation strategy to help people adapt to the adverse effects of climate change”. An example of this concept is the role of intact ecosystems (eg mangroves, wetlands) in attenuating coastal storm surge and protecting human communities along coastlines (Kaplan et al. 2009). Recognition and application of EBA has been growing internationally, but the term has not yet been widely adopted in the US.

**Managing for change, not just persistence**

Ecological systems have always been dynamic, characterized by variability at annual, decadal, and longer temporal scales. Indeed, the Quaternary paleoclimatic record provides a striking view of the degree to which species assemblages and ecosystems are characterized by change rather than stasis (Millar and Woolfenden 1999; Williams and Jackson 2007). Nonetheless, stationarity – the idea that natural systems fluctuate within a defined and constant range of variability – has been a foundational concept in many fields of natural resource management (Milly et al. 2008; Keane et al. 2009). Directional changes in climatic variables have made clear that, in the words of Milly et al. (2008), “stationarity is dead”. Accordingly, adaptation to climate change in the context of biodiversity conservation and natural resource management is largely about managing change (Millar et al.
Approaches to adaptation can range from resisting change – in order to protect high-value and climate-sensitive assets – to actively facilitating changes, so that inevitable system transitions will retain desirable ecological attributes rather than resulting in the collapse of ecosystem functions and services. One commonly used framework for adaptation responses to change consists of the continuum of resistance, resilience, and transformation (Millar et al. 2007; Glick et al. 2011b). Under this framework, resistance actions are intended to promote system persistence and maintain current conditions. Resilience has multiple meanings (e.g., Holling 1996; Walker et al. 2004; Folke 2006), but in this context it typically refers to actions designed to improve the capacity of a system to return to desired conditions following a disturbance, or to maintain some level of functionality despite being in an altered state. Transformation refers to efforts that enable or facilitate the transition of ecosystems to new functional states.

To date, most adaptation work in the biodiversity and ecosystem conservation community has focused on strategies for maintaining existing conditions. Even the widely embraced objective of “enhancing resilience” usually reflects a persistence-oriented approach by emphasizing the assumption that healthy systems will more likely rebound to their prior state following perturbations. In the past few years, however, many scientists and conservationists have begun focusing not just on resisting changes and retaining existing ecological conditions but also on the challenging task of managing or even facilitating what many now see as inevitable system transformations (Figure 1).

### Reconsidering conservation goals

Effective conservation and natural resource management relies on the articulation of clear goals, which make possible the development of specific management objectives and measures of success. Goals are an expression of the desired condition of a landscape or other resource and inherently reflect human values. Such societal values can include prevention of species extinctions (as expressed in the US Endangered Species Act), maintenance of unimpaired “natural” conditions in national parks, or sustained yield of products and services from systems as varied as national forests and marine ecosystems. In a sense, goals articulate the “why” of conservation, while strategies describe the “how”. However, the choice of conservation or management goals is driven as much by societal values, economic constraints, and political feasibility as by scientific knowledge.

As climatic factors continue to shift they are expected to cause realignments and alterations in both the spatial and temporal patterns of biodiversity, including the reshuffling of community composition and the emergence of “novel ecosystems” (Hobbs et al. 2006; Williams and Jackson 2007). Such shifts and realignments will make protecting species and ecosystems in their current
locations increasingly difficult and in some cases impossible. As a result, one theme that repeatedly emerges in the adaptation literature is the need to move from a paradigm of preserving current conditions or designing restoration for “historical fidelity” to one of being open to managing for future systems that may differ in composition, structure, and/or function (Cole and Yung 2010).

Given the rate and magnitude of climate-mediated ecological changes, natural resource managers will be faced not with a choice of whether to reconsider many of our conservation and management goals, but rather when, how much, and in what ways they should change (Julius and West 2008; Glick et al. 2011a). In particular, goals will need to be forward-looking instead of retrospective in nature, and managers may need to expand their definitions of what constitutes a desirable ecosystem (Hobbs and Cramer 2008; Lemieux et al. 2011). There are, however, formidable institutional, legal, and psychological barriers to shifting current conservation paradigms and realigning goals (Jantarasami et al. 2010).

Among the most common suggestions for how conservation goals may need to shift is from those that focus on preserving current spatial patterns of species toward goals that focus on maintaining underlying ecological and evolutionary processes that will be important for sustaining functional ecosystems into the future (Harris et al. 2006; Pressey et al. 2007; Prober and Dunlop 2011; Groves et al. 2012). Species composition goals will still have relevance but may need to be expressed at different spatial or temporal scales. For example, rather than retaining the full diversity of species at specific sites (eg individual reserves), such goals may need to be restated as maintaining compositional diversity across larger landscapes. Similarly, these goals may be framed as applying to a specified time period (eg > 20 years, 20–50 years, etc.). Others have suggested adopting the goal of protecting diverse geophysical settings (or “enduring features”) in order to sustain current biodiversity and enable future diversification (Anderson and Ferree 2006; Pressey et al. 2012). Targeting ecosystem services of direct benefit to people has also been promoted as a primary conservation goal, to ensure the societal relevance of adaptation efforts and thereby maintain or increase support for conservation (Chan et al. 2006).

Summarizing the range of possible goals in light of climate change, Camacho et al. (2010) asked whether we want to be “curators seeking to restore and maintain resources for their historical significance; gardeners trying to maximize aesthetic or recreational values; farmers attempting to maximize economic yield; or trustees attempting to actively manage and protect wild species from harm even if that sometimes requires moving them to a more hospitable place”.

### Convergence on adaptation principles

A considerable body of work has spurred the recent emergence of general principles for use in biodiversity and ecosystem adaptation (eg Julius and West 2008; Heller and Zavaleta 2009; West et al. 2009; Hansen and Hoffman 2010; Peterson et al. 2011). Notable among these principles is the need for adaptation to be carried out as an intentional process, rather than assuming that existing conservation practices will suffice in the face of rapid climate change. Such an intentional approach depends on an understanding of likely impacts and vulnerabilities, with strategies and actions explicitly built on that understanding. The following five principles draw from a set of “key characteristics of climate-smart conservation” developed by an expert workgroup convened by the National Wildlife Federation (Stein et al. 2013; Stein et al. in review). While there are many other conservation best practices (eg importance of priority setting and collaborative partnerships), these principles highlight attributes that are especially important from a climate-adaptation perspective.

#### Embrace forward-looking goals

Conservation goals should focus on future, rather than past, climatic and ecological conditions; strategies should take a long-term view but account for near-term conservation challenges and needed transition strategies. Although the historical and paleoecological records provide important insights, past-oriented goals may no longer be achievable. Accordingly, managers will need to be open to re-evaluating and modifying goals as needed. Most resource management plans have relatively short (3- to 10-year) time horizons; effective adaptation will require that ecologists improve predictive capabilities and that managers incorporate longer term implications of climate change into current actions.

#### Link actions to climate impacts

Conservation strategies and actions should be designed specifically to address the impact of climate change in concert with non-climate stressors; actions should be supported by an explicit scientific rationale. In this context, climate impacts include both direct effects, such as changes in temperature or precipitation patterns, as well as indirect effects, such as rising sea level, disruptions to ecological interactions, or increased toxicity of contaminants. As climate adaptation increases in prominence, there may be a temptation to relabel existing practices and projects as adaptation. Climate adaptation actions – whether based on traditional practices or involving novel approaches – should therefore demonstrate an explicit understanding or hypothesis for how they are likely to reduce key climate-related vulnerabilities or take advantage of climate-related opportunities.

#### Consider the broader landscape context

On-the-ground actions should be designed in the context of broader geographic scales to account for likely shifts in species distributions, to sustain ecological processes, and
Adaptation as a means to reduce vulnerability

Understanding adaptation as “initiatives and measures to reduce vulnerability” (IPCC 2007a) provides one framework for designing and evaluating possible options and approaches. Climate-change vulnerability is typically defined as consisting of three primary elements: exposure, sensitivity, and adaptive capacity (Glick et al. 2011b). Strategies can therefore be designed that address one or more of these vulnerability components by: reducing the degree of change experienced by the organism or system (ie exposure); reducing the sensitivity of the organism or system to those changes; or enhancing the ability of the species or system to accommodate or adjust to those changes (ie adaptive capacity; Dawson et al. 2011). Depending on the intended outcome, these approaches can seek to either maintain the persistence of current conditions or facilitate transitions to alternative states. Table 1 illustrates the interplay among these factors in several example adaptation efforts.

Key adaptation strategies

Recently, there has been broad convergence on various adaptation strategies, many of which build on existing conservation techniques and principles but differ in when, where, and how they are applied (Lawler 2009; Hellmann et al. 2011). Strategies for biodiversity and ecosystem adaptation can be grouped into three basic categories: improving current conditions; protecting and managing large landscapes; and pursuing species- and site-specific approaches (Table 2). First, several proposed approaches focus on improving the current condition of systems, with the stated goal of enhancing resilience to climate-change impacts; these strategies involve restoring ecosystem functioning and reducing other anthropogenic stresses. A second set of approaches involves protecting and managing large landscapes; these strategies include increasing the size of reserves, placing more reserves on the landscape, changing the way reserve networks are designed, and increasing connectivity among protected areas. The remainder of the strategies – generally classified as site- or species-specific – includes such approaches as managed translocation (assisted migration), supplemental watering, habitat manipulations, and ecosystem engineering.

Advances in adaptation planning

A growing number of adaptation planning approaches are being designed to help practitioners integrate climate change into conservation decisions and translate general principles and strategies into actionable recommendations (eg Peterson et al. 2011; Cross et al. 2012; Stein et al. in review). Even though these approaches vary considerably in terms of analytical techniques used, most can be...
characterized as containing a number of similar steps; Figure 2 represents a generalized adaptation planning and implementation cycle that reflects several of these commonalities. This planning and implementation framework draws from, and mirrors, many standard conservation planning processes but is designed specifically to incorporate climate considerations, particularly through its emphasis on assessing climate-related vulnerabilities (step 2) and on reconsidering goals and objectives in light of those impacts and vulnerabilities (step 3). Although this cycle explicitly addresses climate considerations, the critical phase of evaluating and selecting adaptation options (step 5) necessarily considers not just technical feasibility and the likelihood of achieving desired ecological outcomes but must also take into account cost, institutional capacity, and legal/social considerations.

A particular challenge in adaptation planning is addressing the uncertainties involved in projecting future climatic changes as well as the resultant ecological impacts and human responses; these uncertainties must be considered in the individual steps of the adaptation cycle and addressed through iterative rounds of planning, implementation, and evaluation. Adaptation planners can, however, turn to many existing tools for making management decisions in light of uncertainty. Structured decision making, for instance, is a useful approach for clearly defining key issues, creating logic models, and identifying relevant strategies despite knowledge deficits and uncertainty (Runge 2011; Gregory et al. 2006). The coastal impoundment project profiled in Figure 1, for example, is based on the results of a formal, structured decision-making process. Other approaches include risk management (Willows and Connell 2003), robust decision making (Lempert et al. 2006), and scenario-based planning (Peterson et al. 2003). The last option, in particular, is being used to identify actions that may be relevant across multiple possible futures, which can often be considered “no regrets” or “low regrets” actions.

Table 1. Illustrative adaptation efforts

<table>
<thead>
<tr>
<th>Adaptation action</th>
<th>Description</th>
<th>Key climate concerns</th>
<th>Adaptation mechanism</th>
<th>Intended outcome</th>
</tr>
</thead>
<tbody>
<tr>
<td>Protect cold-water refugia</td>
<td>To sustain salmon runs on California’s Klamath River, cold-water refuges (eg mouth of Blue Creek) have been identified and their protection is the subject of a new Thermal Refugia Protection Policy</td>
<td>Warming water; decreasing summer flows</td>
<td>Reduce exposure of salmon to warming water</td>
<td>Persistence-oriented</td>
</tr>
<tr>
<td>Reintroduce beavers as ecosystem engineers</td>
<td>To enhance water retention in mountain watersheds, an important factor for buffering climate impacts on an array of fish and wildlife, beavers are being reintroduced in southern Utah</td>
<td>Increasing aridity; more variable stream flows</td>
<td>Enhance adaptive capacity of watersheds</td>
<td>Persistence to transition</td>
</tr>
<tr>
<td>Modify post-fire reforestation practices</td>
<td>To enable reforested areas to better survive under future climatic conditions, post-fire restoration efforts can use species and genetic stock drawn from wider geographic ranges and with broader climate tolerances</td>
<td>Warmer and drier conditions</td>
<td>Reduce sensitivity of forest community to warming</td>
<td>Transition-oriented</td>
</tr>
<tr>
<td>Relocate/restore habitat and create corridor</td>
<td>To sustain native Hawaiian birds by providing access to cooler habitat and a disease-free refuge, upslope forest restoration is connecting two forest reserves on the slopes of Mauna Kea, Hawaii</td>
<td>Warming temperatures; upslope shift in mosquitoes carrying avian malaria</td>
<td>Reduce exposure of birds to warming and disease vectors</td>
<td>Transition-oriented</td>
</tr>
</tbody>
</table>

Table 2. Example adaptation strategies

| Improve current conditions | • Reduce non-climate-related threats  
|                           | • Restore floodplains  
|                           | • Remove dams  
|                           | • Reduce forest-fire fuels  |
| Protect and manage large landscapes | • Increase connectivity for species and ecological processes  
|                             | • Create additional protected areas  
|                             | • Enlarge protected areas  
|                             | • Protect enduring features (geophysical)  
|                             | • Protect climate refugia  
|                             | • Increase redundancy of protection provided by reserves  |
| Species- and site-specific approaches | • Relocate organisms (managed translocation)  
|                                          | • Manage for heat-tolerant phenotypes  
|                                          | • Increase genetic diversity  
|                                          | • Re-establish ecosystem engineers  |
Slow progress on implementation

Implementation of adaptation plans and strategies continues to lag, and overcoming barriers to their execution is one of the current challenges for climate adaptation. Moser and Eckstrom (2010) provided a diagnostic framework for identifying barriers that may impede the adaptation process, along with suggestions for overcoming these barriers. One particular impediment for many resource managers is the perceived need to focus on urgent, short-term threats rather than on longer term adaptation needs, especially in an era of severe budgetary constraints. An approach for helping reconcile this dilemma is identification of management options that have near-term benefits but are consistent with longer term adaptation needs. Another important barrier is the sense among some managers and institutions that addressing climate change is a distinct (and often unfunded) activity to be carried out in addition to their existing responsibilities. While early efforts to develop adaptation plans began as stand-alone endeavors, adaptation increasingly is being integrated into and informing existing planning and decision-making processes. Implementing climate-adaptation actions will also be highly dependent on the capacity and culture of the institutions charged with managing US lands and waters. Indeed, while the concept of adaptive capacity is often thought of in reference to the species and ecosystems that are the targets of adaptation action, the ability of institutions themselves to adjust and evolve will be key to their ability to manage for change.

The adaptation paradox

There are limits to adaptation, which revolve around thresholds of an ecological, economic, or technological nature (Adger et al. 2009). For instance, ecological or physical thresholds exist beyond which adaptation responses will be unable to prevent serious climate-change impacts (eg temperature thresholds for organisms, such as thermal stress in corals or cold-water fishes). Economic thresholds can be defined as when the costs of adaptation exceed the costs of averted impacts (ie it is more expensive to adapt than to experience the impacts). Finally, there are technological thresholds beyond which engineered or management solutions cannot avert the effects of climate change.

The rate, magnitude, and character of climatic changes will influence whether and when these limits are exceeded. For instance, a given species may be capable of accommodating a level of change that occurs gradually, through either phenotypic adjustments or adaptive evolution (Hoffman and Sgro 2011), but may be incapable of accommodating the same degree of change if it occurs rapidly. Similarly, a species or system may have the capacity to adapt to changes in an ecologically intact setting but is unable to adjust when additional anthropogenic stresses, such as a highly fragmented landscape, are also present. Although shifts in climate have been a factor throughout evolutionary history, there now exists a unique combination of rapid rates of climatic change together with profound and pervasive human impacts on the landscape that may limit the natural adaptive capacity of many species and systems. Indeed, depending upon the rate, magnitude, and character of future climatic change, society may be unable to prevent losses of biodiversity or serious degradation of ecosystems and their services even if aggressive adaptation actions are implemented.

Global average temperature increases will likely exceed the 2°C target that scientists and policy makers had identified as a threshold for avoiding dangerous interference with the climate system (IEA 2011). Accordingly, the need to adapt to increasing climate impacts will only become more acute as higher levels of warming and associated changes occur. The central paradox is that, as higher levels of warming make the need for adaptation more imperative, these temperature increases, and the
scale of attendant impacts, are likely to substantially limit the effectiveness of adaptation options. As the rate and magnitude of climatic changes increases, adaptation efforts will be tested and possibly compromised as ecological, economic, and technological thresholds are reached. This paradox highlights the importance of viewing adaptation as fundamentally about managing rather than resisting change and a complement to and not a replacement for serious action on climate mitigation.

Despite the challenges that rapid climate change poses to the nation's biodiversity and ecosystems, there is now much energy and effort underway, focused on how the emerging field of climate adaptation can make a difference for conservation and resource management. With ecosystems expected to undergo continuing climate-mediated changes for years to come, however, conservation goals and adaptation strategies will need to be revisited regularly and viewed as an ongoing process rather than a fixed endpoint. Climate change represents a uniquely 21st century conservation challenge, but biodiversity and ecosystem adaptation can draw from and build on a rich conservation tradition. Indeed, successful adaptation over the long term will likely depend on what the eminent conservationist Aldo Leopold presciently referred to more than 60 years ago as the “capacity for self renewal” (Leopold 1949).

Acknowledgements

This article is based on a technical input to the National Climate Assessment and grew out of a workshop on biodiversity, ecosystems, and ecosystem services hosted in January 2012 by the Gordon and Betty Moore Foundation in Palo Alto, CA. The authors gratefully acknowledge input from the following for discussions that contributed to development of this paper: D Beard, R Bierbaum, E Girvetz, P Gonzalez, S Ruffo, and J Smith. We also thank members of the National Wildlife Federation-led Climate-Smart Conservation Workgroup for their help in developing Figure 2 and the adaptation principles presented here. Financial support for preparation and publication of this paper was provided by the US Geological Survey’s National Climate Change and Wildlife Science Center and the Gordon and Betty Moore Foundation.

References


IPCC (Intergovernmental Panel on Climate Change). 2007a. Climate change 2007: synthesis report. Cambridge, UK, and
Climate adaptation for biodiversity and ecosystems