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Climate Change Adaptation Strategies for Resource Management and Conservation Planning

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Recent rapid changes in the Earth's climate have altered ecological systems around the globe. Global warming has been linked to changes in physiology, phenology, species distributions, interspecific interactions, and disturbance regimes. Projected future climate change will undoubtedly result in even more dramatic shifts in the states of many ecosystems. These shifts will provide one of the largest challenges to natural resource managers and conservation planners. Managing natural resources and ecosystems in the face of uncertain climate requires new approaches. Here, the many adaptation strategies that have been proposed for managing natural systems in a changing climate are reviewed. Most of the recommended approaches are general principles and many are tools that managers are already using. What is new is a turning toward a more agile management perspective. To address climate change, managers will need to act over different spatial and temporal scales. The focus of restoration will need to shift from historic species assemblages to potential future ecosystem services. Active adaptive management based on potential future climate impact scenarios will need to be a part of everyday operations. And triage will likely become a critical option. Although many concepts and tools for addressing climate change have been proposed, key pieces of information are still missing. To successfully manage for climate change, a better understanding will be needed of which species and systems will likely be most affected by climate change, how to preserve and enhance the evolutionary capacity of species, how to implement effective adaptive management in new systems, and perhaps most importantly, in which situations and systems will the general adaptation strategies that have been proposed work and how can they be effectively applied.

Key words: **adaptation; adaptive management; climate change; conservation planning; management; scenario planning; triage**

Introduction

Over the past century, global average annual temperatures have risen 0.7°C (IPCC 2007b). In the Arctic, temperatures have risen at approximately twice that rate. This trend is very likely to continue into the future, as global average surface temperatures are projected to rise between 1.1 and 6.4°C by 2100, and temperatures at the high northern latitudes are projected to rise between 3 and 12°C by the end of the century (IPCC 2007b). Precipitation patterns are also projected to change, although the direction, magnitude, and confidence surrounding precipitation projections vary by region and season.

These changes have profound implications for the Earth's natural systems. Recent climatic changes have been linked to decreases in snowpack (Groisman *et al.* 2001; Mote 2003), increases in the frequency and severity of large wildfires (Westerling *et al.* 2006), and rising sea levels (IPCC 2007b). These changes in turn have the potential to alter the timing and magnitude of stream flows, the structure and

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composition of vegetation communities, and the nature of coastal systems. As temperatures and sea levels continue to rise, many ecosystems will undergo significant changes. Coastal wetlands will be inundated, alpine zones will shrink, and some wetlands, ponds, and lakes will dry up (IPCC 2007a).

Many ecological systems are already showing the effects of recent climatic changes (Walther *et al.* 2002; Parmesan and Yohe 2003; Root *et al.* 2003; Parmesan 2006). The most well documented changes include changes in phenology, species distributions, and physiology. Recent phenological changes have been observed in many different ecological systems (Sparks and Carey 1995). Spring events, for example, have been occurring 2.3 days earlier per decade over the last century (Parmesan and Yohe 2003). Plants are flowering and fruiting earlier (Cayan 2001), birds are laying eggs earlier (Brown *et al.* 1999; Crick and Sparks 1999), and some amphibians are mating earlier (Beebee 1995; Gibbs and Breisch 2001). Changes in phenology have the potential to decouple interdependent ecological events, resulting in changes in species interactions, community composition, and ecosystem functioning (Stenseth and Mysterud 2002).

The paleoecological record indicates that species have shifted their geographic ranges in the past in response to changes in climate (Brubaker 1989; Davis and Shaw 2001). More recent records indicate that species have also shifted their distributions in response to recent climate change. Many species of plants, birds, butterflies, and amphibians have shifted their distributions in patterns and at rates that are consistent with recent climatic changes (Parmesan 2006). In general, these species are shifting their ranges upward in elevation and poleward in latitude (Parmesan *et al.* 1999; Thomas and Lennon 1999; Seimon *et al.* 2007; Lenoir *et al.* 2008). In a few cases, population and even species extinctions have been attributed to recent climatic changes (Pounds *et al.* 1999). As species move in response to climate change, new communities will form, new invasive species will emerge, and ecosystem functions will be altered.

Plants, corals, and other organisms have clear physiological responses to climate change. Increased atmospheric CO_2 concentrations can result in increased water-use efficiency in plants. Because different species will respond differently to increased CO_2, differential increased water-use efficiencies will likely result in shifts in competitive relationships and changes in plant communities (Policy *et al.* 1993). Many corals are extremely sensitive to changes in temperature. Increases of just a few degrees for even a short period can result in bleaching (a loss of the coral's symbiotic zooxanthellae and their photosynthetic pigments). Extensive bleaching events have occurred during the past 20 years in several regions around the globe (West and Salm 2003). Several species of fish also have well-documented thermal thresholds for survival at different life stages (e.g., McCullough 1999; Moyle 2002). Even small changes in temperature have the potential to affect population dynamics and habitat use for many species.

Managing natural systems in the face of such widespread change is a daunting task. Perhaps the largest challenge for mangers is making decisions based on limited and often highly uncertain projections of future climate impacts (Lawler *et al.* in press-b). Over the past 10 to 20 years, researchers have begun to suggest ways that managers and planners can begin to address climate change. Here, I summarize these recommendations. I begin with an overview of the general, largely conceptual, recommended adaptation strategies. I go on to describe some of the more specific suggestions that have been made for addressing climate change in freshwater, marine, and terrestrial systems. Although many of the recommended approaches for addressing climate change are already used to manage resources and protect biodiversity, effectively implementing these approaches will require new perspectives. I conclude with a brief discussion of the most pressing research needs for successfully developing and implementing adaptation strategies.

General Strategies for Addressing Climate Change

The vast majority of the proposed strategies for managing resources in a changing climate are general concepts. These concepts can be loosely grouped into three basic types of strategies: those promoting resistance, resilience, and change (Millar *et al.* 2007). Resistance is the ability of a system to remain unchanged in the face of external forces. Resilience can be defined as the ability of a system to recover from perturbations (Holling 1973). A resilient system will change in response to external forces but will return to its original state. With respect to climate change, systems that are more resilient are those that are better able to adapt to changes in climate. Resilient systems will continue to function, albeit potentially differently, in an altered climate. Less resilient systems will likely undergo messy transitions to new states, resulting in the loss of ecosystem functioning, populations, or even species. Strategies that promote change are those designed to help move a system from one state to another. The most commonly recommended strategies for promoting resistance, resilience, and change are briefly discussed below.

Removing Other Threats and Reducing Additional Stresses

Perhaps the most obvious approaches to increasing resilience are the removal of other, non-climate-related threats to a species or system and reducing other stresses on species. Decreasing the impact of exotic species, habitat loss and fragmentation, overharvest, and other threats generally results in larger populations that will likely be better able to absorb perturbations (Rogers and McCarty 2000; Noss 2001; Soto 2001; Hansen *et al.* 2003). Not only do other threats reduce the ability of a population or system to respond to or to absorb new impacts, but in many cases, climate change may exacerbate the effects of other threats. For example, increases in temperature may increase toxicity of pesticides or the infection rates and severity of diseases (Kumaraguru and Beamish 1981). Likewise climate change may increase competitive pressure from invasive species, as some invasive species may benefit from increased atmospheric CO_2 concentrations or changes in temperature or precipitation, allowing them to spread and/or outcompete native species (Dukes and Mooney 1999; Schlesinger *et al.* 2001; Zavaleta and Royval 2001; Rahel and Olden 2008).

Environmental stresses may also reduce the resilience of individuals and populations to climate change. For example, *Drosophila melanogaster* exposed to parasitic attacks while in the larval stage were more susceptible to desiccation that those not exposed to parasitic attacks (Hoang 2001). Similarly, streamside salamanders, *Ambystoma barbouri*, exposed to the herbicide atrazine were more susceptible to desiccation than were unexposed salamanders (Rohr and Palmer 2005). Removing or reducing existing environmental stresses and threats to populations or species will, in some cases, enhance their resilience to climate change.

Expanding Reserve Networks

Protected areas are arguably one of the best ways to conserve biodiversity. However, climate change will challenge the ability of the current reserve network to provide protection when the climate shifts so much that plants and animals no longer thrive where their current reserves are located (Peters and Darling 1985). Many researchers have suggested expanding reserve networks to give systems and species room to move and places to go (Halpin 1997; Shafer 1999). Increasing redundancy in the reserve network can also increase resilience by providing more opportunities in different places or chances in which species or communities might persist. Some have recommended increasing the size of existing reserves, adding buffers around existing reserves, and adding larger reserves to reserve networks (Halpin 1997; Shafer 1999; Noss 2001) (Fig. 1A). Larger reserves are

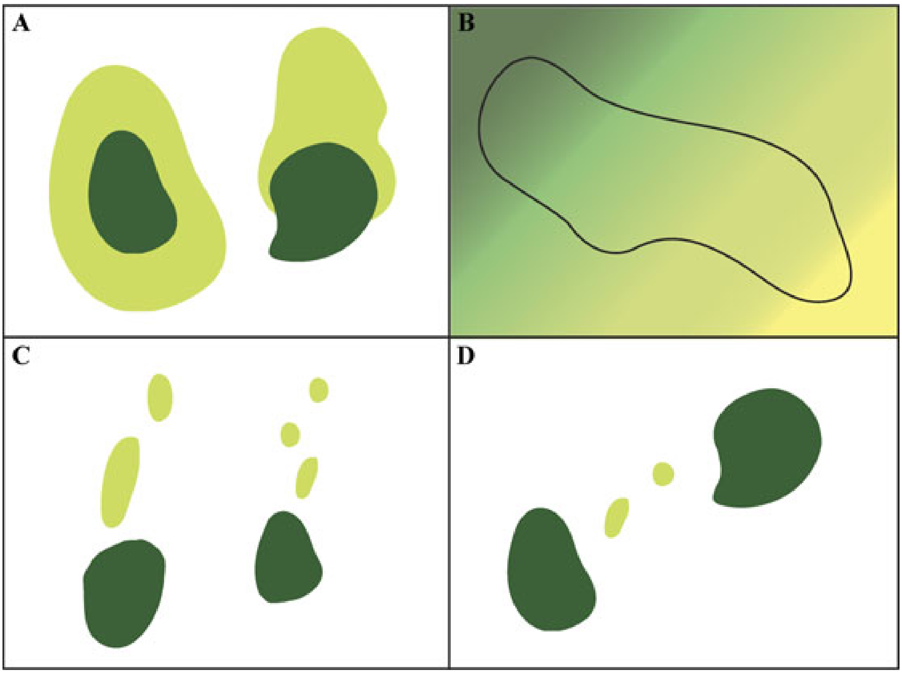


Figure 1. Proposed strategies for augmenting existing reserve networks to address climate change. Additional reserves can be placed (**A**) to enlarge existing reserves, (**B**) to span climatic or edaphic gradients, (**C**) to facilitate directional species movements in response to increasing temperatures, and (**D**) to help connect existing reserves. Existing reserves are represented by *darker shapes*, and new reserves are represented by *lighter shapes*.

likely to preserve a greater diversity of environmental conditions and allow for movement within the reserve. Coastal systems in particular will require large reserves that extend inland, allowing species to shift as sea levels rise.

Simply developing more and larger reserves might not be enough if they are not located in the right places. One more strategic possibility entails locating reserves so that they capture the most potential for habitat heterogeneity under any climate scenario. Such areas would cover diverse topographic, edaphic, and hydrologic conditions (Halpin 1997). Placing large, long reserves across biotic transition zones such as ecotones may allow for the continued protection of that transition as it shifts with climate change (Fig. 1B). Others have suggested placing reserves at the poleward edge of species ranges (Shafer 1999), arranging reserves longitudinally (Pearson and Dawson 2005) (Fig. 1C), and placing new reserves between existing reserves to facilitate connectivity (Fig. 1D).

Ideally, ecological forecasting could be used to identify sites that would best protect biodiversity in a changing climate (Hannah 2008). Dynamic global vegetation models (DGVMs; e.g., Cramer *et al.* 2001; Bachelet *et al.* 2003) and climate-envelope models (Pearson and Dawson 2003) have been used to assess the ability of reserves or reserve networks to protect species under different climate-change scenarios (Scott *et al.* 2002; Burns *et al.* 2003; Araújo *et al.* 2004). A few studies have used such models to suggest reserve networks that would be resilient to climate change. For example, Hannah *et al.* (2007) used climate-envelope models to project species' range shifts in three different regions of the globe in response to climate change and then selected reserves that adequately protected those species in the future. Likewise, Williams *et al.* (2005) used climate-envelope models to identify potential corridors that would allow movement between current ranges and species' potential future ranges. Such approaches rely heavily on the ability of the models to predict species' responses to climate change. Given both the uncertainty in projected future climates and the uncertainty inherent in most relevant ecological forecasting approaches (e.g., Thuiller 2004; Lawler *et al.* 2006), use of these models for the selection of reserves will require, at the very least, that meaningful uncertainty estimates are evaluated in conjunction with, or incorporated into, the future projections. A second limitation of this approach is that data will be lacking for the vast majority of biodiversity, and reserve selection based on this approach is likely to be biased toward well-studied species with ample data.

One alternative to using predicted shifts in species' ranges or changes in vegetation is to use projected changes in climate alone or in conjunction with static elements of the environment to determine where conditions are likely to be more or less constant. Saxon *et al.* (2005) used a combination of edaphic conditions and projected future climates to identify environments that would likely change more and those that would likely change less. Reserves could be located in areas projected to experience less change, or in areas that connected shifting environments. Such an approach relies on projected future climatic conditions, and thus is still imbued with uncertainty, albeit less uncertainty than approaches that involve additional climate-envelope or DGVM modeling.

Another alternative that has been proposed is to base reserve selection on the underlying edaphic conditions and/or current climatic or bioclimatic gradients. Bedrock, soils, topography, and climatic gradients largely define the natural distribution of flora, fauna, and ecosystems. By protecting diverse combinations of these factors, it may be possible to preserve the ecological stage on which new players (species) will find themselves in future climates. One such approach that captures current climatic gradients would be to select multiple reserves for a given species that protect a wide range of climatic conditions within that species' range (Pyke *et al.* 2005; Pyke and Fischer 2005).

Increasing Connectivity

In the past, species have moved across continents as climates changed and glaciers advanced and retreated (Davis and Shaw 2001). One of the biggest differences between those historic periods and today is that humans have dramatically altered the Earth's surface. Agricultural lands, roads, dams and water diversions, urban areas, and residential development all act as barriers to movement for some species. These barriers will make it difficult for many species to move from areas that become unsuitable or to occupy new climatic zones or habitats that emerge in the future. Using a combination of statistical climate-envelope modeling and mechanistic dispersal models, Iverson *et al.* (2004) explored the potential of five eastern American tree species to colonize newly emerging climatic space over a 100-year period. None of the five species was able to colonize more than 15% of the areas projected to be suitable under future climates. Such work implies that the number of species that are able to move successfully in response to today's anthropogenic climatic changes will be a small fraction of the number that were able to move in response to historic climate shifts.

The highly fragmented nature of today's landscapes has led many conservation biologists to promote increasing connectivity among protected areas to enhance movement in a changing climate (Shafer 1999; Noss 2001; Hulme 2005; Welch 2005). Most of the research and discussion on connectivity has focused on wildlife corridors, although some work has addressed corridors for plants (e.g., Williams *et al.* 2005). Almost all of this work has taken a species-by-species approach to corridors. Such an approach is justified, given that corridors, like habitat, are species-specific concepts. The ability to move through a corridor depends on species-specific behavior and habitat affinities.

Given that many species, with diverse habitat requirements and dispersal abilities, will need to move in response to climate change, species-based corridor approaches may not be adequate or feasible (Hulme 2005).

Two additional approaches to increasing connectivity have been proposed. First, as mentioned earlier in this chapter, small stepping-stone reserves can be placed between larger preserves to facilitate movement (Shafer 1999) (Fig. 1D). This approach may provide connectivity for a more general group of species than species-specific corridors, but small reserves will be limited to a small range of environmental conditions, and thus may only provide habitat for select and potentially small groups of species. Similarly, new reserves, whether they are small or large, can be placed in close proximity to existing reserves to facilitate movement (Halpin 1997). The second approach is to manage the lands or waters between protected areas in ways that allow the most species to move through these spaces. Such approaches have been referred to as softening or managing the matrix (Franklin *et al.* 1992; Noss 2001). Some combination of matrix management, stepping-stone reserves, and corridors will likely allow the most movement in response to climate change.

Restoring Habitat and System Dynamics

Clearly, the restoration of ecosystem functioning and habitat in degraded areas plays a key role in increasing resilience for systems and species. Many have highlighted the need to restore functioning ecosystems to address climate change (Hartig *et al.* 1997; Mulholland *et al.* 1997; Joyce *et al.* 2008; Peterson *et al.* 2008). However, climate-induced changes in hydrology, disturbance regimes, and species distributions will make restoration goals moving targets, thereby challenging the way restoration is typically done (Harris *et al.* 2006).

Climate change calls into question two of the basic tenants of restoration (Harris *et al.* 2006). First, most current restoration aims to return a system to historic or predisturbance conditions (Swetnam *et al.* 1999). In some cases, this may still be a viable option. However, for many systems, climate change will make it costly if not impossible to recreate past ecological states. Changes in atmospheric CO_2 concentrations will likely alter competitive relationships between plant species in multiple ways (Schlesinger *et al.* 2001). For example, increased water-use efficiency due to increased atmospheric CO_2 concentrations may allow trees to move into more arid environments, shifting shrublands to woodlands and woodlands to closed-canopy forests. Trying to maintain a shrubland in such an area of transition will be costly and potentially ineffective. Second, much current restoration takes a species-based approach, focusing on restoring species composition. Successfully restoring specific species assemblages will require relatively accurate predictions of which sites will be suitable for which species in the future and how those species will interact under projected climatic conditions. Given the uncertainty inherent in future climate projections, our limited knowledge of species-specific responses to climate change, and the inherent uncertainties in most ecological forecasting tools, it is unlikely that we will soon have future predictions that are accurate enough to successfully describe specific species assemblages at a given site in the distant future.

Harris *et al.* (2006) suggest a shift away from restoring historic conditions and specific species assemblages. As an alternative to these traditional approaches, they propose restoring process instead of structure. By focusing on ecosystem services instead of species composition, ecosystems can be managed in a more flexible way in which species assemblages change with changing climates, but ecosystem functioning—although the nature of those functions might change—is preserved. Several suggestions have been made for restoring disturbance regimes, river and streamflow regimes, and wetland hydrology (Hartig *et al.* 1997; Noss 2001; Harris *et al.* 2006).

Concentrating on the abiotic aspects of systems will help to prepare sites and systems for new conditions and new sets of species.

Although ecological models may not yet be able to provide accurate enough predictions of future species assemblages to allow managers to concentrate all of their efforts on a few key species, models are currently accurate enough to inform restoration efforts. Climate-envelope models and DGVMs can provide an estimate of how the species composition at a site might shift over time, giving managers an idea of the types of new species that they might incorporate into restoration actions and the species for which continued preservation at a site might be futile. Simulation models can also be used to explore the potential effects of restoration efforts in a changing climate. Battin *et al.* (2007) integrated the results of climate models, land-use models, hydrology models, and populations models to investigate the potential effects of restoration efforts for Chinook salmon under two different climate-change scenarios. Higher stream temperatures, higher peak winter flows, and lower flows during spawning are likely to lead to decreases in salmon populations. Because changes in flow regimes had the largest effect at higher elevations and restoration efforts were concentrated at lower elevations, their model indicated that the combined effect of climate change and restoration would shift salmon breeding to lower elevations.

Adaptive Management

Adaptive management is often cited as a critical approach to addressing climate change (Millar *et al.* 2007; Kareiva *et al.* 2008; Lawler *et al.* in press-b). Adaptive management involves an iterative process in which managers learn from experimental management actions (Holling 1978; Walters and Hilborn 1978). Management actions are applied as experiments, the system is monitored, and actions are then potentially changed to address changes in the state of the system. In theory, adaptive management allows for the management of highly uncertain systems. Thus, it is potentially an ideal approach for dealing with the uncertainties surrounding future climatic changes and future climate impacts (Arvai *et al.* 2006). Adaptive management can be passive or active (Walters 1986; Walters and Holling 1990). Passive adaptive management generally involves building a management strategy based on historic data and then altering that strategy with new data as the system is monitored over time. Active adaptive management involves conscious experimentation, generally exploring the outcomes of multiple management strategies. Both types of adaptive management will likely be needed to address climate change.

Applying adaptive management to address climate change will be an iterative multistep process (Kareiva *et al.* 2008). First, such a process will involve assessing the potential impacts of climate change on a system. This would necessarily be a comprehensive assessment in which as many of the potential ramifications of changes in climate, including changes to disturbance regimes, hydrology, species composition, food resources, phenology, and interspecific interactions are all considered. Second, management actions will need to be designed to address these impacts. These actions should be seen as experiments. In some cases, in which the scale and the nature of the problem are amenable, it will be possible to conduct multiple experiments to explore competing hypothesized effects of climate change or to account for different potential shifts in climate. However, for large-scale management problems, a passive adaptive management approach will be necessary. Third, the system will need to be monitored for both climatic changes and potential system responses. Finally, management strategies will need to be reevaluated and potentially redesigned before the cycle is repeated (Kareiva *et al.* 2008).

Although adaptive management is a very appealing concept and it is often written into management plans, it has been implemented in relatively few instances (Walters 1997). Two of the better known examples include water management in the Florida Everglades (Walters *et al.* 1992) and the management of flows for the Glenn Canyon Dam (National Research Council 1999). Some of the barriers to successfully implementing adaptive management include the lack of institutional flexibility and capacity, the perceived risks of failure, high degrees of uncertainty, and large spatial and long temporal scales of management (Gregory *et al.* 2006). All of these factors will challenge adaptive management as a tool to address climate change. Nonetheless, it is still likely to be one of the best tools managers and scientists have to address climate change and to learn about its effects.

Translocations

Even with increased connectivity between protected areas, some species will need to be moved to prevent extinction. Species with limited dispersal abilities and small, isolated ranges may have trouble tracking shifting habitats or may be left without suitable habitat altogether. For at least some of these species, translocations may be the only solution (Bartlein *et al.* 1997; Honnay *et al.* 2002). Although recommendations for translocation are not new (Peters and Darling 1985; Orians 1993), conservation biologists have generally been reluctant to tackle the issue of the purposeful movement of species outside of their known native range. Such translocations raise critical ecological and ethical questions that will need to be addressed before attempts to relocate species are made (Hunter 2007; McLachlan *et al.* 2007).

Given the impacts that invasive species have on ecological and economic systems, translocations may have costly ramifications even if well researched, planned, and executed. McLachlan *et al.* (2007) discuss two of the basic barriers to implementing translocations. First, it is difficult to predict which potential candidates for translocation will potentially become invasive. Although research on invasive species has produced some information about common traits of invasive species, in general, even with this information, predicting invasion is difficult. Second, determining where to transplant species requires an understanding of how environments will change in the future and what new areas will provide suitable habitat. As discussed earlier in the chapter, projections of future climatic conditions and ecological forecasts based on those projections are still relatively uncertain. To be useful for assessing potential sites for translocations, these projections and forecasts will need to incorporate these uncertainties. Given these potential barriers to implementing translocations, a framework for assessing the feasibility of, and risks associated with, a given translocation is essential.

Hoegh Guldberg *et al.* (2008) recently proposed just such a framework (Fig. 2). Their proposed framework involves several basic questions and management options. The first question asks what the risk of extinction or population decline is likely to be under future projected climates. If the risk is low, assisted migration is not likely to be needed. If the risk is moderate, the authors suggest enhancing resilience by increasing landscape connectivity, reducing non-climate-related threats, and increasing genetic diversity. If the risk is high, one asks whether translocation and establishment is technically possible (the second question in the framework). If not, actions may still be taken to help create suitable habitat in new areas in hopes that organisms will get there on there own. If translocation is possible, one asks the third question—whether the benefits of a translocation outweigh the potential ecological and socioeconomic costs. If the benefits outweigh the costs, translocations can be undertaken.

Specific Recommendations for Addressing Climate Change

The strategies discussed in the preceding sections are all basic concepts or general recommendations. Here, I provide a few examples of more specific actions that have been proposed

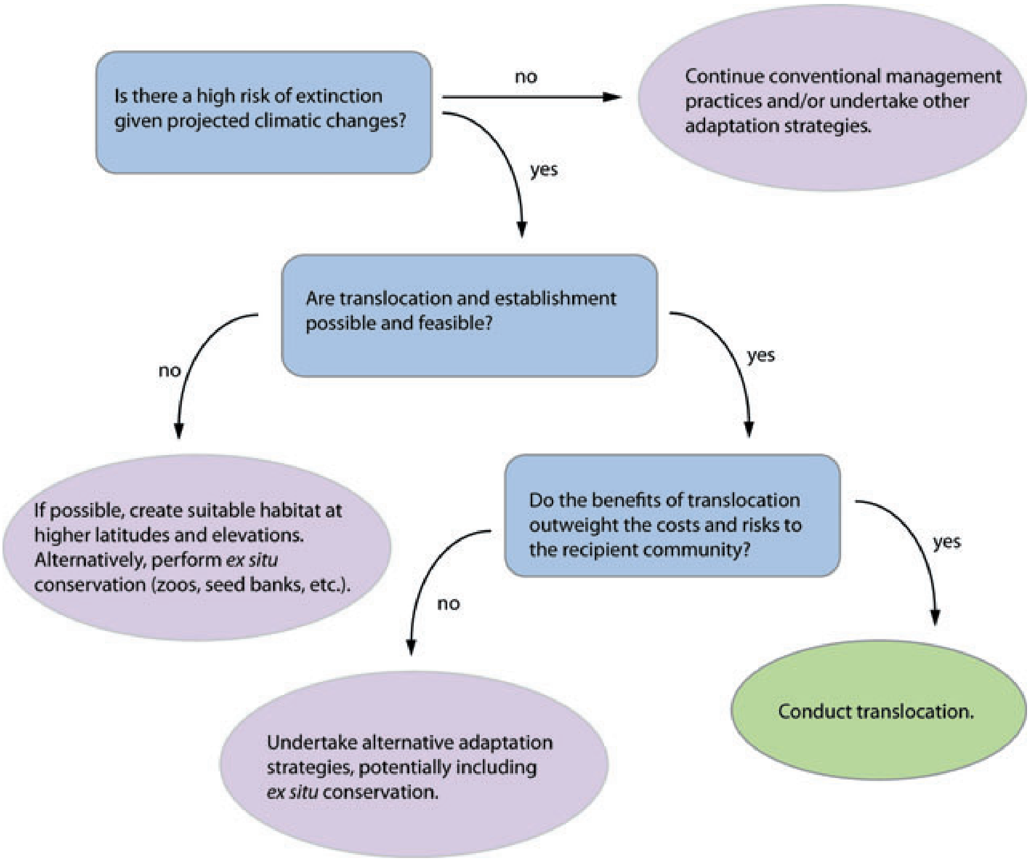


Figure 2. Framework for planning potential species translocations in a changing climate. [This figure was adapted with permission from Hoegh-Guldberg *et al*. (2008) and AAAS.]

for addressing climate change in freshwater, marine, and terrestrial systems.

Freshwater Systems

In response to climate change, freshwater systems are expected to experience changes in temperature, flow, evaporation rates, water quality, and species composition (Frederick and Gleick 1999; Poff *et al.* 2002). In many montane systems, reduced snowpack and earlier spring melts will result in changes in the timing and intensity of spring and summer stream flows (Barnett *et al.* 2005; Milly *et al.* 2005). Wetlands, particularly those that are dependant on precipitation, are likely to be some of the most susceptible to climate change of all aquatic systems (Burkett and Keusler 2000; Winter 2000). Increased evaporation rates and changes in temperature will result in reduced dissolved oxygen concentrations and changes in species composition.

Rising water temperatures will result in shifts in species distributions, including the potential loss of cold-water fish from some lower stream reaches and from other streams all together and expansions of the ranges of warm-water fish (Carpenter *et al.* 1992; Eaton and Scheller 1996). Riparian restoration has been proposed as one method to reduce stream temperatures and create cool water refugia (Palmer *et al.* 2008; Scott *et al.* 2008). Riparian restoration projects would also help to provide connectivity among some terrestrial systems. Protecting headwaters and identifying and protecting existing thermal refugia will also enhance the ability of cold-water fish to persist as temperatures rise (Hansen *et al.* 2003).

A number of management actions have been suggested for dealing with increases and decreases in flows (Palmer 2008). Some of these include channel reconfiguration, dam removal or retrofit, floodplain restoration, dam-based flow management, and bank stabilization. For example, creating wetlands and off-channel basins for water storage during times of extreme flows may prevent excess water from reaching reservoirs and reduce downstream flows (Palmer *et al.* 2008). The removal of sediment from reservoirs may also increase water storage capacity in the short term (Palmer *et al.* 2008). Water releases from dams and transporting fish may be necessary short-term solutions in times of drought or extreme low flows (Palmer 2008). Finally, reducing water extraction will be a key, although controversial, approach to maintaining flows (Hansen *et al.* 2003).

Marine Systems

Although marine systems are less studied than terrestrial systems and the Intergovernmental Panel on Climate Change (IPCC) has documented fewer significant biological changes in marine systems, many of those changes can be linked to climate change (Richardson and Poloczanska 2008). As in freshwater and terrestrial systems, species movements, phenological shifts, and physiological effects of climate change will have significant effects in marine systems (Perry *et al.* 2005; Portner and Knust 2007). Marine species and systems, however, face an additional challenge as increased CO_2 concentrations continue to acidify the oceans (Ruttimann 2006; Guinotte and Fabry 2008).

Increasing ocean temperatures have resulted in the bleaching of corals around the world. A number of specific adaptation strategies have been proposed to address the loss of corals (Hansen *et al.* 2003). One such strategy involves the reduction of synergistic stressors such as high irradiance. Shading and water disruption (with sprinklers) are two methods that are being explored to reduce irradiance during periods of elevated water temperatures. Another approach to protecting coral reefs involves identifying resistant and resilient coral populations that are less susceptible to higher temperatures (Hansen *et al.* 2003; West and Salm 2003). These populations may be able to recolonize bleached reefs, or may be transplanted in attempts to restore damaged reefs.

As in other systems, reducing other threats to species or ecosystems will likely enhance the resilience of marine systems. Reducing fishing pressure and damaging fishing techniques such as dynamite and cyanide fishing will increase the resilience of fish stocks and reefs (Hansen *et al.* 2003). Reducing nutrient pollution will likely reduce the frequency and extent of harmful algal blooms that are a combined result of increased nutrients and increased ocean temperatures (Mudie *et al.* 2002). Decreasing loading of nutrients and other pollutants will require changing land-use practices in coastal watersheds and in many cases over much larger areas (Hansen *et al.* 2003).

Terrestrial Systems

A common recommendation for enhancing the adaptive capacity of terrestrial systems, particularly forested systems, is to broaden the genetic variability and the species diversity of managed sites (Harris *et al.* 2006; Millar *et al.* 2007). Instead of using seed or individuals from local or even regional populations, it may be advantageous to maximize the genetic diversity at a restoration or reintroduction site by taking genetic material from a broader range of locations within a species, range.

Many researchers have called for aggressive forest-management practices to address climate change in forested systems. For example, widely spaced thinning and shelterwood cuts may allow forest stands to withstand increased insect outbreaks and fires (Dale *et al.* 2001; Joyce *et al.* 2008). Prescribed burning can be used to reduce fuel loads, and hence the risk of catastrophic fire (Spittlehouse and Stewart 2003; Scott *et al.* 2008). Furthermore, aggressive site preparation has been proposed to enhance regeneration after disturbances (Spittlehouse and Stewart 2003).

Manipulative management strategies have been suggested for other systems as well. For example, moderate grazing has been proposed to increase the hydroperiod in vernal pools threatened by increasing temperatures and decreasing precipitation (Pyke and Marty 2005). The placement of snow fences has been proposed to increase snow pack in areas where sensitive alpine plant communities are threatened by reduced snowpack (Hansen *et al.* 2003). For a wide variety of systems, invasions by nonnative species may be minimized through vigilance, early detection, and aggressive removal (Hansen *et al.* 2003; Baron *et al.* 2008).

New Perspectives

None of the general or specific strategies mentioned here is new. For example, even translocations are not without historic analogs. Reintroductions are merely translocations within the historic range of a species. Furthermore, the introduction of species for biological control should, theoretically, evoke a similar set of precautions that need to be taken when species are moved to address climate change. In fact, most of the general adaptation strategies and many of the specific actions described earlier are the basic accepted strategies for protecting biodiversity in general. How, then, will management need to change in the face of climate change?

Although many of the traditional strategies for protecting biodiversity will be critical for addressing climate change, applying these strategies will require a new perspective. Thus, most of the necessary change in management will revolve around how established strategies are applied. For example, as discussed earlier in the chapter, restoration will be a critical tool for addressing climate change. However, successful restoration in a changing climate will require largely abandoning historic conditions and managing for dynamic processes and communities. Other shifts in perspectives that will be required to address climate change include broadening the scale of management, engaging in scenario-based planning and management, and embracing triage as a necessary tool.

Scale

Effectively managing resources in a changing climate will require taking a broader spatial and temporal perspective (Franklin *et al.* 1992; Scott *et al.* 2002; Welch 2005; U.S. Envioronmental Protection Agency 2008). Instead of considering a population, community, or ecosystem in isolation, it will be essential to manage these within a regional or even continental context. For example, it will be necessary to consider the relative location of a population within the geographic range of the species and to coordinate the management of that population with others throughout the range. Given changes in climatic conditions, it may be necessary to abandon efforts to manage a population at one edge of the species' range and to shift efforts to other populations elsewhere in the range. Because management strategies and practices will need to cross both land-ownership and political borders, they will require both intergovernmental and interagency coordination (Soto 2001; Hannah *et al.* 2002). In particular, some researchers have called for new administrative structures such as interagency teams or programs with a mandate to address climate change (Kareiva *et al.* 2008).

Scenario-Based Planning

The uncertainty inherent in future climate-change projections means that it will often be risky to manage for one anticipated future climate. Current practice often involves managing for a set goal, for example, a population size, a particular forest structure, an allowable sediment load, or a specific species composition. One or more strategies are then developed to attain that set goal. In certain climates, a given goal may be unattainable. Climate change will force managers and planners to evaluate multiple potential scenarios of change for a given system and then to develop alternative management goals and strategies for those scenarios.

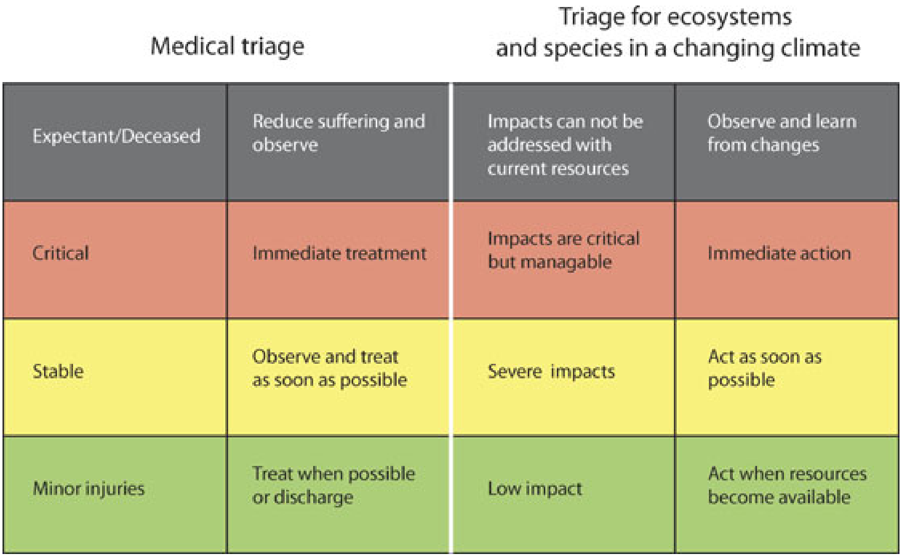
Scenario-based planning has its origins in military theory, and it has been used to explore planning strategies in a variety of disciplines when future conditions are uncertain (Peterson *et al.* 2003). The IPCC uses a scenario-based approach to exploring the range in potential future climates given different greenhouse-gas emissions scenarios (Nakicenovic *et al.* 2000). The different scenarios make different assumptions about human population growth, economic and social cooperation, advances and acceptance of new technologies, and consumption. Applying these scenarios results in different projected concentrations of greenhouse gasses, which, in turn, result in different degrees of warming and different changes in precipitation (IPCC 2007b). Alternative future scenarios have also been used to evaluate the impacts of alternative development strategies on biodiversity (White *et al.* 1997; Schumaker *et al.* 2004). In these studies, land-use scenarios were developed based on preferences for conservation and urban and suburban development. Models were then used to evaluate the potential impact of the different scenarios on population persistence.

Battin *et al.* (2007) explored the effects of two different climate-change scenarios and three different restoration scenarios on salmon populations. The two different climate scenarios were projected to increase peak flows during the salmon incubation period by 7% and 28%, respectively. The six different scenario combinations resulted in different changes in population size, ranging from a 40% decrease to a 19% increase, depending on the scenario. This study illustrates how different management actions will have different impacts, depending on the way climate changes in the future. Nonetheless, it also demonstrates the possibility of identifying management options that yield benefits across all scenarios—in other words, "robust" options. Regardless of which climate scenario was applied by Battin *et al.* (2007), restoration and protection of lowland salmon habitats yielded significant benefits. Attempting to identify these robust management options may prove more fruitful than trying to determine an optimal management strategy.

Scenario planning can be incorporated into adaptive management to help managers address climate change. Whereas a more traditional approach to active adaptive management might involve simultaneously testing several alternative management strategies to attain a set goal, active adaptive management for climate change will require testing several different management strategies designed to attain different goals under different climate-change scenarios. Developing the different scenarios and goals will require knowledge of the range of plausible future climate-change projections and some estimate of how those different climatic changes will affect the system or species in question. This type of scenario-based approach will require managers to think in parallel, in essence, planning for a system with several potential future states.

Triage

Given the relative scarcity of funding for conservation and management of natural resources, prioritizing management needs is already an integral part of the organization-wide planning of most government agencies and environmental nongovernmental organizations. Climate change will likely stretch those funding resources even thinner. With many systems, species, and sites requiring active adaptive management to address climate change, managers and planners will have to make difficult decisions about where to allocate funds and efforts. In many cases, we will have to choose which populations, and perhaps even species, to let go extinct. As the ecological effects of climate change grow in magnitude in response to more rapid changes in climate and disturbance regimes, triage will likely become



Medical triage		Triage for ecosystems and species in a changing climate	
Expectant/Deceased	Reduce suffering and observe	Impacts can not be addressed with current resources	Observe and learn from changes
Critical	Immediate treatment	Impacts are critical but managable	Immediate action
Stable	Observe and treat as soon as possible	Severe impacts	Act as soon as possible
Minor injuries	Treat when possible or discharge	Low impact	Act when resources become available

Figure 3. Triage classification schemes for medical emergencies and for managing ecosystems and species in a changing climate.

an integral part of higher-level planning and management.

Triage—from the French verb *trier,* to sort—is a method of prioritization developed for treating patients in emergency situations. Priority for treatment is based on the severity of the injuries and the potential for survival. There are generally four basic triage classifications: deceased or expectant, critical, severe, and minor. Patients in each of these categories receive a different treatment (Fig. 3). Applying triage to conservation and management decisions is not a popular topic, and as such, has received relatively little attention. There are both ethical and ecological reasons that triage is a bitter pill for both conservationists and conservation biologists to swallow (Kareiva and Levin 2003). The loss of a population or a species may have massive implications for the functioning of an ecosystem in some cases or very little effect on a system in others.

A simple triage system for addressing climate change would provide a classification based on severity that paralleled the medical classification (Fig. 3). Some systems, species, or sites will likely undergo such substantial changes that they will be beyond managing with the available resources. Others will need to be managed immediately and constantly, but such management will be feasible. Still others will need to be managed but might be able to wait a few years if they are closely monitored. Finally, the rest of the species and systems will either require no management or will require some management in the future, but won't be lost if action isn't taken soon. These systems and species can be monitored if resources are available.

Medical triage approaches are often modified to address specific situations. For example, in a widespread emergency, if some of the injured include members of the medical profession, those doctors or nurses may receive a higher priority, even if they have relatively minor injuries, due to their value to the emergency response effort. A triage system for addressing climate change could likewise take the relative importance of species or ecosystems into account (Fig. 4). Rare species or systems, or highly valued species might be deemed of higher priority even if the severity of climate impact was projected to be relatively low. Species with high interaction strengths, particularly ecosystem engineers and keystone species, might, for example, receive higher priorities than other

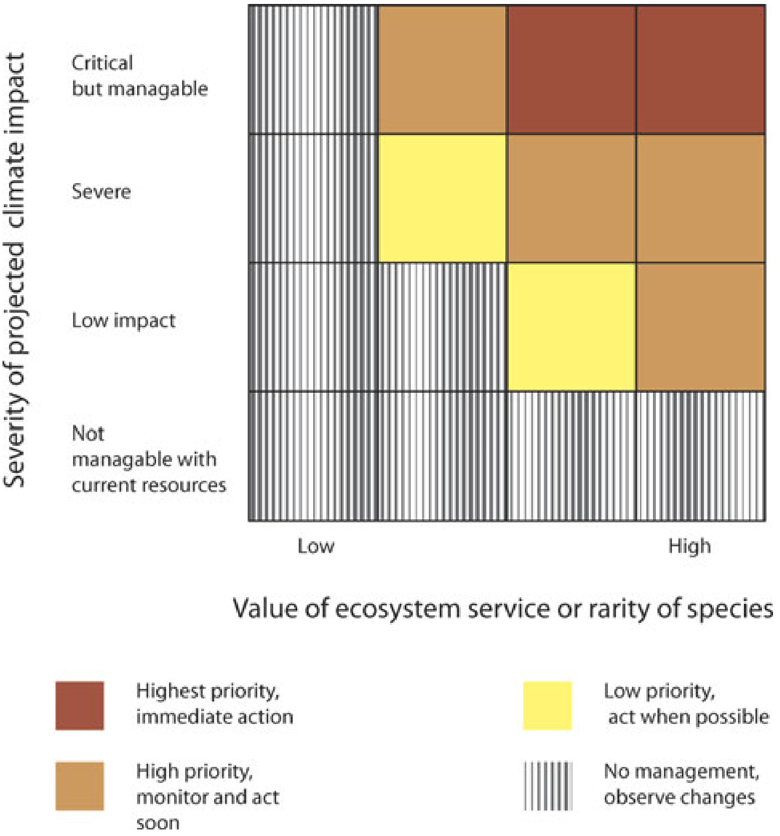


Figure 4. Triage classification for managing natural resources in a changing climate that accounts for both the severity of the climate threat and the value of the resource. The classification presented here is just one of a many potential manifestations of such a classification.

species. For example, beaver have the ability to alter hydrological systems in ways that may buffer streams from the effects of reduced snowpack and earlier spring runoff events. Thus, even if beaver are not likely to be highly affected by climate change, it may be wise to ensure the resilience of beaver populations in some systems for the benefit of the system as a whole. Systems and species that provide critical ecosystem services (again, beaver are a good example for services such as flood control and trout) might also be given higher priorities. There are clearly other ways to evaluate species and ecosystems that go beyond ecological impact. For example, the loss of a species may have little impact ecologically, but a large impact socially or economically (Ruckelshaus *et al.* 2003). Here again the concept of ecosystem services may be able to play a key role in prioritization and triage in the face of climate change.

Future Research Directions

The vast majority of recommendations for future research involve better understanding how species and systems will respond to climate change (Peters and Darling 1985; Kappelle *et al.* 1999; Noss 2001; Schlesinger *et al.* 2001; Hulme 2005; Root and Schneider 2006). Although such an understanding is clearly important, directing the bulk of our research efforts to this goal will likely produce far too little, much too late. Because responses to climate change will be species and system specific, we will likely discover few new generalities that will allow us to develop widely applicable adaptation strategies. Arguably, many of these generalities are already known (e.g., species will move in response to climate change, changes in phenology will decouple ecological systems). Instead of solely attempting to document system- and species-specific responses to climate change, to successfully address the challenge of how to respond to these changes, research efforts will need to have a much more applied focus.

Because understanding how each species and system will respond to climate change is not feasible, perhaps the most critical task for researchers is to determine which, if any, of the general concepts and basic prescriptions for adaptation will work and where and how they will work best. With respect to conservation planning, we should be asking whether aligning reserves along latitudinal or elevational gradients, connecting reserves with stepping stones, and expanding the bioclimatic footprint of reserves will provide more protection than merely increasing the number or size of reserves. With respect to removing other threats and environmental stresses, we will need to determine which existing threats and stresses will have the strongest synergistic interactions with rising temperatures and changing precipitation regimes.

Many of the general adaptation strategies focus on managing systems and landscapes to either lessen the impacts of climate change or to allow species to move in response to climate change. Fewer strategies are aimed at increasing the potential for evolution in the face of climate change. For many long-lived species, evolution will not be an option. Others, however, may be able to evolve in response to warmer temperatures, wetter or drier conditions, or changing habitats. Which populations and which species will have more evolutionary potential? How can we promote evolutionary potential through restoration, management, and conservation planning?

Given the critical role that adaptive management is likely to play in addressing climate change, one of the most important research needs involves gaining a better understanding of how to implement adaptive management. What is the best way to explore multiple climate-change scenarios in an adaptive management setting? What will need to be monitored? How often will monitoring need to be done? There has long been a call for increasing the amount of adaptive management that is actually implemented. Implementing adaptive management in a changing climate will both allow us to learn more about the ecological effects of climate change and to provide flexible management approaches.

Assigning priorities will require an understanding of which systems and species will be most vulnerable to climate change. Assessments of climate-change vulnerability and potential impacts can provide that knowledge (Desanker and Justice 2001; Kareiva *et al.* 2008). Although there are many potential approaches to developing a vulnerability assessment for climate change, any assessment would need to include at least two basic elements: (1) a measure of inherent sensitivity, and (2) projections of how and where climate will change. Additionally, a vulnerability assessment might include estimates of the adaptive capacity of a system, species, management agency, or society in general (McClanahan *et al.* 2008). Measures of inherent sensitivity can be taken from the literature, although, for many species and systems there is still little knowledge about their sensitivities to changes in temperature or precipitation. The vulnerability of individual species could be determined by factors such as physiology, specific habitat requirements, interspecific dependencies, dispersal ability, and population dynamics and location. An assessment of ecosystem vulnerability would include factors such as hydrologic or fire sensitivities, component–species sensitivities, and vulnerability to sea-level rise.

Determining where the largest climatic changes are likely to occur will require fine-scale predictions of future climate. There are several methods that take local climatic conditions and topographic variation into account to derive finer resolution climate data from coarse resolution general circulation model (GCM) projections (Wilby *et al.* 1998). Because of the variability across GCM projections, it will be necessary to assess potential future climatic changes based on a range of different climate-change projections. In addition to assessing climatic change, it will often be necessary to assess where potential climate-driven changes in disturbance regimes, the structure of vegetation, and species composition will be the greatest. Hydrological models can be used to generate predicted changes in hydrology (de Wit and Stankiewicz 2006), and fire models can be used to project changes in fire frequency, size, and severity (McKenzie *et al.* 2004). DGVMs can be used to generate predicted shifts in basic vegetation types corresponding to general habitat types (Bachelet *et al.* 2001; Cramer *et al.* 2001) and climate-envelope models can be used to assess how particular, sensitive species will likely respond to climate change or where changes in flora or fauna might be the greatest (Thuiller *et al.* 2005; Lawler *et al.* in press-a). Ideally, these species distribution models should take species dispersal abilities and landscape patterns into account to determine how species will move and where greenways and habitat corridors might be placed to enhance movement.

Finally, understanding how climate change will affect ecosystem services will be critical for setting priorities, conducting triage, and designing restoration projects. As discussed earlier in this chapter, assigning limited resources to a large number of potential management projects in an efficient way will require prioritizing those projects based on both the severity of potential climate impacts and the values of the systems, species, or populations. The concept of ecosystem services is one such valuation approach. Moving from species-based restoration to a concentration on restoring ecosystem functioning and ecosystem processes will also be aided by the concept of ecosystem services, and will require an understanding of how ecosystem services will be affected by climate change.

Conclusions

Managers already have many of the tools necessary to address climate change. The vast majority of these tools are those recommended for protecting biodiversity and managing natural resources in general. What is needed in the face of climate change is a new perspective. Each of these tools—enhancing connectivity, restoration, translocations—will need to be applied in light of the fact that disturbance regimes and ecosystems will change and species and pathogens will move. This new perspective will require expanding the spatial and temporal scale of management and planning. It will require restoring ecosystem functioning and managing for ecosystem services instead of species composition. It will include active adaptive management using scenario-based approaches. And, it will involve prioritization, and as climatic impacts become more acute, triage to determine which species and which ecosystem processes we will save.

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Conflicts of Interest

The author declares no conflicts of interest.

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