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Climate Change and Species Range Dynamics in Protected Areas

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Protected areas are key conservation tools for biodiversity management, but they are failing to protect species from current climate change. Focusing on protected areas representing montane, arid, coastal, and marine ecosystems, we provide examples of climate change–induced range dynamics, including species' moving out of protected areas, disease range expansions, severe population declines, and even extinctions. Climate change thus presents an immense challenge to protected areas but also an unparalleled opportunity to shift from managing for static, historical community composition toward managing for dynamic, novel assemblages, thus complementing the traditional individual-species approach with an ecosystem-services approach. In addition, protected areas are well positioned to lead the way in climate change mitigation. Protected area managers can start achieving these goals by strengthening their commitments in climate change research, community outreach, and sustainability.

Keywords: climate change, protected areas, range shifts, species distributions, mitigation

Climate change is driving many species of animals and plants to alter their geographic distributions. The ranges of some species contract, expand, or shift as individuals track favorable climate conditions (Parmesan and Yohe 2003). In some cases, threatened species are moving out of protected areas (Parmesan 1996, Hannah et al. 2007), and invasive species or pests are moving in (Benning et al. 2002, Logan et al. 2003). Biologists now recognize climate change as a serious threat to the viability of many species (Thomas et al. 2004) and one of the primary drivers of our present extinction crisis (Stork 2010). For example, the IUCN (International Union for Conservation of Nature) Red List of Threatened Species currently registers 1610 species as being threatened by climate change and severe weather. These threats have been implicated in the extinction of 19 animals, 3 of which were birds endemic to Hawaii: the Laysan rail (*Porzana palmeri*), the Kauai oo (*Moho braccatus*), and the Hawaiian thrush (*Myadestes myadestinus*) (table 1). The latter two species, which were formerly abundant, went extinct in the 1980s partly because of the upward invasion of disease-carrying mosquitoes and hurricane damage of upland forest in their last refuge, the Alaka'i Wilderness Preserve (IUCN 2011), thus challenging our notion of "protected area."

Biodiversity conservation has traditionally relied on systems of protected areas with static, artificially designated boundaries often established using criteria other than ecological ones, but climate systems, ecosystems, and species ranges are all dynamic. Protected areas are remarkably successful at buffering species from the historical drivers of population declines, such as habitat degradation, fragmentation, and unlawful harvest. However, protected areas cannot similarly buffer species from climate change. Although protected areas are key conservation tools, their limited surface coverage and the inflexibility of their political boundaries hinder their ability to fulfill their conservation mandates under future climate change; this is true both for the global network (Rodrigues et al. 2004) and for the US (Burns et al. 2003) network of protected areas. Therefore, protected areas should modify their strategies to address the root causes and effects of climate change. Altered species ranges are just one of many ecological symptoms, but they exemplify how protected area management is fundamentally challenged by climate change; the challenge, however, can be addressed effectively by an increased focus on social solutions and climate change mitigation.

Many peer-reviewed articles and "gray literature" reports have been written on the subject of climate change and protected area management (e.g., Hannah et al. 2007, Baron et al. 2009, Heller and Zavaleta 2009, Dudley et al. 2010, Hobbs et al. 2010). There has been an exponential increase in the number of related articles published in recent years; however, many authors have tended to present their recommendations in vague terms that lack specificity and are rarely useful for protected area managers. Also, most recommendations have focused on ecological solutions and have largely neglected social solutions (Heller and Zavaleta 2009). However, social solutions are crucial during a time when anthropogenic climate change is posing a major threat to species, a threat that protected areas alone cannot overcome. In this article, we highlight some climate-induced range changes in recent and paleontological history and also describe generally how future range changes can be projected using

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Table 1. Nineteen species of animals now extinct or extinct in the wild partly because of climate change and severe weather.

Class	Scientific name	Common name	Geographic range
Ray-finned fishes	*Acanthobrama telavivensis*	Yarkon bleak	Israel
	Telestes ukliva	Ukliva dace	Croatia
	Tristramella magdelainae		Syria
Amphibians	*Anaxyrus baxteri*	Wyoming toad	Wyoming
	Atelopus ignescens	Quito stubfoot toad	Ecuador
	Atelopus longirostris	Longnose stubfoot toad	Ecuador
	Craugastor chrysozetetes	McCranie's robber frog	Honduras
	Craugastor escoces	Heredia robber frog	Costa Rica
	Incilius holdridgei	Holdridge's toad	Costa Rica
	Incilius periglenes	Golden toad	Costa Rica
Birds	*Fregilupus varius*	Réunion starling	Réunion Island
	Moho braccatus	Kauai oo	Hawaii
	Myadestes myadestinus	Hawaiian thrush	Hawaii
	Porzana palmeri	Laysan rail	Hawaii
	Psephotus pulcherrimus	Paradise parrot	Australia
Gastropods	*Pachnodus velutinus*	Pachnodus snail	Seychelles
	Pseudamnicola desertorum		Algeria
	Rhachistia aldabrae	Aldabra banded snail	Seychelles
Mammals	*Geocapromys thoracatus*	Little Swan Island hutia	Swan Islands (Honduras)

Source: IUCN 2011.

species distribution models. Although we acknowledge that climate change is expected to affect most—if not all—of the world's ecosystems, we discuss a variety of case studies from protected areas that represent montane, arid, coastal, and marine ecosystems because of their particular sensitivity to climate changes (Heller and Zavaleta 2009). We also discuss how climate change alters the spatial distribution of wildlife diseases. Last, we provide some clear, practical, and actionable recommendations that protected area managers can implement to strengthen climate change mitigation through research, community outreach, and sustainability.

Range dynamics

Contemporary changes in species ranges consistent with global warming have already been observed in a wide variety of species, communities, and ecosystems on all continents and in most oceans (Parmesan 2006). In general, these expected distributional changes are poleward in latitude and upward in elevation. In their meta-analysis of 99 species of plants and animals, Parmesan and Yohe (2003) estimated that the average shift per decade in northern range and upper elevation boundaries is 6.1 kilometers (km) northward and 6.1 meters (m) upward, respectively. However, Hickling and colleagues (2005) reported an average shift of 30 km per decade northward in the range margins of 37 species of dragonflies and damselflies in the United Kingdom, and Moritz and colleagues (2008) reported an average shift of 50 m per decade upslope in 14 species of small mammals in Yosemite National Park over the past century. Remarkably, whole warm-water zooplankton communities in the North Atlantic Ocean have shifted northward in distribution up to 1000 km since 1960 (Beaugrand et al. 2002).

Range shifts induced by climate change are not a new phenomenon. Many species shifted their ranges during the late Quaternary in response to climate change, which included glaciations and warming (Lyons 2003, Gill et al. 2009). Lyons (2003) determined that Pleistocene mammals in North America shifted their ranges 1200–1400 km, on average, but changed their range size very little. The individualistic responses of species to past climate change also shuffled community compositions. Although the time scales are very different, these paleontological observations have implications for protected area management. Species no longer have the ease of shifting ranges that their Pleistocene ancestors enjoyed because contemporary climate change is more rapid and habitats are smaller and more fragmented. Adaptation strategies for expanding and connecting protected areas are certainly meritorious, but the role of protected areas in curtailing the causes of anthropogenic climate change needs more attention.

In addition to the examples of range shifts already observed, scientists employ species distribution models to simulate distributional changes under future climate scenarios. Modelers use two general approaches: correlative and mechanistic. Correlative approaches, such as climate envelope models, are used to find environmental characteristics that can predict various metrics of species' presence. These models essentially characterize a species' *realized niche*, the set of environmental variables associated with its current distribution. However, the realized niche is constrained not only by the environment but also by competition with other species and by historical distribution limits. Mechanistic models have been developed that use species-specific biophysical properties (e.g., physiology, morphology, behavior) to characterize a species' fundamental niche (Kearney and Porter 2009). The *fundamental niche* is constrained only by the environment and is therefore broader than the realized niche. These models can be used to predict where and when climate change is expected to drive range shifts caused by limited physiological tolerances (figure 1). This approach has been used successfully for both endotherms and ectotherms (Kearney and Porter 2004). When appropriate species and environmental data are available, the integration of mechanistic and correlative approaches holds enormous potential for real-world ecological applications such as protected area management (Kearney and Porter 2009). So far, only correlative analyses have been applied to large numbers of species at the same time to explore species representation in protected areas under various climate change scenarios (e.g., Thuiller et al. 2006, Hannah et al. 2007). However, except for an examination of mammalian diversity (Burns et al. 2003), no such analysis has been carried out for the United States' protected area network.

Case studies

Here, we present several examples of climate-induced range dynamics from some sensitive ecosystems. Range shifts of threatened or charismatic species have received much attention, so we conclude this section by highlighting how climate change also alters the ranges of pathogens.

Montane ecosystems. Wilderness and protected areas are located disproportionately in mountainous regions (Scott et al. 2001). These same regions are expected to experience some of the largest climatic changes (Root et al. 2003). Most montane species are expected to respond to warming temperatures by moving upslope. Because of the conical shape of mountains, upslope displacement leaves species with smaller and more isolated habitat patches, increasing the likelihood of local extinction for plants and animals (Dirnböck et al. 2003, Ditto and Frey 2007). Guralnick (2007) found that North American montane species typically moved upslope in response to Quaternary warming, whereas flatland species typically moved north. Consistent with these theoretical and paleontological patterns, recent altitudinal range shifts and population declines at low elevations have already been observed for multiple species in the Great Basin (Beever et al. 2010).

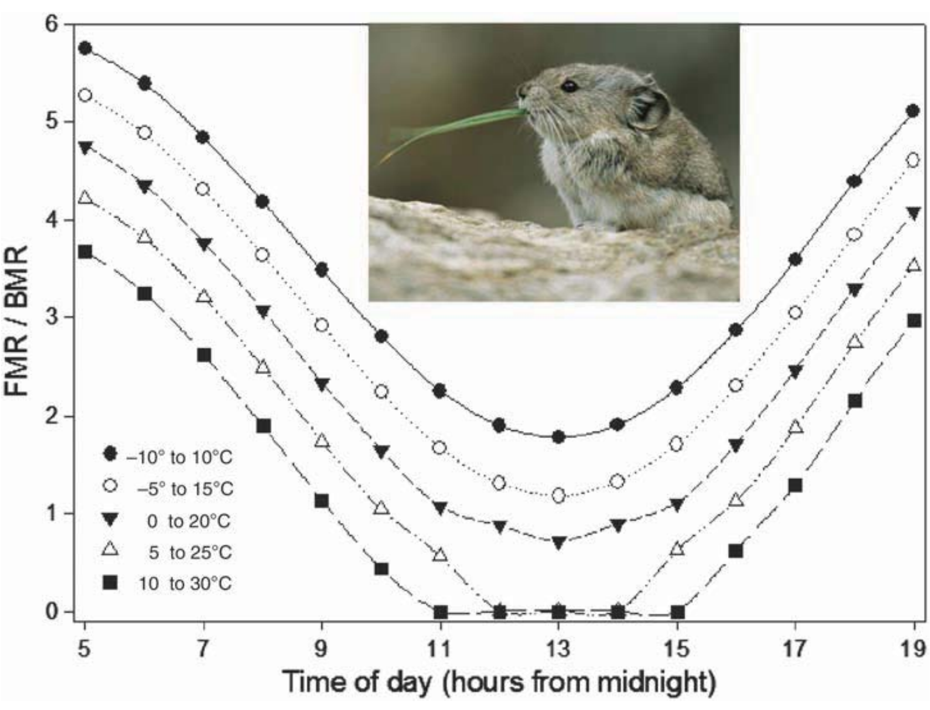

Figure 1. Niche Mapper (see Kearney and Porter 2009) biophysical model simulations of American pika field metabolic rate (FMR) as a proportion of basal metabolic rate (BMR) when above the talus during August daylight hours in Glacier National Park, Montana. We modeled four daily temperature ranges that are typical for the park's elevations, and the fifth temperature range (10°C–30°C) is expected at the lowest elevations by 2100. The coldest temperature occurs shortly before sunrise (0500) and the warmest occurs in the early afternoon (1300). Ambient temperature is given, although the temperature at pika height (9 centimeters) is typically 3°C–7°C higher because of ground boundary layer effects of sunlight on the rock or ground surface. Wind speed was held at a constant 1.5 meters per second. Pikas running an FMR less than 1.5 × BMR would be unlikely to be active above the talus. When FMR/BMR < 1, the animal experiences acute heat stress and eventually death. An FMR/BMR > 4 would likely be difficult for the pika to achieve because of high caloric demands.

Montane species will be subject not only to increasing temperatures but also to changing precipitation regimes. Species may be stressed by either or by both. Epps and colleagues (2004) predicted that bighorn sheep (*Ovis canadensis*) will be affected most by water stress. Western North America has already experienced decreased snowpack (Mote et al. 2005). The quantity and timing of snowpack deposition and melting can have significant effects on species adapted to the long stretches of resource scarcity typical of mountain ecosystems. Some species, such as wolverines (*Gulo gulo*), depend on persistent spring snowpack for gene flow through dispersal (Schwartz et al. 2009). In addition, long winter stretches of reduced snowpack imperil many hibernators that depend on snow's insulating qualities, whereas earlier growing seasons leave plants susceptible to frost damage (Inouye 2008). For example, the fecundity of American pikas (*Ochotona princeps*) increases when the birth of their first litter is synchronized with spring snowmelt and vegetation emergence (Smith 1978). Pika extirpations in the Great Basin were best explained by both chronic heat stress and acute cold stress, the latter attributed to reduced winter snowpack (Beever et al. 2010). These recent pika extirpations occurred even in protected areas, such as Fremont National Forest and Pine Forest Recreation Area.

Climate change in montane regions also affects community composition and phenology. Cross and Harte (2007) observed losses of shallow-rooted alpine forbs concurrent with an expansion of tap-rooted forbs and grasses during warming experiments. The authors concluded that this community shift could increase the system's sensitivity to perturbation. Climate change is already affecting altitudinal migrants, montane hibernators, and flowering plants that rely on seasonal climate cues (Inouye 2008). Increased monitoring of particularly sensitive and detectable species in protected areas, especially those with abundant historical and paleodistribution data, such as American pikas and alpine plants, will allow managers to make better-informed decisions; this is especially important in mountain systems that have complex weather and climate.

Arid and semiarid ecosystems. Water scarcity is the norm in arid and semiarid ecosystems; lasting changes in temperature, precipitation, and humidity are likely to have implications for the biodiversity in these and neighboring systems. Riparian and interdunal wetlands in dry landscapes provide stopovers for millions of migratory birds and habitat for many plants and nonmigratory animals. In Great Sand Dunes (GSD) National Park and Preserve, in Colorado, water is important not only for the park's geology but also for the park's ecology. The seasonally flowing waters support a remarkable diversity of plants and animals. For example, the headwaters of Little and Big Spring Creeks support populations of large ungulates, such as bison, elk, mule deer, and pronghorn. The physical location of these headwaters depends on the water table, which itself depends on precipitation over the dune field and the Sangre de Cristo Mountains to the east. A drying climate in this region would lower the water table and shift the creeks' headwaters farther west. Predictably, the extent of the ungulate populations would also shift westward. It is not unreasonable to imagine whole populations and communities moving out of arid and semiarid reserves to track water resources as hydrological regimes change. Fortunately, in November 2000, Congress passed the GSD National Park and Preserve Act, which authorized the conversion and expansion of GSD National Monument into a national park almost four times its original size. The western boundary of the park is currently more than 8 km west of the headwaters of Little and Big Spring Creeks, thereby ensuring that the park's species do not lose representation within the park even if the water table drops. On the other hand, more than 100 interdunal wetlands have disappeared from the GSD dune field since 1937. Wurster and colleagues (2003) concluded that this phenomenon was not caused by ground water pumping in the San Luis Valley but is best explained by a drop in the water table brought about by climatic changes since the late 1930s.

Coastal and marine ecosystems. An obvious climate-related phenomenon that affects species distributions is sea level rise. The extent of natural land in coastal protected areas will be squeezed between the ocean and human-dominated landscapes as sea level rises (Shirley and Battaglia 2006). The only way for terrestrial species in coastal protected areas to survive is to move upslope. In the Florida Keys, threatened species, such as the Florida Key deer (*Odocoileus virginianus clavium*), the endangered silver rice rat (*Oryzomys palustris natator*), the Key ringneck snake (*Diadophis punctatus acricus*), and the striped mud turtle (*Kinosternon baurii*), are vulnerable to rising sea levels. Under a scenario of moderate sea level rise (0.6 m), the range of the Lower Keys marsh rabbit (*Sylvilagus palustris hefneri*) is expected to contract its current extent by 74% to 90%, depending on the species' ability to move upslope and human activity in already developed areas (LaFever et al. 2007). In Mandalay National Wildlife Refuge, Lafitte National Historic Park and Preserve, and Grand Bay and Weeks Bay National Estuarine Research Reserves—all protected areas in the Gulf of Mexico—marsh vegetation is being replaced by open water in the south and scrub shrub in the north (Shirley and Battaglia 2006).

Climate change–related threats to coral reefs have serious ecological and socioeconomic implications for protected areas in the United States, such as Dry Tortugas and Biscayne National Parks and Florida Keys National Marine Sanctuary. Climate change stresses coral reef communities in at least four different ways: coral bleaching, acidification, disease, and physical disturbance. Coral bleaching occurs when the thermal tolerance of corals and their algal symbionts is exceeded, which results in the coral's loss of color. Recent rises in sea surface temperature (SST) have caused bleaching and subsequent mortality in reef-building corals throughout the world. The worst worldwide bleaching episode on record was in 1998 and coincided with the strongest El Niño Southern Oscillation event on record (Hoegh-Guldberg 1999). An analysis of future SST from three climate models revealed some alarming results: An SST that exceeds the thermal tolerance threshold is predicted to occur yearly in the next few decades (Hoegh-Guldberg 1999). Increases in atmospheric carbon dioxide (CO_2) drive not only global warming but also ocean acidification. Projections of oceanic pH, even under a conservative CO_2 emissions scenario, predict a more acidic ocean by 2050 that may be unable to sustain coral calcification (Hoegh-Guldberg et al. 2007). This translates to contracting coral cover and brittling of existing coral skeleton. Temperature-induced disease outbreaks can also occur, as in the Great Barrier Reef of Australia, where temperature appeared to be a key variable associated with a bacterial outbreak that elevated partial colony mortality from 20% to 80% and caused complete mortality in six tagged colonies (Jones et al. 2004). Porter and colleagues (2001) documented a dramatic increase in the number of localities and species with coral disease in the Florida Keys: Relative to 1996 values, there was a 404% increase in the number of locations exhibiting disease and a 218% increase in the number of species affected. Finally, the predicted increase in frequency of category 4 and 5 hurricanes with rising SST (Hoyos et al. 2006) poses a physical threat to coral reef communities. A meta-analysis showed that Caribbean coral cover is reduced by 17% in the year following a hurricane impact and that there is no evidence of recovery to the prestorm state even eight years after the hurricane (Gardner et al. 2005).

One interesting example that demonstrates the interconnectivity of marine and terrestrial ecosystems is that of the Farallon National Wildlife Refuge. This protected area, most of it designated wilderness, is a group of islands about 43 km west of San Francisco Bay. It supports the largest sea bird breeding colony south of Alaska. More than 250,000 sea birds live there, representing 13 species, including the Cassin's auklet (*Ptychoramphus aleuticus*), an obligate planktivore. However, the plankton in these waters has decreased in biomass by 80% since 1951 (Roemmich and McGowan 1995), probably because of a community-wide range shift. Consequently, the population of cold-water auklets underwent a cumulative decline of 75% between 1971 and 2002 (Lee et al. 2007).

Diseases. The geographical ranges of most species, including those of pathogens that confer infectious diseases, are mainly limited by their temperature tolerances. As the world gets warmer, we should expect to see changes in the way animals, plants, and their pathogens are distributed. Habitat suitability for infectious disease has been and will be affected by climate change. Although the range of some infectious diseases will probably shift geographically as temperatures increase (Lafferty 2009), other diseases will likely expand their ranges, affecting even larger extents of land or water where the climate is favorable for both the pathogen and its vector. For example, mosquito survivorship declines with increased altitude because cooler temperatures impair mosquito development rates (Bødker et al. 2003); cooler temperatures and high altitudes also prevent some infectious agents from completing their life cycles. As a result, endemic forest birds in Hawaii find refuge from avian-malaria-infected mosquitoes when shifting their territories to higher and cooler elevations (van Riper et al. 1986, Benning et al. 2002). But those high-elevation refuges are shrinking as the climate envelope of mosquitoes creeps upslope. It is not currently known whether the birds can adapt to a new environment as fast as the temperature changes or whether the forest vegetation that provides food and refuge for the birds is also shifting upward.

Climate change has had devastating effects on ectothermic hosts because it interacts with other biotic threats. Entire communities of amphibians, including as many as 30 species of the harlequin toad (*Atelopus*), have been decimated from Neotropical forests by a highly virulent fungal disease, chytridiomycosis (La Marca et al. 2005, Pounds et al. 2006). Growth of the pathogenic fungus *Batrachochytrium dendrobatidis* is favored by warming at high altitudes so that disease outbreaks and subsequent amphibian die-offs usually follow warm years. Furthermore, increased cloud cover contributes to warmer nights and cooler days, which thereby expands the altitudinal range with conditions near the pathogen's growth optimum (Pounds et al. 2006). Most of the species declared extinct because of climate change are amphibians (table 1). Many of those declines and extinctions occurred and continue to occur in protected areas. Evidently, protected areas are not protecting *Atelopus* and other amphibian taxa.

Climatic changes can also affect the migration patterns of host species. Environmental conditions in an area can become favorable enough for year-round survival on breeding grounds, which could stop migration completely (Harvell et al. 2009). The problem of resident Canada geese (*Branta canadensis*) populations in the southeastern United States is a good example of this behavioral change. Another important complication that comes from changes in migratory patterns is contact with novel species, which can facilitate cross-species transmission of pathogens to immunologically naive populations. Pathogens that encounter a naive population can spread quickly, taking a huge toll on host abundance (Harvell et al. 2009). A good example is the northward movement of elk (*Cervus canadensis*) and white-tailed deer (*Odocoileus virginianus*) toward the range of caribou (*Rangifer tarandus*) and musk ox (*Ovibos moschatus*); the elk and deer carry with them a whole new suite of pathogens for which the ox and caribou have no natural resistance (Dobson 2009). At the same time, because of warmer temperatures, the parasites of ox and caribou, such as Protostrongylid nematodes, now complete their life cycle in a third of the time, taking only one year to cycle and producing a much higher number of parasites, which leads to high levels of morbidity and mortality in their hosts (Kutz et al. 2005).

Management challenges and opportunities

Climate change presents immense challenges to protected area managers but also unparalleled opportunities to manage for change and to engage the public. Challenges should be met with careful reassessment of local and regional management goals and consideration of potential climate change impacts. Thinking creatively and optimistically is vital to treating the climate crisis as an opportunity for constructive change (Hobbs et al. 2010). Although we recognize that different protected area designations have different management objectives, we maintain that protected areas can still conserve individual species, ecosystem services, and entire landscapes through climate change mitigation and adaptation strategies (Dudley et al. 2010). Protected area managers can achieve these goals by strengthening their commitments in three areas: climate change research, community outreach, and sustainability.

Climate change research. More research needs to be done, especially to resolve at least some of the compounding uncertainties associated with species distribution models, emissions projections, and climate models. The field of predictive climatology is still young. Finer-scaled regional climate models are needed to predict the effects of climate change at a scale suitable for on-the-ground management (Heller and Zavaleta 2009). Protected area managers should team up with climate and species modelers to explore how climate is predicted to change in their particular jurisdiction and how this may influence vegetation and species ranges.

Field studies of species' responses to climate change are invaluable. These studies would include gathering baseline distribution and behavior data with continued monitoring. Unfortunately, protected areas typically lack the funding and capacity for such research to be carried out alone. Citizen science programs, in which visitors volunteer to collect data for ongoing monitoring studies, alleviate some of the monetary and workforce deficiencies while providing a medium for the fusion of science, education, and outreach. Citizen science also provides a forum for positive interaction between protected areas and the public. These communications are based on mutual interests (e.g., learning about wildlife) rather than confrontation, which is common between protected area managers and landowners. Importantly, volunteers may also enhance their understanding of global change biology and of the scientific process in general (Bonney et al. 2009). Citizen science is also becoming more convenient for all parties involved. In an ingenious marriage of technology and natural science, mobile phone applications for environmental data collection and georeferencing are available. Some examples are Project NOAH (*www.projectnoah.org/mobile*) and WildObs (*http://wildobs.com*). People can be made aware of such free applications at protected area visitor centers or Web sites, can download the applications voluntarily, and can assist in monitoring species of interest. Protected area managers can also partner with the USA National Phenology Network (table 2), which encourages and trains people to monitor the influence of climate on the phenology of plants, animals, and landscapes.

Greater collaboration between academic scientists and protected area managers would provide necessary expertise, increase student involvement, and expand protected area research capacities. The US National Park Service (USNPS) is an exemplary agency that has numerous climate change research and education initiatives underway, such as the newly established George Melendez Wright Climate Change Fellowship for graduate and upper-level undergraduate research (table 2). In addition, some universities already have citizen science research programs—for instance, the Cornell Lab of Ornithology's FeederWatch and NestCams projects. Protected areas can offer new arenas for programs such as these that are already in action.

Considering the challenges that climate change presents to traditional protected area management strategies, a careful reexamination of goals is necessary. Biodiversity management and conservation have traditionally been guided by the philosophy of preserving or restoring historical species assemblages, but these assemblages themselves are the result of species distributions changing and reshuffling in response to previous climatic shifts. One adaptation strategy is to accept the dynamic nature of species ranges and to focus on ecosystem integrity and resilience (Lawler 2009, Hobbs et al. 2010). Whereas intensive management actions to maintain species in their historical and current ranges are widely advocated, we encourage a shift from managing for static, historical community composition toward managing for dynamic, novel assemblages (Baron et al. 2009, Heller and Zavaleta 2009, Hobbs et al. 2010). Although this recommendation marks a significant departure from the mission of most protected areas, we maintain that this strategy is better aligned with reality. Resisting change by forcing species to remain in a geographical space that no longer represents their evolved climate envelope, for example, is as impractical and inefficient as erecting fences around protected areas.

Note that we are not advocating for an abandonment of species-focused conservation goals. Not only are species-specific action plans mandated by the Endangered Species Act (in the United States) and other state laws but they also help prevent local extinctions in the short term. Clearly, increasing protected areas' surface coverage and connectivity would benefit species conservation (Hannah et al. 2007). But we also recommend an increased focus on preserving ecosystem services and the environmental heterogeneity that drives evolutionary processes and species richness in the long term. Anderson and Ferree (2010) revealed that species richness in the temperate area of North America is best explained by geological diversity. They concluded that conserving the geophysical setting is a robust alternative to individual-species approaches for lasting conservation success; this is because land protection decisions based on geological characteristics are not rendered obsolete by a changing climate. Interestingly, this supports the idea of conserving areas with unique or highly diverse geologies, the same reason for which many protected areas, especially

Table 2. Climate change mitigation and adaptation programs and strategies in the US Department of the Interior (USDOI), which manages more than 2,000,000 square kilometers of protected areas, and their involvement in research, community outreach, and sustainability.

Program or strategy	Agency	Research[a]	Community outreach[b]	Sustainability[c]	Web site
Climate Change Response Council	USDOI	✓		✓	*www.doi.gov/whatwedo/climate*
Climate Science Centers	USDOI	✓	✓		*www.doi.gov/whatwedo/climate/strategy/CSC-Map.cfm*
Landscape Conservation Cooperatives	USDOI, led by USFWS	✓			*www.fws.gov/science/shc/lcc.html*
WaterSMART	USDOI, led by USBR	✓	✓	✓	*www.doi.gov/watersmart*
Interagency Climate Change Adaptation Task Force	USDOI, with NOAA, OSTP, et al.	✓			*www.whitehouse.gov/administration/eop/ceq/initiatives/adaptation*
US Global Change Research Program	USDOI, with NOAA, OSTP, et al.	✓	✓		*www.globalchange.gov*
Climate Change Response Program	USNPS	✓	✓	✓	*www.nature.nps.gov/climatechange/response.cfm*
George Melendez Wright Climate Change Fellowship	USNPS	✓			*www.nature.nps.gov/climatechange/internshipsresearch.cfm*
Inventory and Monitoring Program	USNPS	✓			*http://science.nature.nps.gov/im/climate/index.cfm*
Climate Friendly Parks	USNPS		✓	✓	*www.nps.gov/climatefriendlyparks*
Strategic Plan for Responding to Accelerating Climate Change	USFWS	✓	✓	✓	*www.fws.gov/home/climatechange/strategy.html*
National Fish, Wildlife, and Plants Climate Adaptation Strategy	USFWS	✓			*www.wildlifeadaptationstrategy.gov*
Rapid Ecoregional Assessments	USBLM	✓			*www.blm.gov/wo/st/en/prog/more/climatechange.html*
National Climate Change and Wildlife Science Center	USGS	✓			*http://nccwsc.usgs.gov*
Climate Change and Western Water Group	USGS, USBR, NOAA	✓			*www.esrl.noaa.gov/psd/workshops/mwwcc/docs.html*
National Phenology Network	USGS, USFWS, USEPA, et al.	✓	✓		*www.usanpn.org*

[a]*Research* refers to programs or strategies that focus on the natural and physical sciences and their implications for adaptive management.
[b]*Community outreach* refers to efforts to engage the general public. Efforts to educate the public on sustainable living are included here.
[c]*Sustainability* refers to programs or strategies that aim to implement sustainable practices in agency operations and facilities.
NOAA, National Oceanic and Atmospheric Administration; OSTP, Whitehouse Office of Science and Technology Policy; USBLM, US Bureau of Land Management; USBR, US Bureau of Reclamation; USEPA, US Environmental Protection Agency; USGS, US Geological Survey; USFWS, US Fish and Wildlife Service; USNPS, US National Park Service.

national parks and monuments, were initially established in the United States.

Community outreach. Protected areas provide ideal environments for strong and interactive educational programs. Protected areas' natural resources are now threatened by global human activity and even also by their own visitors, who, for example, unwittingly carry potentially invasive nonnative species on their clothes, in boats, and in automobiles. Visitors can be educated about how their actions affect natural resources and what they can do to help protect them. Protected area managers should engage in more climate change education, offering examples of how their own species and landscapes have been and are predicted to be influenced. Information could be provided on observed and projected geographic shifts in species and disease distributions. This can be done through pamphlets, Web sites, plaques, and communications with staff or volunteer naturalists. For example, the USNPS Web site has a "For Teachers" section for each management unit; educational resources about climate change and local species could be placed here for teachers to use in the classroom curriculum.

Protected area managers should also encourage people to explore and identify with nature so that they feel a stronger connection to it, one that is remembered and taken home with them. Activities that promote conservation action and encourage reflection on one's relationship with nature can produce immediate changes in resource consumption and attitude (Moyer-Horner et al. 2010). Protected areas should encourage such reflection and urge visitors to communicate their experiences to their friends and family. One way to do this is by taking the protected area to the people: Scientists, staff, and volunteers can give outreach talks to schools and communities. Having live animals and plants present would be especially useful because this engages people of all ages and leaves a lasting impression. Citizen science programs, mentioned above, are yet another way to do this. For example, a "Report Your Sighting" section can be added to each protected area's Web site for visitors to report species sightings and to upload photographs; this information can be used to estimate abundance and phenology at a local scale.

Sustainability. The rate and scale of projected climate change expose our lack of knowledge on ecosystem, community, and species range dynamics and are sure to overwhelm our adaptive management capacities. Unless climate change can be mitigated, managers are doomed to a Sisyphean task. For this reason, climate change must be addressed at its root cause: resource consumption (Myers and Kent 2003, Ehrlich and Goulder 2007). Natural resource agencies and the protected areas they manage are well positioned to champion a cultural shift toward reduced resource consumption. Agencies' offices, visitor centers, and vehicles should reflect the latest energy-efficient and emissions-reducing technologies. In addition, each protected area's visitor center should have a recycling station and use recycled or local materials. Recent initiatives by the USNPS and the US Fish and Wildlife Service (USFWS) are commendable. Both agencies made firm commitments to substantially reduce their carbon footprints. The USNPS established the Climate Friendly Parks program, which supports individual units of the USNPS network that wish to implement more sustainable practices in their operations. The USFWS developed a strategic plan to become carbon neutral by 2020. The USNPS also introduced the Climate Change Response Program, which focuses on science, adaptation, mitigation, and public education (table 2).

Protected areas, with their defined governance structures and legal conservation-oriented frameworks, are well situated to lead the way in climate change mitigation (Dudley et al. 2010). In addition, protected areas are ideal arenas in which the effects of climate change can be observed, and as such, they can also become ideal stages where creative solutions to climate change are spotlighted. The institutional and cultural changes necessary to mitigate climate change and allow protected areas to truly protect their resources are large scale, but if sustainable practices are modeled in protected areas, the public and other agencies will notice. Protected area managers, like all of us, must continue to find and execute strategies to operate in a more sustainable manner.

Protected areas alone cannot accomplish so much. Protected area managers can find help to achieve their goals by partnering not only with local private landowners but also with community organizations, indigenous peoples, nongovernmental organizations, county boards, and local schools and universities. One such new effort by the US Department of the Interior, called the Landscape Conservation Cooperatives, is an example of how increased collaboration can be catalyzed (table 2). However, most current efforts by protected area agencies focus on the natural and physical sciences and their implications for adaptive management (table 2). These are important, but clearly, more social solutions in the areas of community outreach and sustainability are needed. Ultimately, climate change research, educational outreach, and sustainability programs create opportunities for communities to unite for a common cause. For example, many religious groups have found common ground in environmental stewardship and sustainable resource use. Communities can renew their connection with nature by collaborating with protected areas to preserve species, restore ecosystem services, and mitigate climate change.

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