



Climate Change Threats
to the National Parks
and Protected Areas
of the United States and Canada



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CLIMATE CHANGE THREATS TO NORTH AMERICAN NATIONAL PARKS AND PROTECTED AREAS

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I. EXECUTIVE SUMMARY

"There is, as yet, no sense of pride in the husbandry of wild plants and animals, no sense of shame in the proprietorship of a sick landscape."

Aldo Leopold

Introduction

This study represents the first time that the threat from global warming to our National Parks and protected areas has been reviewed. The resulting report presents a startling picture, not just of change to come, but of visible changes already on our landscape. More than 250 million people visit the National Parks of the United States and Canada every year. If climate change continues to accelerate as a result of pollution of the atmosphere by greenhouse gases (primarily from burning coal oil and gas), our children and future generations will be robbed of at least part of the "National Park experience" that we take for granted today.

We present here an overview of the current state of scientific knowledge about what the changes in the parks and in other preserves will be. The report is based on careful review of the existing scientific literature and extensive interviews with dozens of scientists working on the ground. Many scientists have given us access to unpublished data and materials. The report also includes an entirely new World Wildlife Fund (WWF) scientific analysis of climate threats to vegetation zones in and around U.S. protected areas under different climate scenarios (see Appendix 1).

Evidence of Change

The effects of global warming are not merely a future impact in faraway places. The first signs of climate change have been detected and can already be seen in our own backyards. Alarming, many of North America's most cherished natural areas, the National Parks, are clearly feeling the effects of global warming. Some of the strongest physical evidence of the accelerating warming trend of the last century is provided by the melting of glaciers. National Parks including **Glacier Bay** and **North Cascades** show evidence of melting ice. Detailed monitoring in Montana's **Glacier National Park** shows that it has already lost some of its smaller glaciers during the past 30 years, and massive melting has been recorded for the Sperry and Grinnell glaciers. A strong warming trend in the Arctic is leading to the melting of the permafrost that underlies ecosystems in many places, including Alaska's **Denali National Park** and **Wood Buffalo National Park** in Canada.

Other evidence includes the warming of the oceans, which is causing changes in marine ecosystems and resulting in sea level rise threatening many coastal reserves with permanent inundation and flooding. Because warming water has reduced their food supply, more than 90% of the population of the albatross-like sooty shearwater have

disappeared from the coastal waters off U.S. west coast reserves such as the **Channel Islands National Park** and **Point Reyes National Seashore**. Rising seas have already affected the **Everglades National Park** and **Key Deer National Wildlife Refuge** in Florida, as well as destroying large parts of the marsh at **Blackwater National Wildlife Refuge** on the eastern shore of the Chesapeake Bay.

Even the forests are showing the first signals of change. Warming is causing the ancient, stunted, shrubby forms of spruce at the tree line, high in the **Rocky Mountain National Park**, to put on spurts of vertical growth. The beautiful subalpine wildflower meadows of **Mount Rainier National Park** and **Olympic National Park** are being invaded by trees as the temperature warms, and the preponderance of evidence points to an increased fire risk in **Yellowstone National Park** partly as a result of recent and rapid changes in the climate.

The Major Categories of Threat to Protected Areas from Global Warming

1. Sea level rise and coastal inundation

One of the most direct impacts of global change is sea level rise caused by the melting of glaciers and the warming of the oceans. Many low-lying coastal reserves are at risk, particularly along the mid-Atlantic and southeastern coast of the United States. **Assateague, Cape Hatteras, and the Gulf Islands National Seashores** are among the threatened sites, along with **Everglades National Park**. Two of the United States' most important sites for migratory shorebirds and water fowl, the **San Francisco Bay National Wildlife Refuge** and the **Yukon Delta National Wildlife Refuge**, are unlikely to be able to adapt to an accelerating rate of sea level rise.

2. Habitat loss and species extinction

Major ecological impacts of climate change will stem from the redistribution of plant species and habitats for wildlife. For example, warmer, drier conditions, should they occur, can be expected to reduce important habitat for grizzly bears (the high elevation whitebark pine forest of **Yellowstone National Park**) by as much as 90% within 50 years. Whitebark pine is already under threat from the spread of an exotic fungus called white pine blister rust. Large-scale changes in, and die-back of, boreal forests due to changing climatic conditions and drought is predicted under some climate scenarios for forests in northern reserves such as **Nahanni and Denali National Parks**. Plant species at the edge of their ranges such as white pine at **Indiana Dunes National Lakeshore** (at the southern edge of Lake Michigan) may go extinct locally. Alpine flower meadows, which attract millions of visitors to **Olympic, Mount Rainier, North Cascades, and Rocky Mountain National Parks**, will gradually be lost to shrubs and trees moving upslope as the mountains warm.

3. Increased fire frequency and risk

The warmer temperatures and drier conditions predicted for much of North America are expected to significantly increase fire risk in National Parks. Years of fire suppression in the parks has often led to a buildup of flammable material in the forests, and larger, more intense burns are likely in reserves such as **Yellowstone, Rocky Mountain, Wood Buffalo, Banff, Jasper, and Glacier National Parks**. Although fire is a natural and desirable part of the ecology of forests, changes in frequency or intensity of large fires can radically change the structure of the forest as well as endangering lives and causing parks to be temporarily closed to visitors. Changes in fire regime will exacerbate problems of invasive grasses along the Snake River in the **Birds of Prey National Conservation Area**.

4. Vulnerability to invasive species, exotic weeds, and insect pests

Many pests and weeds are expected to benefit from a changing climate to the detriment of native species and vulnerable plant communities. Scientists using tree-ring analysis have linked the current unprecedented insect damage in Alaskan forests such as at **Katmai and Wrangell-St. Elias National Parks** to global warming (Glen Judee, pers.com.). Non-native plants such as cheatgrass and quackgrass will be aided in their spread by global warming, and reserves with remnants of native prairie, including **Badlands and Wind Cave National Parks**, are particularly threatened. In Hawaii, increased frequency of storms would help to open the tropical forests of **Haleakala National Park** to invasion by non-native weeds.

5. Changes in rainfall patterns

Changes in precipitation are critical in determining vegetation change and are harder to predict than increases in temperature, but much of North America is expected to become drier overall, with changes in the seasonal patterns of rain and snow. Extreme weather events, especially droughts and floods, are likely to become more frequent and snow melt may come earlier in the year. Few reserves will remain unaffected by these changes. The prairie potholes and prairie parkland areas that are vital for an estimated half of all North American waterfowl production are extremely sensitive to climate change. Climate-induced reductions in numbers of ducks could have serious implications for recreational hunting in the U.S. and Canada. A few of the many preserves at risk include **Audubon and Lacreek National Wildlife Refuges** in the Dakotas and **Prince Albert and Riding Mountain National Parks** in Saskatchewan and Manitoba, respectively.

Impacts on the Ground: Four Examples of the WWF Case Studies

The report contains detailed case studies on 19 sites and regions. Here we present highlights from four of these.

1. **Great Smoky Mountains National Park** (North Carolina/Tennessee)

The United States' most popular National Park, the **Great Smoky Mountains** receives more than 9 million visits every year and is famous for its wonderful vistas and extraordinary diversity of plant life. Global warming is expected to have severe impacts on this park. Recent studies predict that the park's unique high-elevation mixed red spruce/Fraser fir forest, already under threat from pollution and insect attack, could be wiped out by climate change. More than 90 endemic Southern Appalachian plants are judged to be vulnerable to decline or extinction as a result of climate change. Similarly, the warming of mountain streams is expected to cause substantial losses in brook trout populations, including the rare southern Appalachian strain. Of worldwide importance as a center of diversity for salamanders, the Park is likely to experience changes in their distribution and probably local extinction, as they are highly sensitive to changes in moisture.

2. **Everglades National Park** (Florida)

Already under threat from wetland drainage, agriculture and urban development, the southern Florida ecosystem, best known for the **Everglades**, is highly vulnerable to climate change. According to the Department of the Interior, **Everglades**, **Biscayne**, and **Dry Tortugas National Parks** as well as **Key Deer**, **Crocodile Lakes**, and **10,000 Islands National Wildlife Refuges** and **Big Cypress Preserve** have all suffered changes in plant life as a result of accelerating sea level rise in the past 50 years. Wildlife that is restricted to areas under threat from sea level rise includes several species of beach mouse, the Key deer, and the Cape Sable sparrow. Increased frequency or intensity of storms and hurricanes would present a major threat to many of the remnant ecosystems of southern Florida. Hurricane Andrew in 1992 hit the coastal mangrove forests and rare stands of mahogany, gumbo limbo, and *Lignum vitae* trees particularly hard. Coral reefs too are threatened by increased storm damage and warming seas which can cause death by "bleaching." The **Everglades** has been described as the world's most notable National Park at risk of loss from climate change.

3. **The Arctic National Wildlife Refuge** (Alaska)

Successfully defended from opening up to the oil industry, the **Arctic National Wildlife Refuge** now faces a new threat, this time from global warming. Scientists predict that warming at high latitudes will be greater than anywhere else in the world, and despite their remoteness and near pristine nature, no Arctic preserves are likely escape the consequences. Some scientists predict that in the long term, tundra may all but disappear from the mainland. There is, however, no evidence that such a massive displacement of

tundra has occurred during warm periods in the past 10,000 years. First signs of changes in plant communities have already been detected. The **Arctic National Wildlife Refuge** is vital for the survival of the Porcupine caribou herd, which currently consists of more than 150,000 animals. Late in the summer, the caribou provide one of the earth's most awe-inspiring spectacles when the massive herds migrate hundreds of miles south from the coast to their wintering areas. Recent warming of the Arctic and a string of early springs are already disrupting the caribou herds, which are now hard-pressed to arrive at the breeding grounds before food plants run to seed. On average, the herd is now leaving its wintering grounds a month early.

4. **Ellesmere Island National Park** (Northwest Territories, Canada)

The world's most northerly National Park, **Ellesmere Island** lies high in the Canadian Arctic, where average summer temperatures stay below 5° C, and the snow-free period lasts only a matter of weeks. The polar bears that populate the Park may be among the most vulnerable of Arctic animals to climate change. Polar bears are entirely dependent on the marine environment, where they spend the winter hunting on the seasonal pack ice. If the Arctic Ocean were to become ice free for long enough, polar bears would face extinction. As it is, their principal prey, ringed seals, are expected to suffer population declines because warmer conditions will reduce their breeding success. The sparse vegetation of **Ellesmere Island** allows musk oxen, arctic hares, collared lemmings, and caribou to survive. Caribou, in particular, are vulnerable to frequent freezing rain events and conditions that ice over their foraging grounds before the winter snows arrive. Exactly these types of dangerous weather conditions have been increasing during the past 40 years, and are thought to be connected with global warming and responsible for declines in several caribou herds.

Climate Change Modeling Studies

A recent climate and vegetation modelling study suggests that under different scenarios, 15%-22% of U.S. protected areas, and an alarming 32%-37% of Canadian reserves, are likely to experience a major change in habitat type in the next 30 years. New WWF analysis, presented for the first time in this report, shows that, for the U.S. at least, even these figures are likely to be underestimated. The WWF study (Appendix 1), which looked at terrestrial ecosystems in National Parks, National Wildlife Refuges, National Monuments, and Designated Wilderness Areas in the lower 48 states, found 106 protected areas that were affected under seven or more of the nine scenarios used. The **Voyageurs, Bryce Canyon, Theodore Roosevelt, and Wind Cave National Parks**; the **Ansel Adams, Platte River, and Organ Pipe Wilderness Areas**; and the **Cabeza Prieta National Wildlife Refuge** were among those sites in the most sensitive category.

However, studies like these are best used to show general patterns of geographic vulnerability, and in this analysis, a clear pattern emerged showing threats to be particularly strong in the west and southwest, as well as in the central part of the country.

States consistently showing high levels of vulnerability are North Dakota, South Dakota, Iowa, Nebraska, Illinois, Minnesota, Kansas, Wisconsin, Missouri, Oklahoma, Idaho, Montana, Colorado, Utah, Arizona, Texas, California, and New Mexico.

Acknowledgments

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II. INTRODUCTION AND OVERVIEW

Global warming is not a problem only for future generations and faraway countries. It is a problem that is manifesting itself here and now, not just in our own backyards, but in our most cherished natural spaces, the National Parks.

About This Report

This WWF report represents the first-ever summary of the state of scientific research on how global warming is affecting and will increasingly affect the National Parks and protected areas of North America. Too little attention has been paid to the problem of protecting and managing nature reserves in a rapidly changing climate, and this report sets out to provide the information needed to enable conservationists and policymakers alike to understand the magnitude of the problem. A dual strategy, on one hand aimed at reducing the rate of global warming and on the other at integrating climate change into parks management plans, is urgently required.

The authors have reviewed the scientific literature, interviewed dozens of researchers active in the field, and been given access to a great deal of unpublished material and preliminary research results. Where enough information exists, a short section of the report has been devoted to individual National Parks or National Wildlife Refuges. Fourteen areas, including Yellowstone, Everglades, Glacier, and Great Smoky Mountains National Parks have been treated in this way. Five other sections take a more regional approach (such as the Great Plains, Alaska, and the Californian coast) and include information from a wide variety of different protected areas.

In addition to the review of place-based climate impacts, this report contains an entirely new scientific analysis of the vulnerability of terrestrial protected areas in the lower 48 states of the U.S. (see Appendix 1). This analysis uses the latest results from computer models of climate change and potential vegetation change to identify geographic regions where National Parks, Wilderness Areas, National Wildlife Refuges, and National Monuments may be particularly vulnerable to global warming. Results indicate that previous analyses of this type may have significantly underestimated the threat to protected areas, and that certain areas of the country, including the plains states, seem especially sensitive to change.

The report is fully referenced throughout and is also available on WWF's web site: **www.worldwildlife.org** with links to the web sites of affected National Parks and protected areas, and to local nonprofit groups working to conserve the reserves and their surroundings.

Paths to Extinction

For more than a decade, global warming has been emerging as a major new threat to our National Parks. In 1985, in a groundbreaking scientific paper, biologists Robert Peters and Joan Darling predicted that climate change would force many species of plants and animals to move out of the parks that had been set up to protect them. As the climate changed, so too would the geographic distribution of conditions suitable for wildlife. In many cases, this would mean that while the park boundaries remained static, a species at the edge of its range would be forced to find new habitat. Since many parks exist as islands of wilderness in a sea of agricultural and urban development, this could easily lead to the extinction of certain species (Peters and Darling 1985). In the years since Peters and Darling first theorized about the impacts of climate change on National Parks, hard evidence has started to roll in giving every indication that they were right.

The vast majority of the world's scientists now agree that the Earth is undergoing an accelerating warming trend, and the projected rate of global warming is greater than any in the last 10 thousand years (Houghton et al. 1996). Some areas, such as the high Arctic, for example, may not have experienced conditions as warm as are expected in the coming decades at any time in the past 20 million years (Crowley and Kim 1995). Despite the overwhelming scientific consensus about the likelihood of unprecedented human impacts on climate, governments are still struggling to reach agreement on international controls on greenhouse gas emissions as the clock ticks away toward the international Climate Summit in Kyoto in December 1997. Scientists have been examining the potential impacts of global warming on environment and society. Most such impact assessments have focussed on so-called "market sectors" such as agriculture and forestry. We believe that nature is also at great risk and that now is the time to look at the impacts of climate change on the National Parks and protected areas of the United States and Canada.

A Pattern of Change

During the long, hot summer of 1988, the most devastating fire for around 300 years swept through **Yellowstone National Park**, burning more than a third of the forest area. Also in 1988, at a conference sponsored by WWF, scientists Larry Harris and Wendell Cropper stated "*Of all the National Parks on earth that are most likely to be lost, the most notable is Everglades National Park*". The next year, in 1989, Hurricane Hugo scythed through the Florida **Everglades** and the U.S. **Virgin Islands National Park**. Meanwhile, as the warming trend of the 1980s continued, scientists at **Glacier and Banff National Parks** were recording that the great ice masses for which the park was named were melting, and forest experts working in **Mount Rainier and Olympic National Parks** had begun to record changes at the tree line, high in the mountains.

Despite the growing evidence for change in the parks and a steady flow of results from university- and government-funded research in places such as **Rocky Mountain National Park** and **Mount Rainier National Park**, scant attention has been paid to this growing problem. Parks managers in particular have been reluctant to shoulder another burden,

perceived largely as a long-term threat, at a time when they are under immense pressure from budget cuts, rapidly climbing visitor numbers, logging and mining interests, and myriad other environmental threats.

The research gathered in this report demonstrates that climate change impacts are not merely a problem for the future; in many places they are happening right now. For example, permafrost is thawing in **Denali National Park** and glaciers are receding in **North Cascades National Park**. Wildflower meadows are being invaded by trees in **Mount Rainier**, and the risk of wildfire is increasing in **Yellowstone** and **Yosemite**. As warming accelerates and the weather becomes increasingly unstable, the catalogue of likely future impacts grows. Scientists predict massive loss of the boreal forest in places such as Canada's **Wood Buffalo National Park** and **Voyageurs National Park** in Minnesota. Melting permafrost and loss of tundra ecosystems threaten the caribou of the **Arctic National Wildlife Refuge**, melting sea ice could harm polar bear populations at **Ellesmere Island** and **Wapusk National Parks**, and the unique Fraser fir ecosystem of the **Great Smoky Mountains** is threatened with extinction. Many wildlife species, including California clapper rail, Key deer, sooty shearwater, Shenandoah salamander, southern Appalachian brook trout, Tarmigan, Sprague's pipit, ringed seal and pectoral sandpiper, are identified as being at risk from climate change impacts.

In 1996, the more than 2,500 scientists of the Intergovernmental Panel on Climate Change (IPCC) concluded that global warming has been occurring over the past century, that the warming has been speeding up in the past two decades, and that air pollution from human activities (particularly energy generation) is the most likely cause (Houghton et al. 1996). The IPCC also singled out ecosystems as one of the sectors most vulnerable to climate change, and predicted that there would be a loss of biological diversity and species extinctions. A new regional IPCC assessment for North America predicts major changes in all forest types, almost total loss of the taiga and tundra habitat in the southern Arctic, and major disruption to waterfowl and shorebird populations in the Arctic, the Great Plains, and along much of the east coast of the U.S. (IPCC, in prep).

No single fire, hurricane, drought, or flood can be attributed to global warming, and every change within the National Parks comes about because of the combined effects of a variety of environmental pressures. But when all these changes are considered together, and in the context of global and regional trends of changing climate and weather patterns, there can no longer be any doubt that our National Parks and protected areas are under threat as never before. For some parks, global warming may turn out to be the biggest single threat to their ability to preserve these precious spaces and the wildlife within them for posterity. Climate change does not respect park borders, and it is tightening its grip on the ecosystems of many of North America's most cherished protected areas. Seemingly small changes — warmer winters, earlier springs, heavier rainstorms, centimeters of sea level rise — are starting to act both independently and in concert to radically alter the conditions under which species struggle to survive.

Computer Modeling Shows Scale of Impacts

One way in which scientists can assess the likelihood of damage to animal and plant life is to simulate potential changes using sophisticated computer modeling programs. Changes in vegetation patterns can be predicted by looking at the climatic conditions favoring different types of plants and comparing them with the different climate scenarios produced by experiments using computer models called Global Circulation Models (GCMs). GCMs provide the best tools available with which to analyze how the climate is expected to change in the future.

Dutch government scientists have recently used these models to assess the sensitivity to global warming of large nature reserves around the world.¹ Results indicate that under different scenarios, 12%-17% of the world's protected areas would experience a major change in vegetation type during the next 30 years. Threats to U.S. reserves are slightly higher, at 15%-22%, and the results for Canada are quite startling, with between 32% and 37% of nature reserves expected to change by the year 2025. According to this analysis, Canada will experience the most rapid rate of change of the vegetation zones in its protected areas of any region of the world during the coming three decades. Because of the more northerly distribution of Canadian nature reserves and the greater warming that is expected at northerly latitudes, most climate scenarios show rapid and massive change in Canada. By the end of the next century, nearly half of Canada's reserves are likely to have changed because of climate forcing. For the U.S., with its larger land area and much more varied ecosystems - from tropical forest to Arctic tundra - the range of uncertainty is greater. In the best case, just under a quarter of its reserves would be affected and in the worst case, nearly three quarters would change (Leemans, in litt.). In fact, many changes are likely to occur in the National Parks well before 2025, as the transition from one vegetation zone to another begins to take place, often with rapid and unpredictable consequences.

Presented for the first time in this report (see Appendix 1) is a new WWF scientific analysis that demonstrates that for the lower 48 states of the U.S., even the Dutch study may underestimate the eventual likely change. The WWF study looked not only at how vegetation classes could change within the protected areas but also at the changes in the landscape surrounding them. When this approach is taken, significantly greater levels of change are detected. Because of the coarse nature of the GCM and vegetation models, a study like this cannot be used to make accurate predictions about what will or will not occur in a particular protected area, but broad patterns can be determined. And by comparing results from different models, an indication can be given of which regions may be the most sensitive to global warming.

The WWF analysis, which looked at National Parks, National Wildlife Refuges, National Monuments and Designated Wilderness Areas found that the most affected regions are

1. These results are based on a transient run of the Max Planck GCM together with the IMAGE 2 model. Four scenarios are implementations of the IPCC IS92 scenarios and five others examine the implications of stabilization goals for atmospheric CO₂ that range between 350ppm (parts per million) and 750ppm (Leemans, pers.com, ALSO REF for Alcamo).

likely to be in the west and southwest, as well as in the central part of the country, where national wildlife refuges are likely to be especially hard hit. States exhibiting the most consistent negative response to the nine scenarios² were North Dakota, Iowa, Nebraska, Illinois, Montana, Minnesota, Texas, Missouri, Oklahoma, and Wisconsin. Consistent landscape decline was also indicated in South Dakota, Colorado, Kansas, and New Mexico, and much of California, Arizona, Utah, and Idaho. Five percent of the national wildlife refuges showed decline in under all nine scenarios, and 106 protected areas were affected in seven or more scenarios. Reserves in this latter, “most sensitive” category include **The Voyageurs, Bryce Canyon, Theodore Roosevelt and Wind Cave National Parks**; the **Ansel Adams, Platte River and Organ Pipe Wilderness Areas**; the **Cabeza Prieta, Bowdoin, Audubon, and Chautauqua National Wildlife Refuges**, and; **Capulin Mountain, Scotts Bluff, and Jewel Cave National Monuments**.

Can We Cope with the Change?

There can be no shadow of a doubt that because of the greenhouse gases already in the atmosphere, the world is locked into a certain amount of global warming. The faster we act to reduce the pollution of the atmosphere, the greater will be our chance of lessening the impacts on wildlife and habitat. For the plants and animals that make up the ecosystems of National Parks, it is not only the total amount of global warming that is of concern but also the rate at which it occurs. The faster the rate of warming, the worse are likely to be the consequences for wildlife (Markham 1996). On top of the rate of change problem comes the added complication that ecosystems and the species that make them up do not necessarily show a smooth linear response to change. After passing a certain threshold, say in water temperature for corals or summer drought for some forest types, an ecosystem may exhibit a catastrophic response (Malcolm and Markham 1996). The unpredictability of this kind of change is what will make conservation under conditions of global warming so difficult.

People who are skeptical about the need to act to reduce global warming often claim that ecosystems have survived similarly rapid climatic change and warming in the past, most notably at the end of ice ages. In fact most of the changes we face today are expected to occur in a matter of decades, whereas warming in the interglacial periods generally occurred over hundreds — or even more commonly — thousands of years, thus giving species plenty of time to adapt and move. Even then, species did become extinct because of the changing climate itself. For example, tulip tree, magnolia, hemlock, and white cedar all went extinct in Europe during the Pleistocene ice ages, probably because of the barriers the Alps and Pyrenees presented to their southward retreat from the cold (Peters and Lovejoy 1992). Perhaps more important, even when species were able to adapt to

2. The WWF analysis was based on data provided by the Vegetation/Ecosystem Modeling and Analysis Project (VEMAP). The VEMAP scientists used three biogeographic models (BIOME2, DOLY, and MAPSS) and outputs from three “mixed-layer ocean” GCMs (Oregon State University, Geophysical Fluid Dynamics Laboratory, and United Kingdom Meteorological Office) to produce nine scenarios of vegetation sensitivity in the coterminous U.S. (Kittel, 1995; VEMAP Members, 1995).

rapid changes in the geological past, they did so in the absence of the influence of modern-day humans on the planet, and without roads, railways, farmers' fields, cities, and suburbs to stand in their way. As former WWF biologist Robert Peters puts it, "*Few animals or plants would be able to cross Los Angeles on the way to a new habitat.*"

Today's National Parks and protected areas represent biological havens from a huge array of environmental stresses including agricultural development, road-building, logging and water pollution. The more fragmented the habitat surrounding the park, the smaller the chances for adaptation to climate change. The threat of climate change should only strengthen calls for increased investment in habitat protection. The better our networks of protected areas, the greater will be their resilience to climate change. Resilience to change can be increased by: a) conserving biological diversity; b) reducing fragmentation and degradation of habitat; c) increasing functional connectivity among habitat fragments; and; d) reducing human-caused environmental stresses (Markham and Malcolm, 1996)

Managing for Change

The successful management of National Parks and protected areas is a goal that is fraught with problems at the best of times. Many National Parks are sorely understaffed and underfunded, but the continued growth in visitor numbers dictates that increasing amounts of park funds be directed to road maintenance, waste management, and visitor safety. As a result, park staff have little time to devote to long-term environmental planning, and funds for vital biological research are scarce. Nevertheless, it is essential that managers of protected areas begin to include strategies for coping with climate change impacts in their routine planning and research activities.

There are many ways in which management authorities could begin to integrate climate into their thinking. To give one example, John Peine, a scientist working on climate impacts in the **Great Smoky Mountains National Park**, has proposed a framework for climate change sensitivity analysis that could be used by park managers with minimum additional investment of time or money (Peine and Berish in press). The analysis would be undertaken by a multidisciplinary panel of local experts and would include the following steps:

1. Definition of goals and targets as well as political and ecological boundaries for the assessment.
2. Stakeholder assessment of valued natural and cultural resources.
3. Inventory of data availability and data needs.
4. Agreement on timescale of study (including past climate analogs) and climate scenarios.
5. Preliminary natural resource sensitivity analysis.
6. Preliminary cultural resource sensitivity analysis.
7. Strategic plan for species and landscape conservation.
8. Monitoring program for climate impacts.

A program based on this methodology has been proposed to be carried out by the Southern Appalachian Man and the Biosphere Cooperative (SAMAB) for the the **Great Smoky Mountains National Park**.

Based on these types of sensitivity analyses, which take into account the unique situation and conditions of specific natural areas, several categories of management action can be contemplated that will help to mitigate global warming impacts. According to Thomas Stohlgren (pers. com.), an ecologist with the Biological Resources Division (BRD) of the U.S. Geological Survey at Fort Collins, Colorado, these actions should include the following:

1. Maintain or restore natural disturbance regimes (e.g., through prescribed fire) in order to minimize the impacts of climate-induced changes in extreme events such as droughts and floods.
2. Implement an ecosystem approach to management that takes into account likely climate impacts over various spatial scales. This will require multiple stakeholder involvement and an emphasis on improving or creating connectivity between habitat areas.
3. Step up efforts to control invasive non-native species such as cheatgrass and smoothbrome, which are already a problem and which are likely to benefit from climate change at the expense of native plant communities.
4. Develop and foster an "adaptive management philosophy." This will promote preparedness and allow flexible and innovative responses. Adaptive management will be needed, as climate change impacts will often be unpredictable and will work with other environmental stresses to cause new problems for park managers.
5. Expand research and monitoring activities in order to be able to identify species and habitats at risk, monitor for signs of change, and evaluate the impacts of multiple environmental stresses.

In addition to these strategies, parks should develop visitor education and public outreach programs that explain ongoing and expected ecosystem changes resulting from global warming, highlight park-based climate change research activities, and demonstrate the combined effects of global warming and other local environmental pressures. Such programs could include visitor center displays, information leaflets on climate impacts, ranger training modules, teachers' worksheets, display boards at parking outlooks where direct impacts (such as sea level rise or tree line change) can be observed, and special information and links at park sites on the World Wide Web. Almost no National Parks have yet taken this step of transferring the information gathered on their sensitivity to global change to local communities or seasonal visitors. One place where some of these

outreach methods are being tried is **Glacier National Park** in Montana, where, for example, a short video of computer graphics has been created to illustrate changes in vegetation and the melting of glaciers caused by warming.

No amount of better conservation management will save our Arctic habitats from climate change, however. So, first and foremost, there is a need to reduce the rate at which polluting greenhouse gases, particularly carbon dioxide, are being pumped into the atmosphere. The United States and Canada are responsible for nearly a quarter of all the world's carbon dioxide emissions. In December 1997, nations will meet in Kyoto, Japan, for a United Nations Climate Summit aimed at agreeing on targets and timetables for emissions reductions. The message from this new WWF report on the National Parks is clear: There is no more time to waste — without substantial, near-term, reduction targets being agreed, the irreversible decline of many of our nations' protected areas will be set in motion.

Even with strong action to reduce greenhouse gases, some change will still occur because of the already unnaturally high levels of pollution in the atmosphere. For this reason it is essential that protected areas managers work with scientists to develop conservation strategies aimed at mitigating some of the impacts of global warming. Climate change will force the need for the most resilient protected area system we can create, and this in turn will require increased investment in conservation. Special emphasis must be put on reducing existing environmental pressures such as logging, water pollution, and habitat fragmentation as a result of roadbuilding and agricultural development. The natural areas that are the most resilient to climate change will be those where connectivity and corridors between habitat areas are maintained, and where other environmental stresses are ameliorated.

Because climate change is an added, and often severe, stress that will generally exacerbate existing park problems such as fire management, drought, floods and control of non-native weeds, park managers will require additional resources to try to mitigate its impacts. Some people have suggested that climate change will reduce the importance of National Parks because it will change the distribution of plant and animal species, and in some cases drive protected species out of reserves, or cause local extinctions in parks. In fact, the opposite is true. The current protected area system, although it will be extremely hard hit by global warming, can provide the core habitat needed for species survival if more is done to promote conservation in areas surrounding the parks.

Climate change makes it more necessary than ever to invest in the conservation of natural habitat that can provide buffer zones around parks and maintain biodiversity in the landscape. Preventing the loss of biodiversity, preserving rare habitats, and protecting parcels of land that provide natural links between reserves are all strategies that will play a major part in helping to adapt to the coming changes (Markham and Malcolm 1996). Increased emphasis on this type of ecosystem management is likely to heighten the need for cooperation among various government agencies and local stakeholders. Working more outside the parks to mitigate climate change may increase the need for

conflict resolution between conservationists and local communities, including native peoples (West 1995). However, global warming may be perceived by all stakeholders as a threat to their values or ways of life and could therefore act to bring different parts of the community together to jointly tackle a common threat (West 1995).

III. CASE STUDIES FROM THE FIELD

1. Alaskan Protected Areas (excluding the Arctic National Wildlife Refuge and the Yukon Delta).

Probably nowhere on Earth will the impacts of climate change on National Parks and protected areas be as interlinked with the fate of native peoples as it will be in Alaska. Nearly 70% of U.S. National Park lands are in Alaska, and most of the state consists of federal lands of one sort or another. Much of this land consists of near-pristine tundra, boreal forest, lakes, and rivers. However, the establishment and management of these protected areas has suffered from a lack of recognition of the needs and traditions of indigenous people in subsistence-based economies (Peterson and Johnson 1995). All climate models agree that global warming will be greatest at high latitudes. In Alaska, global warming will lead to glacier retreat, melting permafrost, large-scale change in tundra ecosystems, and altered distribution of wildlife species important to conservationists and native people alike. Alaska has experienced a strong warming trend during the last 50 years, with the greatest change being recorded since 1976 (Weller et al. 1995).

Climatic changes are thought to have had dramatic impacts both on wildlife and human populations of Alaska and the Canadian Arctic in the past. A previous period of regional warming facilitated the expansion of the Thule culture eastward from the Bering Sea along the Arctic coast, eventually to Hudson Bay and then Greenland. Over several millennia, the Thule culture had developed the technology for harvesting many seasonally available and patchily distributed wildlife species including bowhead whales. The first evidence of whaling on the Alaskan mainland, some 3,400 years ago, comes from what is now **Cape Krusenstern National Monument** (Langdon 1995).

Regional warming around 1,000 years ago reduced the extent of summer ice and allowed several marine mammals better access to the central and eastern Arctic. The Thule culture was able to move with the wildlife and eventually completely replaced the 2,000-year-old Dorset culture. When the cooler Little Ice Age (1600 – 1850 A.D.) arrived, bringing more ice and eliminating walrus and bowheads from Arctic waters, Thule populations adopted a more nomadic lifestyle and shifted their resource use to rely more on seals and caribou (Langdon 1995, Wenzel 1995). Archaeological evidence from **Glacier Bay National Park** indicates that major disruptions to Tlingit communities were caused by sea level rise associated with glacial advance during the Little Ice Age. The impacts included forced abandonment of coastal habitation, loss of salmon fishing runs, and destruction of productive shellfish beds (Crowell 1996).

Changes in the distribution and abundance of salmon populations are once again in the cards as a result of modern-day warming, which is expected to be much more rapid than any experienced in at least the past 10,000 years. **Glacier Bay, Katmai, and Wrangell-St. Elias National Parks and Preserves** are likely to be among those areas affected by

these changes. Warming of lakes and rivers could have particularly negative impacts on populations of coho, sockeye, and chinook salmon in the southern parts of their ranges (Beamish 1995). Throughout Alaska, salmon provide important commercial and subsistence resources and are also a major draw to federal lands for many tourists whose main interest is recreational fishing.

Several other Arctic wildlife species that provide significant resources for native communities, and to which conservationists attach great importance, are at risk from climate change in Alaska (see also case studies on **Yukon Delta National Wildlife Refuge, Arctic National Wildlife Refuge, and Ellesmere Island National Park**). Ice-dependent or ice-related species including Arctic cod, polar bear, ring seal, walrus, narwhal, and beluga whale will all likely experience population declines or changes in distribution (Alexander 1992, Ono 1995). The extent of sea-ice in the Bering sea has declined by 5% over the last 40 years (Bering Sea Impact Study (BESIS) 1997). Scientists believe that, along with overfishing, recent warming of the Bering Sea is one factor behind massive declines in several marine species including Steller sea lion, Alaskan populations of harbor seal, spectacled eider, red-legged kittiwake, and common murre (Alaska Conservation Foundation 1994, BESIS 1997). Evidence of these alarming declines can be seen in the reduced numbers of marine mammals and seabirds in the **Alaska Maritime National Wildlife Refuges**, including the **Aleutian Islands, Bering Sea, Chukchi, Sea and Gulf of Alaska** units.

On land, the most immediate threat to ecosystems comes from the thawing of permafrost along a broad band at the southern extent of the zone, where it is already patchy and discontinuous. Further north, the continuous permafrost is less at risk because current mean surface temperatures are generally colder than -5°C . The discontinuous permafrost is usually much warmer, and a change of only 2°C would cause most of the permafrost surrounding the Bering Sea to thaw. Where the permafrost is ice-rich, thawing can cause land subsidence (thermokarst) up to five meters deep. It is thought that all the discontinuous permafrost south of the Yukon River and on the south side of the Seward Peninsula has warmed in the last few years, and that widespread thawing is occurring (Osterkamp and Romanovsky 1996). Reserves in the affected area include **Denali, Lake Clark, and Katmai National Parks**, as well as **Anjatchak National Monument and Izembek, Alaska Peninsula, Kodiak, Togiak, and Innoko National Wildlife Refuges**. Together, these sites provide irreplaceable habitat for Kodiak bear, caribou, Pacific black brant, emperor goose, bald eagle, and dozens of other uncommon species (Riley and Riley 1992).

The thawing of permafrost can be expected to destroy caribou habitat, cause landslides and erosion, clog salmon spawning rivers with silt (Osterkamp and Romanovsky 1996), and trigger the speedy loss of areas of boreal forest and their replacement by wet sedge meadows. Freshwater wetlands in Alaska may be especially vulnerable to climate change, particularly in areas where permafrost is thawing (Rouse et al. in prep.). Scientists have identified the "string bogs" at Cape Espenberg in **Bering Land Bridge National Preserve** as one area that is likely to be extremely sensitive to changes brought about by

loss of permafrost. These wetlands have been vital for communities of humans and for wildlife for millenia (Schaaf 1995). Warming is also generally predicted to result in a significant loss of Arctic peatlands (Rouse et al. in prep.).

It is rapidly becoming clear that no federally protected habitats in Alaska will escape the impacts of global warming and that for some species (and the preserves that maintain them) the changes may be catastrophic. The future of indigenous communities that rely at least in part on wildlife resource harvesting is intimately linked to the health of Alaskan ecosystems and their response to climate change. The Inuit Circumpolar Conference (ICC) has concluded that *“rapid climate change would be a serious threat to Arctic indigenous people’s lifestyles and capacity for sustainable development”* and called for the participation of indigenous peoples in the planning and implementation of climate action plans, as well as the incorporation of traditional knowledge in climate impact studies (ICC 1996). Global warming may turn out to be the threat that brings conservationists together with traditional hunters in an effort to find common ground in the struggle to maintain wildlife populations and wild areas in the Arctic (West 1995).

2. Arctic National Wildlife Refuge

It is fitting that the vast arctic wilderness is home to the largest refuge in the United States and one of the largest in the world. Bounded by the Arctic Ocean to the north and the Porcupine River to the south, its 19.5 million hectares include the easternmost extensions of the Brooks Range and the highly productive tundra of the North Slope. Here, many species once common further south are still abundant, including grizzly bears, lynx, wolverines, eagles, and wolves. The **Arctic National Wildlife Refuge** is also home to a host of specialized arctic species found in the polar regions and nowhere else, including polar bears, arctic foxes, collared lemmings, arctic and tundra hares, and musk oxen. Here, nature reigns supreme, and wildlife spectacles are on a scale that rivals anything on the planet. During the short arctic summer, female caribou of the Porcupine herd congregate in the tens of thousands to give birth and raise their calves. Later in the summer, they begin a migration that will lead them over a route longer than that of any other terrestrial animal to their wintering grounds hundreds of kilometers to the southeast in the shelter of the Brooks, Ogilvie, and Richardson Mountains of northeastern Alaska and northern Yukon (International Porcupine Caribou Management Board 1993). All of these species show unique adaptations to the arctic's extreme climate. Using the sharp edges of their broad hooves, caribou dig through snow as deep as 60 cm to reach their winter diet of lichens, sedges, and grasses (Leader-Williams 1988). In preparation for the long winter, the diminutive collared lemming almost doubles in size, grows a long white winter coat, and develops claws specially designed for tunnelling through snow (Malcolm and Brooks 1993).

The remoteness and nearly pristine nature of the **Arctic National Wildlife Refuge** does little to protect it against the impacts of greenhouse warming. Detailed computer simulations that superimpose three-dimensional grids over the Earth's surface and solve

the systems of equations that govern mass and energy dynamics in the atmosphere suggest that greenhouse warming will be most intense at high latitudes. To date, more than a dozen such GCMs, are in use or under development worldwide (Cess et al. 1989). Although recent successes have given the scientific community greater confidence in the overall accuracy of the models (Houghton et al. 1996, Kerr 1995, 1996), they still suffer from coarse grid sizes and numerous simplifying assumptions. As a result, predictions at the regional level often differ from one model to another. On one point, however, the models are unanimous: Greenhouse-induced warming will be unusually strong in the Arctic, especially in winter. For example, under simulated doubling of carbon dioxide concentrations, four GCMs all predicted higher temperatures throughout the North American arctic year, with the largest increases occurring in winter (Maxwell 1992). Average increases were close to 4° C in summer and 8° C in winter.

A simple way to investigate the potential impact of this warming is to make use of the fact that the southern floristic boundary of the arctic can be predicted with considerable accuracy based solely on temperature (e.g. Maxwell 1992) and to assume that although temperatures will increase in the future, the gradient of temperatures across the north will remain unchanged, at least in a relative sense. Under this assumption, global warming of 3° C would be expected to move the $\bar{x}$ degree isotherm north to the location of the present $\bar{x} - 3$ degree isotherm. Of particular interest is the 11° C July temperature isotherm, which in North America closely approximates the tree line (and the southern limit of continuous permafrost). If this isotherm and its successive increments are plotted across the north, a startling, and for arctic plants and animals, distressing, result is obtained: A warming of 3° C results in the almost complete loss of mainland tundra ecosystems from North America. A further 3° C of warming would limit arctic ecosystems to the high arctic islands. This simple technique is in agreement with the sophisticated GCM models that invariably predict a massive loss of mainland tundra regions under doubled carbon dioxide concentrations (e.g., Halpin 1995).

To determine how fast the change is likely to occur, dynamic models can take us through the next step and provide an approximate time line. The IPCC has developed several scenarios of atmospheric change that provide a starting point for such modeling (Houghton et al. 1996). Recently, scientists at the National Institute of Public Health and Environmental Protection (RIVM) in the Netherlands linked the IPCC "business as usual" scenario (IS92a + aerosols) with models of global climate and land use (IMAGE 2.1) and eco-climatic provinces (BIOME3). The suite of models predicted that by the year 2100 the tundra would be reduced by nearly 40% and would largely disappear from the continental land masses. Under this scenario, the only remaining large expanses of tundra would be on Banks and Baffin Island in the Canadian Arctic and the Taymyr Peninsula of Russia. The tundra of the North Slope of the **Arctic National Wildlife Refuge** would disappear. Indications are that changes of this magnitude are faster than anything in the recent past, including the ice ages (Peters and Lovejoy 1992). Perhaps most seriously, many arctic organisms have never witnessed changes of this sort. The earth's northern regions have not experienced warm temperatures approximating these for perhaps as

many as 20 million years (Crowley and Kim 1995), a time well before the appearance of many modern arctic taxa (Maxwell 1992).

In an attempt to detail the potential changes in arctic ecosystems under such radical warming, scientists are using several techniques to experimentally warm the tundra and monitor both the short- and long-term effects on the plant community. It is well known that temperature has a pervasive influence in determining the geographic distributions of arctic plants. Young (quoted in Billings 1992, p. 101) noted that "*floristic zones are correlated with the amount of summer warmth to the point that other ecological factors are insignificant in comparison....*" It is thus safe to assume that temperature changes will strongly affect the species composition of arctic ecosystems; the question is in what way. The largest experimental effort is the International Tundra Experiment (ITEX), a collaboration of researchers with the unified task of documenting the response of Arctic and Alpine plants to warming (Molau in press). One experiment, currently in progress at 26 sites in 11 countries, uses small, standardized open-top chambers to warm the plant canopy. These experiments indicate that deciduous species, such as dwarf birch, grow aggressively at the expense of evergreen perennial plants, which respond very slowly or not at all. A steady erosion of plant diversity is the result. A long-term experiment near Toolik Lake in the northern foothills of the Brooks Range in arctic Alaska gives corroborative results (Chapin et al. 1995) and similarly suggests the rapid disintegration of the tundra plant communities in the face of a changing climate. There, researchers used greenhouses to raise temperatures in the tundra and found that in the nine years from 1981 through 1989, species richness was reduced by 30%-50% through a loss of relatively rare species. The decline occurred disproportionately among forbes, which are important forage species for arctic animals, and among mosses, which are important in maintaining the soil thermal regime.

Perhaps most disturbingly, Chapin et al. (1995) observed an unexpected change in the unperturbed tundra that they used as experimental controls. During the near-decade of observations (the warmest on record in the region), the biomass of dominant tundra species changed in the direction that the experiment predicted (and as also predicted by Holocene pollen records). The dominant sedge (*Eriophorum*) was reduced to 30% of its initial biomass, birch biomass was highest during the warmest year of the study, and certain mosses exhibited changes in the direction predicted by the experiments. The authors concluded that regional warming is already under way and rapidly changing the tundra plant community, but there is not yet consensus as to whether these changes constitute a warming signal.

In fact, unusually warm conditions in the arctic in recent decades are part of a long-term pattern. Detailed studies of tree-ring widths along the edge of the tree line across the Arctic indicate a trend of steady warming since approximately the 1840s, and current conditions are warmer than any in the past three centuries (D'Arrigo and Jacoby 1993, Jacoby and D'Arrigo 1989, Jacoby et al. 1996). As a result, the southern permafrost is melting (Kwong and Gan 1994, Halsey et al. 1995), and trees are finding suitable

conditions for growth and reproduction further northward. The local change witnessed by Chapin et al. (1995) appears to be an early signal of widespread change and species loss.

Concern about species extinctions is often focused on diverse ecosystems such as the tropics (Solbrig 1991), but the arctic is of special concern precisely because its communities are so simple. Arctic plants and animals depend intimately on one another, and because of the low diversity, when one species is lost from the system, others may soon follow. A simple change in a community can thus have a disproportionate impact and perhaps lead to profound ecosystem consequences (Vitousek 1990). For example, loss or changes in plant communities such as those described above may lead to changes in the populations of grazers and browsers (including mammals, birds, and insects) that often rely on just a few plant species or groups. In fact, Chapin et al. (1995) suggested that the changes that they observed may have just this sort of disproportionate effect. The forb species that disappeared or were strongly reduced under simulated climatic warming produce inflorescences (fruiting bodies) that are nutritionally important and selectively grazed by caribou during lactation (White and Trudell 1980) and are very important for several species of insect pollinators. Lichens, also reduced in the experiment, are critical for the overwinter nutrition of caribou (White and Trudell 1980).

Indeed, detailed study of the Porcupine caribou herd further suggests that the predicted impacts of global warming are already under way. Perhaps more than any other region, the arctic is a land of seasonal contrasts, and the lives of its plants and animals follow tight schedules dictated by the annual progression of seasons. For example, in their migration to the coastal plain of the **Arctic National Wildlife Refuge** in the spring, female caribou closely track the pulse of vegetation growth as it progresses northward, and eventually concentrate in small and highly productive areas of the plain where they are able to obtain the nutritious forage that they need to raise their calves (Douglas et al. in prep.; International Porcupine Caribou Board 1993). Under the influence of increasing temperatures in the past decades, spring has been arriving earlier and earlier on the coast (Douglas et al. in prep.) and the caribou are hard-pressed to arrive in time to take advantage of the period of maximum plant growth. Indigenous hunters have noted that the caribou are shifting the timing of their age-old migration pattern, presumably in response to these shifts in plant phenology. On average, the herd is leaving its wintering grounds a month earlier than usual and its summer range a month earlier as well (J. Tetlichi pers. com.). In 1990, spring was the earliest on record, and by the time the caribou had reached the coastal plain to calve, their principal food plant (*Eriophorum vaginatum*) had already gone to seed (Douglas et al. in prep.).

The ultimate effect of these changes in the timing of plant development and migration is unknown. As yet, numbers in the Porcupine herd appear to be stable at close to 150,000 (International Porcupine Caribou Board 1995). Certainly, any substantial changes in the Arctic Coastal Plain, particularly the northern part of the **Arctic National Wildlife Refuge** currently under threat from oil development (the "1002 lands"), can be expected to have serious implications for the herd and the indigenous hunters who rely on it. Even though the herd disperses widely during the winter, and from one winter to the next will

often use distant parts of the tundra, the animals unfailingly concentrate on the 1002 lands. There, food is best for nursing cows (and calf survival is greater), wolves and grizzlies are scarce, and some sanctuary from biting flies is found. The consensus of the Porcupine Caribou Management Board is that "*eviction from the calving grounds, for whatever reason, would throw the herd into a chaos from which it may never recover*" (Porcupine Caribou Management Board 1996). Development of the plain by oil companies is one such threat; further changes in the species composition and phenology of forage species, as induced by global warming, is another. In combination, the two may be especially deadly. Phenological changes tend to push the herd closer to the coast (Russell 1993), into the same area where any oil development would be concentrated. Increasingly, even though arctic organisms are following their age-old strategies, they are finding themselves in the wrong place at the wrong time.

3. Yukon Delta National Wildlife Refuge

Perhaps no other single location on the planet is as important for as many species of water birds as the **Yukon Delta National Wildlife Refuge** in Alaska. This Indiana-sized mosaic of wetlands and tundra is dotted with tens of thousands of lakes, ponds, and streams that provide a summer home to millions of migrants from six continents. Rare bristle-thighed curlews make the long journey from Australia and the South Pacific; whimbrels and a host of other species winter as far south as Cape Horn; and Sabinas gulls and arctic terns come from Antarctica, the longest migration in the world. The refuge is an island of productivity in the harsh arctic environment and provides nesting for more than half of the continental population of black brant and most of the world's emperor geese, tundra swans, and cackling and Pacific white-fronted geese. These and other waterfowl species are an important resource for the local Inuit who continue their traditional life style on in-holdings within the refuge. A host of smaller North American shorebirds also use the marsh, including black turnstones, dunlins, western and rock sandpipers, and bar-tailed godwits. Incredibly, in the short arctic summer of less than three months duration, 145 species of birds come here to breed (Riley and Riley 1992).

The low-lying character of the marsh that on one hand makes it an ideal haven for water birds at the same time exposes it to the potential ravages of greenhouse warming. Tidal influences are felt as far as 10–15 km from the ocean owing to the very gradual slope of the delta sediments (Babcock and Ely 1994). Under global warming, strong sea level rise is predicted (Houghton et al. 1996), and the periodic storm surges that carry saltwater inland may become more frequent, damaging the marsh's highly productive freshwater communities. Unfortunately, whereas local salt-loving plants are relatively tolerant of freshwater the converse is not true (Babcock pers. com.). Increased salinization is thus expected to lead to declines in plant productivity owing to osmotic shock. An equally troubling possibility is that a positive feedback may develop, linking reduced marsh cover to increased evaporation, ever more salinization, and hence further vegetation diebacks. In the eastern arctic, the result of this feedback has been a trophic cascade, wherein not only primary productivity is compromised, but the secondary consumers that many bird

species depend on (insects, decomposers, and other invertebrates) are reduced in abundance (Jefferies et al. 1995, Jefferies in prep.). With a high enough rate of sea level rise, the marsh will be unable to expand inland fast enough to keep ahead of the invading ocean, and a steady decline in the area of productive inland communities will result.

Already, global warming appears to have arrived in Alaska, where spring has been coming earlier and earlier for the past two decades (Douglas et al. in prep.). As a result, the timing of key events during the summer breeding season is changing. These changes have important implications for migrating birds, which are on a tight schedule as they move from habitat to habitat during the annual cycle. As grazers, geese are unusual compared with many of the refuge's other bird species in that they depend on a relatively low-quality food source (Sedinger and Flint 1991, Sedinger et al. 1995). Changes in the nutritional quality of the sedges and other forage species that they feed on are critically important for the goslings, who need to grow at prodigious rates to put on weight for the fall migration. As is typical of late, 1994 was a record early spring, and compared with normal years, plants began to grow earlier. As a result, forage quality began to decline early relative to the optimal timing for the growth needs of goslings (Babcock in press). Unable to put on reserves, the young geese may be faced with increased mortality rates during the arduous trip south.

4. Ellesmere Island National Park Reserve

On the northernmost extremity of North America, far to the north of the **Arctic National Wildlife Refuge**, lies the most northerly of the world's parks. In this land of deep fiords and permanent ice caps, plant species are at or near their physiological tolerance limits, and only the hardiest of the arctic flora are able to exist. Nevertheless, in protected sites across **Ellesmere Island**, plants eke out a living and produce enough biomass to support a community of arctic grazers: caribou, musk oxen, arctic hares, and collared lemmings. Remarkably, 166 moss species are known from northern Ellesmere, where they probably outnumber vascular plants (Brassard 1971, 1976). Palaeoecological analysis of diatoms from the sediments of arctic ponds on Ellesmere Island have revealed that what at first appeared to be near-pristine ecosystems that were stable for thousands of years have in fact changed markedly in the past century, probably as a result of global warming (Douglas et al. 1994).

In the high arctic (traditionally defined as areas with mean July temperatures below 5° C), the snow-free period in the summer is extremely short, and in cold years, some vegetated sites remain covered all year. A few consecutive bad years can lead to plant death under the steady accumulation of snow. Remarkably, just such a scenario seems to have played out during the Little Ice Age, a period of markedly cooler temperatures during approximately 1400–1850. In the vicinity of the Twin Glacier at Alexandra Fiord, a steady accumulation of snow during a short cold period entombed plant communities, preserving them markedly intact. The snow subsequently densified into glacial ice, but without destroying the plant communities. In about the mid-nineteenth century, the

glacier began to retreat, exposing the "fossilized" communities (Bergsma et al. 1984, Havström et al. 1995).

Although strong warming is predicted under the greenhouse effect, and indeed arctic (and worldwide) glaciers are retreating (Cogley et al. 1995), some scientists suggest that a return to glaciation in the high arctic is conceivable. As the Arctic Ocean warms under the greenhouse effect, increased precipitation will eventually result, perhaps shifting the high arctic climate into snow accumulation mode (Alley et al. 1993, Svoboda 1995). Increased precipitation, especially as snowfall in winter, is a well-established prediction common to many GCMs (Maxwell 1992). According to this idea, the tenuous balance between snow deposition in winter and heat available for melting and sublimation in summer will tip toward accumulation, resulting in advances in the high arctic ice caps. The Twin Glacier results suggest that such a shift could be almost instantaneous (at least geologically speaking) and result in a rapid loss of tundra from one decade to the next, with dire consequences for high arctic animals. We do not understand the triggers that have led to glaciation in the past (Kukla and Went 1992); it is equally clear that we are far from understanding the potential implications of the giant atmospheric experiment that humankind is unwittingly in the midst of (Svoboda 1995).

Again, caribou herds may provide a barometer of change. Detailed energetic models for the species have been developed to help anticipate the likely impacts of climate change, including both temperature and precipitation (Russell 1993); they suggest that caribou will be highly affected. Field data suggest that the 2°–4° C increase predicted for the coming decades would result in an almost linear increase in the level of insect harassment and a corresponding loss of energy reserves (Russell 1993). When coupled with a scenario of 30%-50% increases in winter snowfall (as suggested in most GCMs [Maxwell 1992]) and the associated increased energetic cost of digging for food, these models predict declines in parturition rates ranging from 40% to complete reproductive failure, with obvious important implications for herd productivity (Russell 1993). In one modeling study, increased summer temperatures and increased winter precipitation lead to declines in the Bathurst Island caribou herd in the Canadian arctic under every climate change scenario (Brotton 1997).

An examination of current trends in caribou herds of the central and eastern Canadian arctic provides evidence of precipitation changes already under way. Several types of weather events are known to have negative effects on caribou populations, including frequent freezing rain, ground-fast ice in fall before snowfall, and poor summer growing conditions. The first two can be especially deadly because they prevent caribou from digging through to their food supplies, and large die-offs of hundreds or thousands have been observed in response. Maarouf et al. (1994) analyzed weather in the high arctic during the past 42 years and found that potentially destructive weather events such as these have been occurring with greater frequency in recent decades. Although causation has not been established (in part because remoteness of the herds prevents detailed studies), the latest and most severe sequence of unfavorable years coincided with declines in the George River herd and deteriorating range conditions in northern Quebec and

Labrador (Maarouf et al., 1994 in prep.). Recent declines associated with unfavorable weather events have also been documented in the Canadian high arctic (Miller 1991) and Banks Island (Gunn 1995).

Terrestrial and marine arctic ecosystems are linked through the weather, but in many other ways they are decoupled, and changes in one may occur more or less independently of changes in the other. However, the overall importance of ice and snow to arctic wildlife is as true in the marine environment as it is on land. Included on the list of mammals that inhabit the arctic oceans are various species unique to the arctic, including walrus, several species of seals, narwhals, and bowhead whales. Surprisingly, an additional member of this group is the polar bear. Even though they are terrestrial animals, polar bears are entirely dependent on the marine environment, where they spend the long winter hunting on the pack ice (DeMaster and Stirling 1981). Polar bears and ringed seals, their principal prey, provide an example of the intricate tapestry of land and ice, seasonal progressions, and interdependencies that defines life on the arctic pack ice as much as it does in the tundra. Just as a continuous cover of snow for several years would devastate terrestrial communities, if the Arctic Ocean were to become ice free for long enough under global warming, polar bears would become extinct (Stirling and Derocher 1992).

Both bears and seals produce their young in the shelter of snow caves and thus are highly dependent on snow conditions. The distribution of polar bear denning sites across the arctic is in fact strongly influenced by the availability of snowdrifts. Land areas, such as Wrangel Island in the East Siberian Sea, that are both close to the ocean and provide the topography necessary for drifting can support very high densities of denning bears (Amstrup pers. com.). Although ringed seals do not require as deep snow, their success in raising young is likewise critically dependent on snow conditions — especially the integrity of the snow cave. Within the caves, temperatures are warm and relatively steady and range from 0° to -9° C, but even in the arctic spring, temperatures can plummet to -30° C, with wind chill reaching -70° C. Young seals born on top of the ice in the spring have a protective wool coat but do not yet have the necessary layer of the blubber. Their thermal neutral zone (the range of temperatures over which temperature decreases require minimal additional energy expenditure) extends only to -20° C, and as a result they cannot withstand the extreme conditions found outside the snow caves (Kelly pers. com.). Unseasonable warming at the southern edge of the snow pack can lead to collapses of the snow caves, and exposed young are rendered helpless when bitter cold returns. Scientists suspect that systematic warming in the arctic, manifested by increasingly frequent bouts of warm weather, will lead to a higher incidence of collapsed caves and ultimately to a contraction in the area suitable for seal denning (Kelly pers. com.), and, indirectly, to declines in polar bear populations. With fewer seal prey, a decline in polar bear populations would be inevitable. This decline would have immediate impacts on the Inuit communities of the high arctic, such as Grise Fiord, that derive important income from the local polar bear hunt.

5. **Wapusk National Park and Central Arctic Bird Sanctuaries**

Polar bears range throughout the arctic wherever there is pack ice, from close to the North Pole to far south into Hudson and James Bay. The most comprehensive studies of polar bears have taken place near Churchill, Manitoba, in the newly created **Wapusk National Park**, near the southern limit of the species' range. Here, adults fast during the summer and early fall when they are forced to remain on land because of the lack of sea ice. Incredibly, because they leave the ice early in the spring to den on land, females may fast for up to eight months. With the return of ice in the fall, the hungry bears immediately move out onto Hudson Bay to begin the winter season of hunting. Any decrease in the abundance of seal prey, or in the length of time the ocean is covered with ice, can be expected to have devastating effects on this southerly population. Again, although causation remains to be established, expectations and observations are matching up. As predicted under scenarios of the effects of global warming, birthrates have declined, and the average physical condition of adult bears appears to be worsening (Ramsey pers. com.; Stirling and Derocher 1992).

Wapusk is outstanding not only as one of the world's most southerly polar bear populations, but because of the diversity and abundance of its tundra and coastal bird communities. Indeed, from a global perspective, the overall importance of the arctic for bird species is truly spectacular. An estimated 15% of all of the world's species breed in the arctic. The mobility afforded by flight allows them to capitalize on the brief pulse of productivity during the ephemeral arctic summer and raise their broods. Coastal areas in particular are productive breeding grounds for many migratory species, and a walk across the tundra is often anything but quiet. The **Queen Maud Gulf Bird Sanctuary** in the central Canadian arctic on the coast of the Arctic Ocean, for example, is home to more than two million geese alone (including snow geese, Ross's geese, greater white-fronted geese, and Canada geese) (Alisauskis pers. com.). Other important sanctuaries in the Canadian arctic include **Bylot Island**, **Harry Gibbons**, **East Bay**, and **McConnell River**. In North America, 55 bird species breed exclusively in the far north, including 29 species that are restricted to the arctic coast and northern islands, 8 species that in addition use areas of inland tundra, and a further 18 species that also extend into the Hudson's Bay Lowlands.

Inadvertently, by altering the planet's atmosphere, we are creating a huge experiment that appears likely to play out at the expense of these arctic organisms. Unfortunately, our ability to predict the outcome of such an experiment is severely compromised both by the complexity of the atmosphere and the complexity of the ecosystems involved.

Ecosystems are defined as much by the relationships among organisms as by the organisms themselves; a change in the abundance of one organism can lead to a myriad of other unanticipated changes. In some cases, these changes are met by compensatory responses, thereby maintaining the overall stability of the ecosystem. In other cases, change, once initiated, can become self-reinforcing, such that it eventually escalates out of control and destroys the ecosystem in the process. Herein lies the real danger of the

experiment: the possibility of radical, unpredictable change (Malcolm and Markham 1996).

This sort of rapid, self-reinforcing change appears to be occurring in snow goose populations of the eastern Canadian arctic, especially in the **Queen Maude Gulf Bird Sanctuary** and in coastal marshes in and around **Wapusk National Park**, such as La Pérouse Bay. At the snow goose colony in La Pérouse Bay, the last 15 years or so have seen a steady increase in goose numbers (including both the Canada and snow geese) under the influence of increased winter food availability in agricultural fields in the United States, concomitant with decreases in hunting pressures and increases in the availability of protected areas and refuges (Jefferies et al. 1995, Jefferies in prep.). At the same time, the eastern arctic has been the site of a recent cooling trend (Chapman and Walsh 1993; Findlay and Deptuch-Stapf 1991). This strange anomaly in an otherwise warming arctic finds support in the GCM created by the United Kingdom Meteorological Office, which predicts a localized cooling trend in the eastern arctic (Houghton et al. 1996). Although far from certain, it appears that this contradictory signal may result from global warming, presumably as a consequence of changes in ocean currents.

As a result of the cooling, the ever-increasing goose populations are arriving at the marsh before spring has gotten under way. In response to the lack of new plant growth, the snow geese use their serrated bills to eat the roots and rhizomes of the still-dormant marsh plants, an activity called grubbing. Unfortunately, the removal of marsh vegetation becomes self-reinforcing: Less vegetation cover leads to increased evaporation during the summer season, which in turn leads to increased salinity and plant mortality. The net effect is decreased nitrogen mineralization in the soil and a collapse of the normal marsh community. Geese, shore birds, soil invertebrates, and grazing ducks (American widgeon, for example) are all negatively affected. The problem may be that the geese simply move on and degrade another area. In this example, once a threshold was crossed (caused by regional climate change in concert with habitat modifications occurring farther south), a rapid and devastating change in the ecosystem followed.

6. Protected Areas of the Boreal Forest

The boreal forest of North America is the largest block of more or less intact forest remaining in the world and is rivaled in area only by the boreal forest of Russia and the tropical rainforest of the Amazon Basin (Bryant et al. 1997). It cuts a broad swath across the northern part of the continent and is bounded to the north by the treeless tundra and to the south by the temperate forests. Within this immense area, diverse ecological conditions are represented, including stunted taiga forests of the far north, extensive peatlands along Hudson Bay in northern Ontario, transition zones from prairie to forest in the prairie provinces of Manitoba, Saskatchewan, and Alberta, and steep mountainous terrain in the cordilleras of northern British Columbia, Yukon, and interior Alaska. In Ontario, **Woodland Caribou Provincial Park** provides refuge for woodland caribou, which face extirpation from their range farther south in the face of clear-cut logging and

other human activities (Cumming and Beange 1993). At the boreal/taiga transition in northern Alberta, **Wood Buffalo National Park** is summer home to endangered whooping cranes. Here, wolves still hunt buffalo, in an ancient contest that once characterized much of the North American west. Other protected areas include **Nahanni National Park**, located farther north in the MacKenzie River Basin and one of the most spectacular river parks in the world. The MacKenzie Valley itself forms one of North America's most travelled migratory corridors for waterfowl (ducks, geese, and swans). Mammals such as Dall sheep, moose, black and grizzly bears, wolves, lynx, arctic ground squirrels, American pikas, hoary marmots, and wolverines and birds such as gyrfalcon and willow and rock ptarmigan still teem in Alaskan National Wildlife Refuges such as **Kanuti, Yukon Flats, Koyuku, and Nowitna**. The northern edge of the boreal forest provides important winter shelter for barren-ground caribou, which move south from the tundra in the fall and spend the winter feeding on the abundant lichens and other forage found in old-growth forests.

Again, the vast and pristine nature of parts of the boreal forest does little to protect it from the invisible reach of atmospheric pollution. Climate models consistently predict widespread ecosystem change under greenhouse warming, with damaging results. Already, these impacts appear to be under way. A pattern of consistent warming in the last 140 years has seen melting of the sparsely distributed and discontinuous permafrost characteristic of the boreal and taiga forests (Halsey et al. 1995; Kwong and Gan 1994); as a result, suitable conditions for tree growth and reproduction are occurring farther and farther north. In addition, the warming trend has been accompanied by changes in photosynthetic rates within the forest itself (Myneni et al. 1997). Models suggest that the warming will lead to lowering of local water tables and hence to reductions in areas of wetlands (Larson 1995). Equally seriously, large-scale disturbances such as fire and insect outbreaks, which the flora and fauna can normally avoid or exploit, are predicted to increase in frequency (Neilson et al. in prep.).

A recent interdisciplinary study of past and future climate in the MacKenzie River Basin is illustrative of predictions that are typical for this region (Cohen 1997). Hydrological models predicted that minimum water levels would decline under warming because of the increased rates of evapotranspiration, which offset increases in precipitation. Levels were predicted to be even lower than the extremely low levels of 1995, especially in the important waterfowl regions of the southern parkland zone. Thinning and outright loss of permafrost contributed to much higher predicted landslide rates in the region. Perhaps most seriously, the study predicted a decrease in forest productivity in the region. The decline was due to a combination of factors, including a doubling of the annual area burned by 2050, massive drought-related die-offs of coniferous trees, and increased susceptibility to insect pests such as white pine beetle. The predicted increase in forest fires, and hence eventual transition to a landscape of young regenerating forests, is of particular concern for wildlife species that make extensive use of mature and old-growth forests, such as marten, fisher, and caribou. Several studies of greenhouse warming in the boreal forest have likewise predicted longer fire seasons and potentially more frequent and larger fires due to more severe fire weather, changes in fire management practices,

and possible forest decline or dieback (Flannigan and Van Wagner 1991; Fosberg et al. 1996; King and Neilson 1992; Price and Rind 1994, Wotton and Flannigan 1993).

The possibility of large-scale forest diebacks is made more alarming by the possibility that they may occur very rapidly. At present, the extent of potential diebacks is unknown because of uncertainty as to how trees will respond to increased availability of CO₂. However, even assuming a diverse range of possible CO₂ responses, most climate scenarios predict a spatially complex mosaic of forest dieback, stasis, and increased growth (Neilson et al. in prep.).

If direct CO₂ effects prove to be small, then widespread forest dieback and large range contractions in the boreal zone are indicated (Neilson et al. in prep.). Several studies have suggested that where temperature-induced drought dieback occurs, it will likely begin shortly after observable warming and, when accompanied by short-term precipitation deficits, could occur within a few decades (Auclair et al. 1996, Elliot and Swank 1994, King and Neilson 1992, Martin 1992, Smith and Shugart 1993, Solomon 1986, Vose et al. 1993). Alternatively, forest growth might increase in the early stages of global warming, only to switch to widespread and rapid drought-induced forest dieback once higher temperatures have increased evaporative demand (Neilson et al. in prep.). Where enhanced growth is indicated, it is likely to be more gradual and take decades to hundreds of years under the constraints of seed dispersal, seedling establishment, and competition (Neilson et al. in prep.).

A recent study of tree growth rates throughout the boreal zone lends strong support to a scenario of an initial burst of tree growth under global warming (Myneni et al. 1997). With appropriate transformation, data from weather satellites can be used to measure photosynthetic activity in the forest canopy (Myneni et al. 1995). Analysis of these data for 1981–1991 indicated that plant photosynthetic activity increased, spring came earlier, and fall arrived later. The effects were strongest in the northwest boreal zone and weakest close to Hudson Bay. The increase was associated with an increase in temperatures, especially in late winter and early spring, consistent with an up to 4° C that has occurred in winter in substantial parts of Alaska and northwestern Canada but is less pronounced close to Hudson Bay (Chapman and Walsh 1993). Studies of tree rings similarly show consistent long-term warming (D'Arrigo and Jacoby 1993, Jacoby and D'Arrigo 1989, Jacoby et al. 1996). Associated with the warming was an approximate 10% reduction in annual snow cover from 1973 to 1991 and an earlier disappearance of snow in spring (Groisman et al. 1994). Myneni et al. (1997) suggest that the changes are consistent with predictions of global warming, and moreover that they support the possibility of disproportionate responses and positive feedbacks leading to marked changes in system properties. Instead of gradual change, rapid, catastrophic change may be the norm as the planet warms.

In addition to providing important habitat for myriad plant and animal species, boreal forests are an important pool of the world's terrestrial carbon. Of the global total, about 14%–17% is in the forests of North America, and about 86% of that is in the boreal forest

(Apps et al. 1993, Heath et al. 1993, Sampson et al. 1993). A further concern about dieback and reductions in forest area in the boreal zone is the possible production of a large carbon "pulse" over the next several decades leading to a positive feedback to global warming, because under some simulations carbon gains from new growth are far slower than carbon losses from fire and decomposition (King and Neilson 1992, Smith and Shugart 1993, Sohngen and Mendelsohn in press, Stocks et al. 1996). Further contributing to the pulse is potential widespread melting of permafrost and the release of soil carbon caused by increased decomposition (Apps et al. 1993). In addition to this feedback between warming and additional carbon release are possible feedbacks leading to changes in local weather patterns. For example, transition from forest to grassland may lead to reductions in local precipitation owing to reduced overall evapotranspiration.

7. Northern Great Lakes National Parks and Protected Areas

The vast Great Lakes region of the United States plays host to a patchwork of human development and natural habitat. Large cities, including Chicago, Detroit, and Cleveland, nestle on the shores of the lakes, and pollution of all sorts has afflicted some local areas for more than a century. Despite the years of heavy human use in many parts of the region, the Great Lakes still harbor many important wildlife areas, and in the north, significant tracts of wilderness. The roadless **Isle Royale National Park** is the largest island in the world's largest freshwater lake — Lake Superior. Of the 700 or so plants found on the island, 22 are relics from the last ice age, more commonly found in the tundra of Alaska or arctic Canada, and are restricted to the cool, moist habitats at the eastern end of Isle Royale. These species would be especially vulnerable to changes in climate that are expected to make the area warmer and drier.

Slightly west of Lake Superior, running along the Canadian border, lies **Voyageurs National Park**, a vast area of glacial lakes, islands and subarctic pine, spruce, aspen, and white birch forest. A new WWF analysis of protected area sensitivity to climate change in the U.S. puts this park at the top of the list of National Parks likely to experience major changes in vegetation as a result of global warming (see Appendix 1). Previous computer modeling exercises have also identified this region as sensitive to change. The IPCC predicts that as much as 40% of the world's boreal forest (like that in **Voyageurs National Park**) could eventually be lost as a result of climate change (Houghton et al. 1996). More detailed analysis for the **Boundary Water Canoe Area**, a designated wilderness within the **Lake Superior National Forest**, shows how rapid and dramatic these changes could be. Scientists Daniel Botkin and Robert Nisbet predict that diverse white birch, balsam fir, and quaking aspen forests could all start to decline and be replaced by sugar maple forest by 2010, and the white cedar bogs would most likely be replaced by shrubby, treeless habitat (Botkin and Nesbit 1992). However, the most critical factor in determining successional patterns in these northern hardwood-conifer forests is the interplay of wind and fire. Alterations in the disturbance regime will ultimately determine how the forests change (Peterson in litt.). In some cases, natural succession in northern forests may be accelerated by global warming. For example,

research has shown that warmer and drier growing conditions in the late 1980s may have hastened the decline of mature paper birch forest in northern Michigan due to infestation with the insect pest, bronze birch borer (Jones et al. 1993). Loss of boreal forest at the southern edge of its distribution and invasion by northern hardwoods would result in lower biodiversity and less overall forest biomass. Similar changes are likely to be seen throughout the boreal zones of the world, and may represent one of the most alarming global impacts of climate change.

An example of how changes in forest composition might affect wildlife can be seen from predictions about the fate of the endangered Kirtland's warbler in a small nature reserve at **Grayling**, on Michigan's northern peninsula between lakes Huron and Michigan. The warbler depends on a few remaining areas of jack pine growing on "Grayling" soils. Models predict that these jack pine stands are likely to be replaced by white pine and red maple, and then, eventually, by a treeless plain. With none of its highly specialized habitat available in alternative nearby areas, the Kirtland's warbler would face extinction (Botkin and Nesbit 1992). The first impacts of global warming may already be identifiable in this region. Biologist Terry Root has recorded that many migratory birds are arriving up to 21 days earlier than they were 35 years ago, possibly because spring is arriving earlier at northern latitudes. Farther south, at **Indiana Dunes National Lakeshore**, plant species that are restricted to this narrow band at the lower end of Lake Michigan may become locally extinct as climate tends to drive the climatic zone northward — into the lake. Species at risk here include white pine and Canada bunchberry (Ken Cole pers. com.).

8. Protected Areas of the Great Plains

The Great Plains are home to the ponds, "potholes," and other wetlands that provide critical nesting habitat for millions of ducks, shorebirds, and geese. An estimated half of all North American waterfowl production occurs in the prairie pothole region. Nowhere else in the continent are there so many protected areas ideally suited to the nesting requirements of migratory waterfowl. Giant Canada geese, once believed extinct, are plentiful nesters on the 120 islands of Lake Audubon in the **Audubon Refuge** of North Dakota. Trumpeter swans, formerly close to extinction, are abundant at **Lacreek** in South Dakota. Some of the largest wintering concentrations of bald eagles occur at **Squaw Creek** in Missouri. During the spring and fall migrations, many of the refuges are home to millions of birds, as at **Sand Lake** in South Dakota, where 2 million of the midcontinental population of snow geese come through in spring. By fall, the refuge may be a temporary home to a half million Franklin's gulls, a quarter million mallard ducks, 5,000 tundra swans, and 12,000 pelicans. Incredibly, half the shore birds in North America are believed to stop at **Quivira** or nearby **Cheyenne Bottoms** in Kansas during annual migrations. In addition, many refuges provide the last remaining habitat for the unique prairie flora and fauna that once teemed across the plains. Refuges such as **Sullys Hill** in North Dakota and **Fort Niobrara** in Nebraska are home to remnant populations of buffalo, sharp-tailed grouse, prairie chickens, and prairie dogs. Other refuges, such as

Walnut Creek in Iowa, are the sites of attempts to restore the endangered prairie ecosystem (Riley and Riley 1992). Far to the north, at the edge of the prairie in Canada, **Prince Albert National Park** in Saskatchewan and **Riding Mountain National Park** in Manitoba provide a unique blend of grassland, parkland, and boreal ecosystems.

Water, and the productivity that it brings, is the lifeblood of the prairie. The abundance of wetlands is in turn closely tied to the weather; interannual variation in climate, including both precipitation and temperature, was found to explain more than 60% of the variation in the number of wetlands from year to year (Larson 1995). This variation has important implications for migrants such as the pectoral sandpiper, one of several sandpiper species that funnels its migration through the Great Plains (Farmer pers. com., see also Weins and Farmer in press). The birds arrive in the early spring, on their way from their wintering grounds in South America to breeding grounds on the northern coast of Alaska and Canada. During their stopover, the birds feed heavily and dramatically increase their energy reserves for the remaining flight to the north. When they arrive in mid-April, body fat typically makes up only 10% of their total weight; five weeks later, it is more than 40%. In dry years, the wetlands they need for feeding are not as abundant, and the birds are not able to put on as much weight. In 1994, for example, an extremely dry year, females arrived with close to the typical 10% of body fat, but as the season progressed, most lost weight. As a result, many did not go north at all and failed to breed (Farmer pers. com.). Research indicated that the sandpiper's foraging activity was concentrated not only in refuges, but in the temporary ponds and moist areas found in agricultural fields (Farmer pers. com.). In a dry year such as 1994, fewer of these small moist areas are to be found. To compound the situation, farmers are able to till their fields earlier, resulting in even fewer temporary wetlands.

Global warming due to the greenhouse effect brings another threat to the region, which in combination with the relentless agricultural development that has led to steady declines in wetlands and waterfowl abundance (Bethke and Nudds 1995) appears likely to be particularly devastating. In one recent analysis in which scientists linked several state-of-the-art climate change models with a suite of ecosystem models, the most consistently threatened protected areas in the conterminous U. S. were the National Wildlife Refuges of the central part of the country (Appendix 1). Ecosystem quality consistently declined in the landscapes surrounding the refuges, in many cases dramatically so. These models demonstrated that the central U.S. is especially sensitive to greenhouse warming, and that widespread ecosystem transformation in the prairie is a consistent prediction of increased greenhouse gas concentrations.

In a detailed hydrological study of potential climate change impacts on a typical small prairie wetland (Poiani and Johnson 1993), warmer annual temperatures similar to those predicted by various climate models resulted in drier conditions, quite irrespective of whether more or less precipitation was received on average. The result was less open water and greater vegetative cover. The study is especially troubling because it suggests that smaller wetlands would be especially vulnerable to global warming. These smaller wetlands are disproportionately important for waterfowl. When the ratio of vegetation

cover to open water is close to unity, as is typical of small prairie potholes, breeding bird density and diversity is at a maximum (Diamond and Brace 1991, Poiani and Johnson 1991). As well, the persistence of the temporary wetlands into the early summer importantly influences brood survival and hence production of the next generation (Diamond and Brace 1991).

Of course, migratory birds of the Great Plains are expert at dealing with the variability in conditions found from year to year and region to region. Typically, as they arrive from the south, the birds settle down in the first good habitat that they find. In a dry year in the prairie, they may move north into the forest transition zone of Alberta, Saskatchewan, and Manitoba, where wetlands are even more abundant (Larson 1995). Again however, climate models provide little hope for the continued success of age-old strategies. Models suggest that the prairie parkland will also be hard hit by global warming. These wetlands appear to be even more sensitive to warming than prairie potholes, perhaps because of the evapotranspirative demand of the willows and other tree species that border the wetlands (Larson 1995).

The net effect of global warming thus appears to be a steady decline in the amount of habitat available to the millions of waterfowl that make use of the prairie region. Avian biologists suspect that an early warning of the decline will be increased transmission of avian botulism and large-scale die-offs as more and more birds are packed into increasingly rare habitat (Price pers. com.). The implications of loss of duck breeding sites and population declines in the Great Plains region could be very serious for the millions of Americans who engage in recreational duck hunting, and for the outfitting industry they support.

In addition to the ubiquitous waterfowl, many bird species make use of the upland prairie itself. Already, these grassland species show some of the steepest declines of all bird species monitored in the Breeding Bird Survey (Price et al. 1995), and a recent study suggested further problems in a warming world. The study made use of the often-strong relationship between a species' geographic range and regional climate patterns to predict range shifts under a scenario of global warming (Price 1995). Under doubled CO₂ concentrations, all 23 grassland species showed range shifts and approximately half showed a range decline. Two were predicted to become extinct (Sprague's pipit and McCown's longspur), and a two others were highly vulnerable (chestnut-collared longspur and Baird's sparrow). Almost all species showed range shifts to the north, into regions that at the moment are mostly forest. Within the time frame of the predicted warming, significant conversion to grasslands was viewed as unlikely, hence the size and fragmented nature of the existing grassland patches in the north would put an additional burden on populations (Price 1995). Shifts such as these will be stronger for some species than others, resulting in a state of flux in the species mixtures from site to site. The resulting changes in competitive interactions among species may lead to further changes in community composition.

Increasing concentrations of atmospheric greenhouse gases and associated global warming does not bode well for prairie ecosystems and their abundant wildlife populations. Many prairie species have suffered enormous declines in the past; some are currently declining, and others are barely able to hold their own in the face of existing development pressures. Protection and restoration can and have done much to improve the situation, but unfortunately will provide little respite in a world of radical climate-induced ecosystem reassortment.

9. **Rocky Mountain National Park**

To the west of the central plains, the topographical diversity of the great mountain chains creates unparalleled ecological heterogeneity. **Rocky Mountain National Park**, for example, includes 13 major vegetation zones, all within a few miles of each other (Stohlgren in prep.). In the prairie ecosystem at the foot of the mountains, prairie dogs perform a keystone role and directly or indirectly support 170 vertebrate species, including endangered black-footed ferrets (Miller et al. 1994). Other threatened species include mountain plovers, ferruginous hawks, and swift foxes. Partway up the slopes, old-growth forests are a key resource for many wildlife species such as caribou, wolverines, Albert's squirrels, fishers, northern goshawk, and several owls. Protected areas are home to several species that today occupy only a fraction of their former range, including grizzlies, wolves, caribou, bighorn sheep, and beaver. Although they occupy only a fraction of the landscape, mature aspen ecosystems play a key role for hundreds of birds and mammals, and are especially important for deer and elk (Stohlgren in prep.). Farther up the slopes, past the tree line, the alpine tundra zone is home to a host of plant species shared with arctic ecosystems (Billings 1988).

Global change brings an additional stress that, in the face of existing pressures, these ecosystem complexes are ill suited to withstand. Increasingly, protected areas are becoming islands of natural habitat in a sea of human development. **Rocky Mountain National Park** and the surrounding region is at the forefront of these impacts (Stohlgren et al. 1995) and provides a poignant example of what may be in store for other mountain protected areas of the Rockies, such as Montana's **Glacier National Park** and **Banff** and **Jasper National Parks** much farther to the north in Canada. A litany of change, so far mainly unrelated to climate, has resulted in the declines of a host of species for diverse reasons (see Stohlgren et al. 1995, Stohlgren in prep.). For example, prairie dog control programs throughout the west resulted in 98% reductions in their populations and the near extinction of black-footed ferrets. Currently, widespread declines in amphibian populations are being observed, including western toads, boreal toads, and leopard frogs.

A long history of fire suppression has caused steady declines in the habitat for species that depend on post-fire seral stages, such as the black-backed woodpecker and many understory plants. Populations of many old-growth specialists are declining, a net effect of logging in the region that has resulted in the loss of the large trees and their replacement with younger, faster growing trees. In contrast, elk have tended to benefit

from reduced predation and hunting, but the steady loss of habitat outside the park has lead to the concentration of more and more animals into the park. Migratory routes are now cut off because of development, and the herd is stationary for the first time in history.

Coupled with these habitat changes are changes in the aggressive exotic competitors that the native flora and fauna must face. More and more non-native species are invading the area, with serious effects. Introduced blister rust in concert with fire suppression appears to be irreversibly damaging white bark pine ecosystems, an important food resource for jays, grizzlies, and other animal species. Introduced moose are now invading the lush riparian zones of the park in increasing numbers. The effect of this population increase is unknown, but increases in moose populations have led to marked changes in plant communities elsewhere (Pastor et al. 1993, Peterson 1977, Peterson et al. 1984, Wedeles and Van Damme 1995).

These are only a subset of the problems that beset **Rocky Mountain National Park**, which include other, more subtle, effects of human activities (Stohlgren et al. 1995, Stohlgren in prep.). Observations and sophisticated mesoscale climate models show that land use outside the park is greatly influencing weather patterns within the park (Pielke et al. 1993). Agricultural development has changed the surface albedo and landscape "roughness" surrounding the park, resulting in increased intensities of summer storms within the park. Other local climate alterations appear to be resulting from this land-use change, including cooler and wetter summers at low elevations. These trends, together with warmer winters resulting from global climate change, will probably combine to increase fire risk.

In addition to pressures that arise from outside the park but drive change within it, there is global warming. As annual temperatures gradually increase, plants and animals will find themselves in a new environment, and a reassortment of the existing ecosystem mosaic will be the result. Just as models predict that arctic ecosystems will be at the forefront of the global impacts of global warming, so too will be montane and high alpine systems. In common with their arctic conspecifics farther north, alpine plants are able to withstand low temperatures and reproduce in the extreme cold of high altitudes. With sufficient warming, and the right precipitation conditions, plants currently at lower elevations could invade and displace high alpine species. If it occurs, this "migration" of ecosystems upslope is predicted to have devastating impacts on alpine ecosystems. Studies of the tree line in **Rocky Mountain National Park** reveal that the impact of the current long-term warming trend may already be under way. Evidence for global warming impacts can be seen in the fact that the stunted, wind-trimmed Engelmann spruce trees at the tree line (termed Krummholz vegetation) are growing at an abnormally high rate and are showing both lateral and height extension. These trees can be hundreds of years old and only a couple of feet high, yet now, warmer conditions (and possibly changes in snowpack) are causing them to sprout and grow like normal trees. The sparse tree community at the tree line is closing in and crowding out understory and alpine tundra plant species (Stohlgren et al. 1995).

Small changes in the amount of snowfall and the timing of snowmelt could have major implications for alpine flora. If warmer or drier conditions cause earlier snowmelt, this will change the competitive relationships between plants in the alpine zones. For example, studies in Colorado show that early snowmelt may initially increase the population of alpine snow buttercups by increasing the growing season, but that eventually will lead to more plants with large seeds in the population. Large seeds improve competitiveness under a stable climate but reduce the ability of plants to spread upslope in response to rapidly warming climate, so the net effect could be negative in the long term (Galen and Stanton, 1993). Another, similar impact has been identified for *Delphinium nelsonii* in dry subalpine meadows near **Rocky Mountain National Park**. Earlier snowmelt exposes the plants to colder spring temperatures, thus delaying flowering and reducing flower production. This impact cascades through the food web and reduces populations of bumblebees and broad-tailed hummingbirds, which depend on the delphiniums. The bumblebees and hummingbirds normally depend on nectar from early-flowering delphiniums, and later in the season act as pollinators for other plants (Inouye and McGuire 1991).

Global warming is expected to bring other changes to already stressed park ecosystems. In **Rocky Mountain National Park**, as in other conifer-dominated systems, fire plays a key role in forest dynamics, and changes in fire frequencies have important implications for old-growth systems. Tree-ring studies of previous fires in the park demonstrate the strong link between climatic conditions and fire occurrence. During the extreme droughts that occur about once per century, nearly half of the entire montane zone burns. Periods of high variability in rainfall also tend to have more fires. Scenarios of global warming suggest increased occurrence of both threats: increased variability in climate conditions and increased frequencies of the once-a-century droughts. Biologists also suspect that increased disturbance rates in the park, wrought both by agents within the park and by atmospheric change, will lead to increased opportunities for invasions by non-native species (Stohlgren pers. com.). These invasions will in many cases displace native species before they become susceptible to the effects of changed climate *per se*.

The overall outlook for **Rocky Mountain National Park** in the coming decades is one of accelerating environmental degradation as a result of rapid population growth and land use change in the near vicinity, exacerbated by accelerating rates of global warming. The park has one of the leading climate change impact research programs, and along with those centered on other mountain protected areas, including **Olympic, Glacier, Sequoia-Kings Canyon** and **Great Smoky Mountains National Parks**, could become part of an invaluable network for monitoring change as well as a crucible for testing the integrated management strategies that will be needed to cope with environmental change in the next few years.

10. **Yellowstone National Park**

Carved out from 2 million acres of pristine Wyoming, Montana, and Idaho lands in 1872 (and celebrating its 125th anniversary in 1997), **Yellowstone** became the world's first National Park, and is now probably the most famous of all. With its intact grizzly bear habitat and rangelands for buffalo, elk, and moose, along with spectacular hot springs and geysers, **Yellowstone** has a wealth of interest to captivate its millions of visitors every year. Connected to **Grand Teton National Park** in the south and surrounded by National Forest areas such as **Shoshone National Forest** and **Gallatin National Forest**, **Yellowstone** is large enough to be somewhat buffered from external environmental influences. It still suffers, however, from many problems. Visitor pressure is particularly high near roads and the most popular hiking trails and view-points, and environmentalists are constantly fighting threats of mining activities and other developments just outside the park's borders. Moreover, despite the size of the park area, grizzlies and wolves (the latter having been reintroduced in small numbers very recently) often range outside and are occasionally shot by local ranchers.

Since the massive fires of 1988, when nearly half the park was burned to some degree, scientists have been paying greater attention to the possible threat from climate change. Although wildfires are a natural and necessary part of the ecology of western forests, global warming is expected to change their impacts on ecosystems. Climate is not the only factor affecting fires in National Parks. Years of management policy aimed at suppressing natural fires have led to a build-up of flammable material in forests, thus increasing the likelihood of bigger, more intense fires. Also, in a completely natural ecosystem, lightning strikes would be the normal trigger for a fire, but now humans have added campfires and deliberate arson to the potential causes.

Experts agree that the fires of 1988 came about as result of a combination of factors. They included a series of winter drought years (low snowfall) culminating in a hot, dry summer with unusually strong winds unaccompanied by rainfall (Knight 1991, Varley and Schullery 1991). Also important was the fact that lodgepole pine hardly ever burns if stands are less than 150 years old, but by 1988 large areas of the park consisted of lodgepole forest of this age. Under normal conditions, large fires like those of 1988 occur only once in every few generations. But with approximately 40% of the park remaining vulnerable to future large-scale burns, any major increase in fire risk due to climate change would pose a significant problem for **Yellowstone** (John Varley, pers. com.).

Analysis of historical climate trends in **Yellowstone National Park** has revealed a significant trend toward conditions that increase the hazard of wildfire (Balling et al. 1992). These studies have shown that fire season (summer) temperatures are increasing and that precipitation is decreasing — even trending toward increased drought probability — in the presummer period of January to June. These factors, along with summer drought stress and wind conditions, are among the most important in determining natural fire risk. The temperature increases recorded in **Yellowstone** are consistent with those predicted by global change computer simulations.

If the current warming and drying climate trends in **Yellowstone** continue, then an increased frequency of massive, stand-replacing fires might be expected. This in turn would lead to a replacement of old-growth forest stands by younger age-classes of tree, and a reduction in this habitat could cause local extinction of old-growth forest species such as northern twinflower, fairy slipper, pine martin, and goshawk (Romme and Turner 1990). Loss of old-growth habitat to fire would be compounded by losses due to a general reduction in forest area as a result of global warming and logging activities in important buffer areas outside the park.

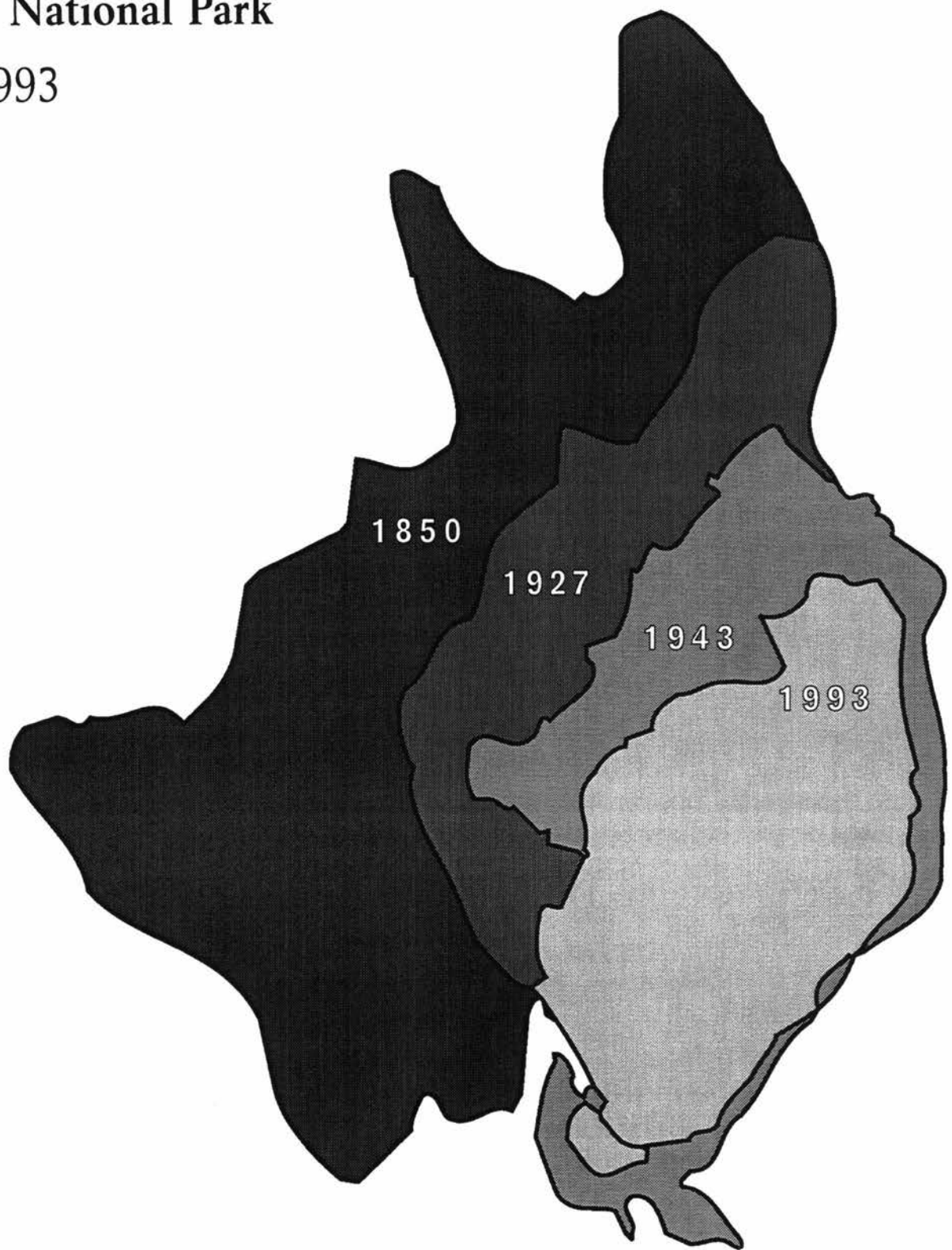
Ecologists William Romme and Monica Turner have speculated about what the most significant consequences of various climate scenarios would be for the Greater Yellowstone Ecosystem, of which **Yellowstone National Park** is a major component. Under all three scenarios they examined, the most significant and negative impacts could occur in the high montane whitebark pine forest and in the alpine zone (Romme and Turner 1990). In Romme and Turner's study, a warmer wetter climate appears preferable to a warmer drier climate for the park, mainly due to increased fire risk in the drier scenario. Unfortunately, today's actual climate trends point toward the more damaging dry scenario. If this situation continues, up to 90% of the habitat suitable for whitebark pine in **Yellowstone** could disappear within 50 years. The whitebark pine nuts and army cutworm moth caterpillars found in these forests both provide vital food for **Yellowstone's** grizzly bear population (Matson and Reid 1991). However, grizzlies are famously flexible when it comes to food and they may be able to adapt to the loss of certain food sources by finding alternatives (John Varley pres.com.).

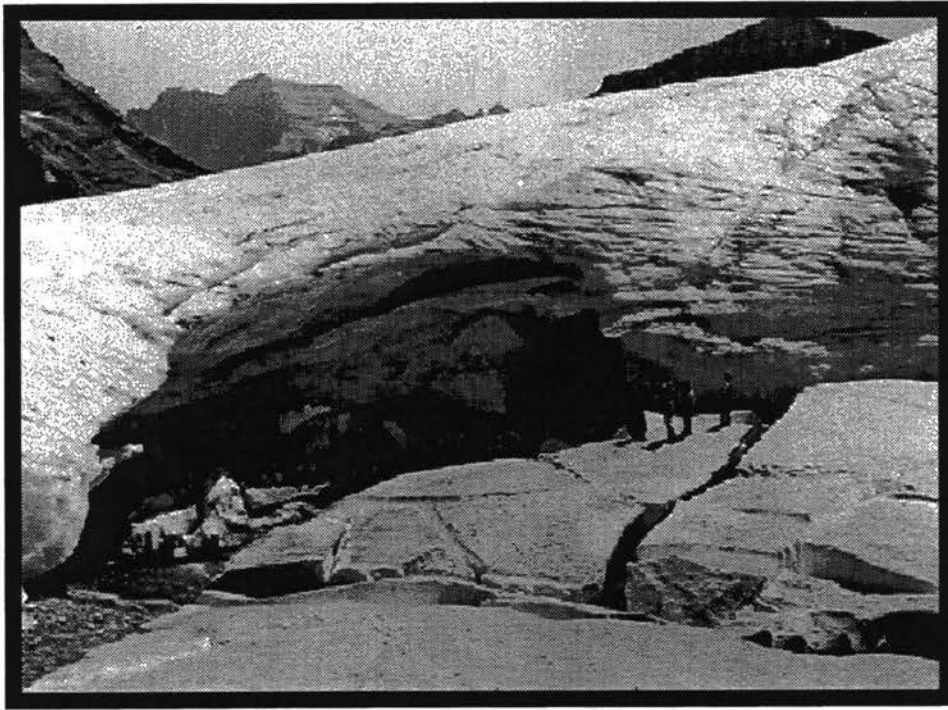
Whitebark pine forest may be replaced with Douglas fir, and on the lower slopes, forest would most likely give way to treeless landscapes dominated by big sagebrush, Idaho fescue, and bluebunch wheatgrass. Local extinctions of alpine species can be expected as a result of loss of some habitat and increased fragmentation of the remainder (Romme and Turner 1990). However, palaeoecological studies in **Yellowstone National Park** and **Grand Teton National Park** show that the tree line has changed little in response to past climate change, but that changes in species distribution and abundance have been quite large. Long-term decrease in snowpack would be the most important factor in causing an upslope movement of the tree line (Peterson in litt.). The most likely impacts on high-elevation habitats will be a re-mixing of the flora and fauna that make up these ecosystems, and perhaps the creation of new communities of species with different plants gaining dominance.

11. **Glacier National Park**

Unlike **Rocky Mountain National Park**, which is located in a region of high human population growth, **Glacier National Park** is situated in a large and virtually pristine area of wilderness. Here, at the headwaters of three major continental river systems, grizzly populations are more dense than anywhere else in the conterminous United States,

Sperry Glacier Recession
Glacier National Park
1850-1993





Ice Cave, Boulder Glacier
July 1932



Same photo point as above
1988

and air and water quality are among the best in the nation. The park is known for its wildflower meadows and abundant wildlife. An extensive network of hiking trails combined with spectacular scenery attracts large numbers of visitors in the summer. Because of its largely pristine condition, the area serves as an important yardstick of climate change in a landscape that is still largely untouched by human influences.

Research indicates that the park has not escaped the change brought by global warming and that even more extensive change can be expected in the near future. As befits its name, **Glacier** is home to approximately 50 glaciers, which because of their small size are highly sensitive to even slight climate changes. During the past century, systematic measurement of some of the larger glaciers has shown decreases in area by more than half. The park's glaciers, including Grinnell, Harrison, and Sperry, started to retreat around 1850, and the rate of recession increased dramatically during a period of dry years with warm summers in the 1920s and 1930s. The period after 1850 saw sustained warming as much of the world came out of the Little Ice Age it had been experiencing. Separating human-induced warming from the natural rebound after the Little Ice Age has been a particularly knotty problem for climatologists. The number of glaciers in the park has dropped from an estimated 150 in 1850 to approximately 50 today (Fagre pers. com.). Since 1968, as the warming trend has worsened, and the human influence on it been more sharply defined, many of the smaller glaciers have disappeared entirely. Park scientists predict that all the glaciers of Glacier National Park will be eliminated by 2030 at current rates of warming (Fagre in press). The loss of glaciers and reduction of summer snowpacks will increase stream temperatures and reduce water volumes in park watersheds. These changes will adversely affect the current aquatic biota, including valued trout species.

Detailed projections of further climate change impacts have focused on the 46,200-ha Lake McDonald watershed, a part of the Flathead River catchment (White and Running 1994). Observations show that water temperatures influence the distribution of stream invertebrates in the McDonald basin. A variety of species of the caddisfly family, for example, dominate or are replaced by others at different elevations along a stream's length. Warming temperatures would likely alter the invertebrate fauna of these streams, thereby affecting the food web that supports amphibians, fish and waterfowl. Some high alpine invertebrate species could be lost completely if water temperatures rise too high, or if reduced water availability results in intermittent flow of streams (Fagre et al. in press). Coupled forest succession and hydrological models indicate the possibility of widespread changes in vegetation communities, including eventual shifts from forests dominated by lodgepole pine and western red cedar to those dominated by western hemlock and spruce (Fagre in press). Additional changes include invasion of alpine meadows by subalpine fir, nutrient stresses at the tree line, and greater potential for intense wildfire in the valley forests. Recent research shows that forest of the lower slopes and bottomland on the eastern side of the Continental Divide may be particularly sensitive to warming temperatures (White et al. in press). These forests consist largely of deciduous species such as paper birch, black cottonwood, and aspen, and vegetation and fire modelling for **Glacier National Park** show that smoke levels could double in the park under certain

future climate scenarios, with consequences for air quality and visibility (Keane et al. in press).

12. **Olympic National Park**

A spectacular outpost of varied habitats on the Olympic Peninsula, **Olympic National Park** represents Washington State's premier wilderness area. Roughly half the world's temperate rainforest is in the Pacific Northwest, and several magnificent tracts are found within the nearly one million acres that make up the park. Some of North America's largest and most spectacular coniferous tree species are heavily represented in the park, including the western red cedar, western hemlock, Sitka spruce, and the giant Douglas fir. These trees can take centuries to reach maturity and may live longer than 1,000 years. **Olympic National Park** is critical for the preservation of large areas of old-growth forest because so many other forests are subject to active or potential logging operations. Old-growth forest is especially important for species such as the Roosevelt elk, spotted owl, marbled murrelet, Olympic salamander, banana slug, Pacific rhododendron, and sword fern. At higher elevations than the rainforest, the park supports subalpine forest, and, higher still, beautiful subalpine and alpine meadows that come alive with wildflowers in the spring and early summer. These mountain habitats are likely to be at greatest risk from climate change.

Recent research from **Olympic National Park** and from **Mount Rainier National Park** farther to the east shows that the warming climate has favored the steady invasion of subalpine meadows by subalpine forest (Rocheffort et al. 1994). There is good evidence that this trend is strengthening as the modern-day rate of greenhouse warming increases. At **Mount Rainier National Park**, the wildflower meadows are the prime attraction for most of the more than 2 million visitors received annually. The gradual diminution of the area of wildflower-rich grasslands is a strong probability with global warming, as it is for the meadows of **Olympic National Park** (Peterson 1994). Scientists predict that under all likely global warming scenarios, trees will invade subalpine flower meadows (Zolbrod and Peterson in press). Warming is not the only factor involved here though. Precipitation regime and winter snowpack may prove critical in determining eventual changes in these high elevation forests.

Climate research in **Olympic National Park** and **Mount Rainier National Park** has recently established that high-elevation forest will react differently from lowland forest in response to global warming. Even the different types of montane forest will have differing responses. These studies demonstrate the difficulty of making broad-brush predictions of climate impacts even for one National Park without taking into account the varying ecological changes that will occur in different habitats. **Olympic National Park** is especially interesting in that the forests of the southwestern region are subject to extremely high levels of precipitation while those in the northeast exist under much drier conditions. These latter areas are dominated by subalpine fir forests and grass-sedge meadows. The wet, southwestern forests of the Olympic Mountains are dominated by

mountain hemlock and ericaceous meadows. The research shows that for most subalpine tree species at many locations, winter precipitation is a critical limiting factor for growth. In addition, longer growing seasons (e.g., warmer springs) can improve growth, and hotter summers and drought conditions inhibit it (Peterson 1994).

According to climate and vegetation models, the drier, northeastern forests may be the most sensitive to both temperature and precipitation change. Over time, and given a warmer, drier climate, drought-tolerant species would become established lower down the mountainsides, the northern slopes being dominated by subalpine fir and the southern slopes by lodgepole pine. In the southwestern region, it is predicted that a warmer climate will push dominant tree species several hundred meters higher in elevation, with subalpine meadows and mountain hemlock forests being replaced by Pacific silver fir (Zolbrod and Peterson in press). Observations in **Olympic National Park** today show that changes are already occurring at the tree line, with forest species beginning to crowd the edge of the meadows and fill the gaps of open grassland (Peterson pers. com.). Much farther south, research on the tree line forests of **Sequoia National Park** of California's Sierra Nevada mountains has shown that drought may limit the ability of tree line to move upslope, even when temperatures are warming (Lloyd and Graumlich 1997). These studies show that while upward tree line change occurs very slowly, there can be relatively rapid changes in the density of forest at the ecotone and distribution of individual species. In many places, soil conditions will limit the ability of tree species to shift distribution with changing climate.

Other potential impacts of climate change on the protected areas and federal lands of the Pacific Northwest are likely to include glacier melt and changes in fire regime. In 1994, the National Biological Survey (NBS) identified the glaciers of **Olympic National Park**, **Mount Rainier National Park**, and **North Cascades National Park** as potential indicators of global warming (see also **Glacier National Park**). Glaciers of the Pacific Northwest are expected to be especially sensitive to climate change because of their low elevation and small size (NBS in litt.). Vulnerability of westside forests to fire is likely to increase under a warmer, drier climate, and potential decreases in humidity or precipitation, higher frequency of easterly winds or lightning storms, or more frequent drought would heighten the risk. Outbreaks of defoliating attacks by western spruce budworms could occur more frequently and become much more damaging for westside conifer forests (which have no natural chemical defenses) under certain climate scenarios (Norse 1990).

13. California Coastal and Marine Protected Areas and Ecosystems

The west coast of the United States is generally less vulnerable to sea level rise than the east coast (Park 1989), and most of California follows this rule. Nevertheless, there is a direct threat from sea level rise in several important federal and private protected areas in California.

San Francisco Bay, for example, which provides a major proportion of California's coastal wetland habitat, is experiencing a rate of relative sea level rise that should arouse concern among conservationists. **San Francisco Bay National Wildlife Refuge** provides a winter stopover or refueling point during migration for more than 70% of all the shorebirds that use the Pacific flyway. The refuge salt marsh is also home to two endangered species — the salt-marsh harvest mouse (which can actually drink saltwater) and the California clapper rail. Both of these species are listed by the federal government as endangered, and both are restricted to within 10 feet of current sea level, making them highly vulnerable to sea level rise as predicted for San Francisco Bay (Reid and Trexler 1991).

Some of the best evidence of biological changes connected with long-term global warming trends has been gathered from the coastal zone and seas off California. The California Current system is a globally important upwelling zone that produces highly productive waters off the Pacific coast of the U.S., and scientists have shown that warming of these coastal waters appears to be having a strong effect on marine ecosystems. Warming of the surface layer of the ocean by as much as 1.5° C in some places since 1951 has led to declines of 80% in zooplankton in the California Current (Roemmich and McGowan 1995). Several of the seabird species for which coastal protected areas, including **Channel Islands National Park** and **Point Reyes National Seashore**, are famous seem to be declining also. As the current warms and plankton declines, so too do marine species such as rockfish and squid that feed on them. At the top of the food chain, birds such as the sooty shearwater are even more strongly affected.

Zoologist Richard Veit has shown a 90% decline in sooty shearwater numbers in the California Current since 1987, and he believes that the warming ocean is at the root of the problem (Veit et al. 1997). Changes in distribution of other inshore seabirds have also been noted, with significant declines of rhinoceros auklet and Cassin's auklet. Some species more associated with open ocean areas, such as Leach's storm-petrel, seem to have benefited from the warming and have been showing small population increases (Veit et al. 1996). Other top predators, including gray whales and blue whales, which can be seen off the shores of **Channel Islands National Park** and migrate along the California Current, could also be affected by reductions in plankton (MacGarvin and Simmonds in litt.). The most disturbing aspect of the recent research on the links among sea temperature, plankton numbers, and seabird communities is how a seemingly small warming of the waters can be magnified through the food chain and cause major impacts on species at the top. In the case of sooty shearwaters, this has amounted to a 90% decline, or the disappearance of as many as 4 million birds.

Even the wildlife of California's rocky beaches has been unable to escape the first effects of global warming. Scientists working at the ecological reserve of **Hopkins Marine Station** in Monterey Bay have recorded major changes in the abundance of different species in the intertidal zone over the past 60 years. More than two-thirds of the species studied had experienced change over that period, and the most plausible explanation lies in an increase of the annual mean shoreline temperature during the period. The

researchers have demonstrated that southerly species, including several gastropod mollusks, snails, and sea anemones, have increased or are newly present, and that the majority of more northerly adapted species are declining (Barry et al. 1995). The faunal community of the rocky intertidal zone has thus altered radically since the 1930s, and this is likely to presage even more changes as the rate of warming accelerates.

14. Coconino National Forest

In response to climate change, different parts of an ecosystem can be expected to change at different rates, with the result that new combinations of habitat variables will be generated (Davis 1986, Dobson et al. 1989, Malcolm and Markham 1996, Markham 1996). A study by Thomas E. Martin (in litt.) in high-elevation forests (2,600 m) of the **Coconino National Forest** of Arizona showed that these novel combinations of habitat/environmental variables can have negative impacts on the wildlife populations of protected areas. In the study area, small valleys provided a gradient in habitat conditions, from dry locust/oak forests on the upper slopes to wet maple/aspen forests on the lower slopes. Local warblers bred at specific locations along the gradient, with species such as Virginia's warbler using the upper end and orange-crowned warbler using the lower end. These differences in position along the gradient paralleled the large-scale geographic distributions of the two species: Virginia's warbler is more typical of xeric southern areas, whereas the orange-crowned warbler is more typical of mesic northern areas. The effect of year-to-year variation in precipitation was to shift the moisture gradient up and down the slope: In wet years, wetter conditions were found farther upslope, whereas in dry years, dry conditions extended farther down into the maple/aspen forest. Of course, the trees stayed in place from one year to the next. In response to unusual precipitation in a given year, a bird seeking to breed would have two choices: Follow the moisture shift and ignore the tree community, or ignore the moisture shift and stay with a certain tree community. In a sense, the bird would find itself between a rock and a hard place no matter what: Either choice would result in a breeding attempt in an "unusual" combination of vegetation and climate. Interestingly, Martin observed that in response to atypical precipitation, the birds followed the moisture gradient instead of the tree gradient but suffered increased nest predation as a result. The alternative choice, a nesting attempt in the preferred vegetation type but the wrong climate, may have incurred physiological or foraging costs.

The negative demographic effects of this disequilibrium between habitat and climate will be especially important at high rates of climate change, because the mismatch between climate change and vegetation will be at its greatest. Martin suggested that it is through disequilibria such as these that the initial effects of climate change in many cases will become manifest. Unfortunately, the birds cannot escape the mismatch by shifting their geographic range.

15. Everglades National Park

"Of the National Parks on earth that are most likely to be lost [to climate change], the most notable is Everglades National Park."

Larry Harris and Wendell Cropper, Jr.

The southern Florida ecosystem, best known for the **Everglades National Park**, represents one of the United States' most extraordinary and endangered habitats. Since the days of European colonization, this rich subtropical ecosystem has been severely damaged by waves of human activity and development. Wetland drainage, agriculture, and urban development have been the most recent ravages, and today the **Everglades** is still threatened by multiple pressures, including water pollution from Florida's huge agro-industrial sugar operations. Roughly half of the **Everglades** natural wetlands have already been drained, half the tropical deciduous forests of the uplands of the Florida Keys have been cleared, and more than 90% of the subtropical pinelands of the eastern **Everglades** have been lost (Bancroft 1996). Only fragments of southern Florida's remarkable biota still remain, many of them in a network of protected areas. Endangered species such as snail kite, wood stork, Florida panther, and Key deer hang on in these last natural outposts.

Climate change, therefore, is certainly not the most immediate threat to these habitats and their many rare and endangered species, but it is a significant problem, and one that will continue to worsen even if other environmental stresses can be ameliorated. There are three main implications for climate impacts in the two south Florida National Parks and the **Key Largo Coral Reef National Marine Sanctuary**. Sea level rise and coastal flooding is a serious threat for **Everglades National Park** and **Biscayne National Park**, and vegetation change due to changes in temperature and rainfall patterns will also cause problems. The third problem is associated with possible changes in storm frequency and severity. The tip of Florida was hit hard by Hurricane Andrew in 1992, and valuable stands of rare mahogany, gumbo limbo, and *lignum vitae* trees were stripped bare or snapped in two by the storm's 130-mile-per-hour gusting winds. Coral reefs do not escape storms either, and the effects of floating wreckage pounded onto fragile reefs by storm-whipped waters can cause damage far in excess of anything the corals have adapted to through thousands of years of natural evolution in a hurricane zone. If predictions of greater frequency or ferocity of hurricanes are correct, then southern Florida's protected areas are in for a rough ride that could ultimately reduce their biological diversity. Even if storms do not become fiercer, sea level rise will increase damage from storms because of higher waves.

Vegetation change is hard to predict for the park areas because of uncertainty about the changes in rainfall conditions that can be expected as the world's climate warms. However, most climate and vegetation models predict that under all likely scenarios there will be a danger of change to the subtropical forest types of the **Everglades National Park**, which will be invaded by more tropical plant species. Reduced rainfall combined with higher temperatures would favor a more open canopied woodland, leading to a

reduction in species richness (Harris and Cropper 1992). Analysis of rainfall trends during the past 60 years already shows a significant decline in mainland areas, possibly as a result of land-use changes (Pielke et al. in press). Florida demonstrates better than most U.S. states how human activities limit the adaptation of natural areas to climate change. The south Florida ecosystem has already been invaded by many exotic species, and it is obvious that in a changing climate, these species would fare better and be able to adapt faster than most of the native and endemic species. The density and intensity of citrus and sugar operations in the region, along with massive urbanization and tourism development, make natural adaptation to climate change a virtual impossibility in this region. Human population growth alone presents one of the most formidable environmental factors in Florida. Between 1950 and 1990, the population grew to 5 million people at an average rate of 3% a year, largely as a result of migration from other parts of the U.S. and from Cuba, Haiti, and Latin America. During the next 20 years, another 2 million new residents are expected (Bancroft 1996).

Coastal development is perhaps the biggest barrier to habitat adaptation and physical retreat of species from coastal flooding caused by sea level rise. Some scientific understanding of past changes in sea level already exists for Florida. Sea level has been naturally slowly rising (because of land gradually lifting as heavy ice-sheets retreated) since the last ice age some 15,000–20,000 years ago. Modern climate change is increasing the rate of sea level rise, and the rate has noticeably accelerated in the past two decades. Postglacial sea level rise has reduced the area of the Florida peninsula by about half, substantially narrowing the land mass, raising the level of the water table, and increasing the distance from the mainland to the islands (Harris and Cropper 1992). These changes have resulted in major biological alteration over thousands of years, including the extinction of large mammal species and the transition from arid savannah to a coastal heathland dominated by pine and cypress. From this history of change it can be seen that the south Florida ecosystem is highly sensitive to climate change.

In many south Florida protected areas, refuges are sandwiched in between the sea and residential or agricultural developments. Sea level rise is predicted to severely limit the survival opportunities of some of Florida's most endangered species. The dusky seaside sparrow has already become extinct as a result of loss of habitat, partly due to sea level rise (Harris and Cropper 1992). Several species of beach mice and the Cape Sable sparrow may soon suffer the same fate. Larger species at risk from sea level rise reducing their habitat include the Florida panther, Key deer, American crocodile, and Everglades mink. National wildlife refuges at risk include **Crocodile Lakes National Wildlife Refuge**, **10,000 Islands National Wildlife Refuge**, and **Key Deer National Wildlife Refuge**. According to the U.S. Department of the Interior, these three, along with **Big Cypress Preserve** and **Everglades, Biscayne, and Dry Tortugas National Parks** have already suffered damage from accelerating sea level rise during the past 50 years.

16. Great Smoky Mountains National Park

The nation's most popular National Park, with nearly 9 million visits annually, the **Great Smoky Mountains National Park** straddles the border between Tennessee and North Carolina, at the southern end of the Appalachian mountain chain. Half the population of the United States lives within one day's drive of the park. **Great Smoky Mountains National Park** is the most biologically important of several federal protected areas in the Southern Appalachians, including **Shenandoah National Park**, **Little River Canyon National Preserve** and the **Blue Ridge Parkway**. The underlying rocks that form the Southern Appalachian Mountains were thrust up around 900 million years ago, and they have been slowly eroding ever since. The richness of wildlife and habitat in the Smokies is partly explained by the height of the mountains and the cascade of ecosystem change from the mountain peaks down to the valley floors thousands of feet lower. Above 4,500 feet can be found the southernmost remnant of the great boreal forests, where red spruce and the locally endemic Fraser fir intermingle to provide habitat for myriad species, including birds such as the Canada warbler and Blackburnian warbler, which are normally associated with forests farther north. This habitat area contains the largest contiguous block of virgin red spruce forest on Earth (Peine and Martinka 1992).

New research indicates that this unique high-elevation spruce-fir forest, 75% of which occurs within the borders of the park, could be wiped out by global warming (Peine and Berish in prep.). Climate models that predict warmer, drier conditions show that conditions suitable for Fraser fir growth are likely to massively decline in a changing climate. This habitat has been described by scientist John Peine as the "crown jewel ecosystem of a crown jewel park," and it is already under significant threat from an insect pest called the balsam wooly adelgid, which was first recorded in the area in the late 1950s (Southern Appalachian Assessment 1996). The adelgid is relatively insensitive to control by extreme climatic conditions, so that a change in climate that weakens the fir trees but leaves the insect pests unscathed could exacerbate the problem and increase the rate of forest loss caused by insect attack.

The park has an extraordinary diversity of plant life. Apart from the spruce-fir forests, there are 13 other major forest types, more than 1,500 species of flowering plants and 2,200 mosses and ferns. Many of the 95 Southern Appalachian endemic (or near-endemic) vascular plants are restricted to high-elevation, north-facing slopes, and this makes them especially vulnerable to population declines or even extinction in a warming climate (Peine and Martinka 1992).

The Southern Appalachians are also extraordinarily rich in diversity of other terrestrial and aquatic organisms. The region is globally important as a center of diversity for salamander species, for example. There are approximately 25 endemic species of salamander, 26 endangered molluscs, and more than 300 species of fish in the streams, lakes, and ponds of the Southern Appalachians. Under particular threat in a changing climate are the native brook trout. These fish, which are highly prized by anglers, are restricted to clear, cool mountain streams. **Great Smoky Mountains National Park** is

home to a genetically distinct southern strain of the brook trout that is already restricted to only a small percentage of the park's 2,000-plus miles of trout stream. Global warming could well cause the extinction of this rare brook trout strain (Peine and Martinka 1992). Guffey et al. (in press) have proposed a series of measures to promote the conservation and restoration of the southern Appalachian brook trout strain. Their strategy includes the removal of hatchery derived brook trout from streams, especially larger low elevation streams, and their replacement with native brook trout populations. This would also help to minimize the impacts of global warming on the native strain. The U.S. Environmental Protection Agency (EPA) has recently released a report suggesting that of all sport fish in America, native brook trout is the most at risk from climate change (U.S. Environmental Protection Agency 1996).

The southern Appalachians are particularly rich in salamander species and are a globally important center of diversity for these animals. Salamanders tend to be sensitive to climatic factors and may provide early signals of change. Recent changes in several salamander populations in the southern Appalachians have scientists wondering if the existing warming trend may be partly to blame. Many isolated populations of different salamander species and forms are distributed throughout the Appalachians, but one appears to be getting the better of many others. The red-backed salamander, which is widely distributed through northeastern North America, is steadily but surely increasing its range at the expense of other species. North of the Smokies, at Hawksbill Mountain in **Shenandoah National Park**, red-backed salamanders are slowly encroaching into the range of Shenandoah salamanders. Even though the Shenandoahs tend to be better adapted to surviving warmer temperatures and periodic droughts, the red-backs aggressively expand into Shenandoah territory where changing habitat conditions allow. It is possible that competition between these species, combined with climatic change, could lead to the extinction of the Shenandoah salamander (Constantz 1994).

Climate scientists predict that certain extreme weather events, such as droughts and floods, are likely to increase over most of North America in a warmer world. Strong evidence of a trend toward heavier rainstorms has already been detected for the east coast of the U.S. (Karl et al. 1997). Recent weather conditions, including a drought and major flood in the **Great Smoky Mountains National Park**, (although they cannot definitely be said to have been caused by global warming) certainly fit within the predicted climate change trend and demonstrate the types of impacts that can be expected more in the future. The park experienced massive snowfalls in March 1994 and then catastrophic floods in October 1995. The cost of repairs after these two weather events has exceeded \$10 million, and restoration of back-country trails has not yet been completed (Peine and Berish in press).

From 1985 through 1988, the Southern Appalachians experienced a period of extreme drought. This resulted in greater than normal frequency of serious forest fires, culminating in 41 within the park in 1988. The drought also resulted in the death or impaired reproduction of adult brook trout because of reduced stream flow and warmer water temperatures. Tourist recreation in the summer of 1988 was also affected because

air stagnation caused a massive increase in haze and, at some peak visitation times, up to a 90% reduction in visibility. Research has shown that visitors to the park largely define the quality of their experience in terms of visibility of long-range views (Peine and Berish, in press). There can be no doubt that over the long term, climate change can be expected both to negatively affect the natural ecosystems of the park and to reduce visitor satisfaction with the park experience.

17. **Blackwater National Wildlife Refuge**

The marshes of **Blackwater National Wildlife Refuge** are being eaten away by the rising sea levels of the Chesapeake Bay. One third of the marsh at **Blackwater** has been lost since 1938, and the refuge managers expect most of the rest of the marsh to disappear within 30 years. **Blackwater** is one of several important protected areas in and around the Chesapeake Bay, including **Eastern Neck National Wildlife Refuge**, **Chincoteague National Wildlife Refuge**, and **Assateague Island National Seashore**. All are vital for migratory waterfowl and shorebirds, and all are under threat from climate change and sea level rise. The Chesapeake Bay itself is the United States' largest estuary, created by natural sea level rise during the period after the last ice age. The bay is fed by some of the nation's most famous rivers, including the Potomac, Susquehanna, York, and James. As postglacial sea level rise stabilized some 5,000 years ago, it allowed the development of vast salt and freshwater marshes that eventually spread around the bay's 8,100 miles of coastline and provided some of the best wildlife habitat in the country. One of the unique features of the Chesapeake is how shallow it is, rarely reaching more than 21 feet deep.

Natural sea level rise (caused by land uplift and rebound after the last ice age) on the bay is about three feet per thousand years. The current rate is more than three times that and seems to be accelerating. During the last century, the waters have risen about one foot, roughly half of which can be accounted for by subsidence (mainly due to extraction of underground water reserves), and half of which is most likely due to global warming (Leatherman et al. 1995). the bay is already suffering from the impacts of pollution and overdevelopment, and sea level rise and ocean warming are predicted to be devastating for some of the bay's natural habitats. **Blackwater** is particularly important as the center of the largest concentration of nesting bald eagles on the U.S. east coast north of Florida (Riley and Riley 1992). The refuge is prime winter habitat for tens of thousands of ducks and geese, including snow goose, Canada goose, blue-winged teal, pintail, gadwall, black duck, and wigeon. The land surrounding the marsh provides protection for a significant population of the endangered Delmarva fox squirrel.

Evidence of the ravages of sea level rise on the **Blackwater Refuge** is not hard to find. Aerial photos taken over the past five decades have documented the already alarming loss of marsh and its reversion to open water and ponds. The marshes are eroding from the inside as plants become waterlogged and then die off. This leads to the creation of larger open water areas, and then the inner banks of the pools erode, sedimentation increases, and the underlying peat turns to a soupy slurry (Leatherman et al. 1995). Local

conservationists have documented large-scale plant die-off in the past few years, and there is real concern over whether this wonderful marsh can survive far into the 21st century if sea level continues to rise at its current, or even an accelerating, rate. Local farmers, who a few years ago did not want to sell bayside fields to the refuge, are now reportedly desperate to rid themselves of land that is constantly decreasing in agricultural value because of sea level rise. Unfortunately for the future of the **Blackwater** marshes, even where land would be available to allow the retreat of the marshes inland, it has become obvious that the breakdown of the existing marsh is happening much faster than the rate at which new wetlands can be created.

18. U.S. Virgin Islands National Park

Situated on the island of St. John, the **U.S. Virgin Islands National Park** is known for its spectacular coral reefs as well as for important tropical dry forest and coastal mangrove habitat. With its beautiful beaches and excellent boating conditions, the park attracts around a million visitors every year and provides a vital source of income for the U.S. Virgin Islands economy. Unfortunately, the park is one of the most vulnerable in the whole of the National Park system to hurricanes, and several severe storms in the past few years have already begun to take their toll on both ecosystems and visitor facilities.

Many scientists believe that one of the consequences of global warming will be increased frequency and severity of tropical storms (Hulme and Viner 1995). Although there is considerable uncertainty as to how likely this effect will be to be manifest in the Caribbean, the hurricanes of recent years provide an alarming indication of the potential consequences. The **Virgin Islands National Park** was one of several important natural areas that was devastated by Hurricane Hugo when it swept through the islands in 1989. Normally a storm like this could be expected to hit the same place again only at intervals of perhaps 100 years, and yet just 6 years later, in September 1995, two powerful hurricanes again cut a swath through the islands and the National Park. Hurricanes Luis and Marilyn left a trail of destruction behind them within a few days of each other in what became the Caribbean's worst hurricane season since 1933. It is impossible to lay the blame for any single storm or extreme weather episode on global warming, but ongoing research by scientists in the park is likely to provide some of the answers to questions about how increased storm frequency will affect wildlife and ecosystems.

Within days of Hurricane Marilyn hitting the islands of St. Thomas and St. John in 1995, WWF sent a two-person rapid assessment team to the park to help report on the extent of the damage. They found extensive physical damage to coral formations, many of which had not fully recovered from Hurricane Hugo in 1989, and much sedimentation on coastal reefs (Zullo et al. 1995). The senior park scientist, Caroline Rogers, who had been in the islands throughout the storms, also reported much coral damage, even down to a depth of about 40 feet at Yawzi Point near Lameshur. Elsewhere, branching corals had been broken, elkhorn corals toppled and star corals split in half. Even where wave action from the storm had not been so great, damage was severe as a result of pleasure boats having

broken from their moorings and then bobbed on the waves, smashing into and sometimes splitting brain corals more than 50 years old.

Three sea turtle species threatened with extinction — hawksbill, leatherback, and green turtles — nest on the park's beaches, and flooding of nests was common during the hurricanes. The worst damage occurred at **Buck Island Reef National Monument** off St. Croix, home to one of the most significant hawksbill turtle populations under U.S. jurisdiction. There, Resource Management Specialist Zandy Gillis reported extensive damage to turtle beaches, with at least 40 nests and some 6,000 eggs destroyed.

Further on shore, virtually all the nests in the park's primary rookery for brown pelicans were lost, and vast numbers of turpentine, kapok, and palm trees suffered from breakage, loss of tops, or uprooting. It was feared that habitat destruction might affect the small population of bridled quail dove and other uncommon bird species. Other protected forests in the Caribbean had previously been flattened by Hurricane Hugo. In 1989, the full force of the storm cut a scythe-like path through the tabonoco and dwarf cloud forests of Puerto Rico's **Luquillo National Forest**. Research by scientists in that forest is beginning to give some indications of how the habitat will be affected by global warming and worsened storm systems. More frequent storms would eventually reduce the lower elevation tabonoco tropical forest to a less biologically diverse state, with fewer mature timber trees (O'Brien et al. 1992). Higher up, in the fully protected cloud forest, where the vegetation grows so slowly that footprints can take decades to disappear, effects could be even worse. Storms open the canopy, allowing light into the forest and creating conditions suitable for the invasion of aggressive non-native species such as grasses (Scatena pers. com.). Epiphytic plants, such as orchids, that live on the branches and trunks of trees can be blown off in large numbers during hurricanes, and if drought episodes increase, they may dry out and die.

Hurricanes are an annual occurrence in the Caribbean, and local ecosystems are adapted to recover over time from most forms of natural damage. However, many of species and habitats are under so much pressure from human stresses such as pollution that they are less able to withstand natural events such as hurricanes. If those hurricanes increase in frequency and severity as a result of climate change, then conservation problems can only get worse. As Caroline Rogers put it shortly after Hurricane Marilyn hit, *"If you superimpose unregulated coastal development, overfishing, and mangrove destruction with multiple hurricanes, you really are tipping the balance of nature."* (Zullo et al. 1995)

19. Haleakala National Park

Haleakala National Park, on the Hawaiian island of Maui, is most famous for the moonscape-like terrain inside the volcano's crater and for the strange, spiky, endemic silversword plants that dot the lava beds. Biologically, though, the tropical rainforest of the steep eastern slopes of the volcano is of the greatest value. The forest protected in the

National Park and the neighboring reserves, including **Hanawi (State) Natural Area Reserve** and the Nature Conservancy's **Waikamoi Preserve**, represents some of the most intact natural ecosystems anywhere on Hawaii (Loope and Giambelluca in press).

Like many island ecosystems, the cloud forests of east Maui are home to numerous endemic species. Approximately 90% of the flowering plants and 65% of the native invertebrates are endemic to Hawaii. Of the more than 100 fern species of these spectacular forests, about half are endemic, and there are nine endemic bird species in the Hawaiian honeycreeper family, including the endangered i'iwi. One reason the beautiful i'iwi has survived in the higher forests of **Haleakala** is because the mosquitos that transmit a deadly form of avian malaria and pox appear to have been deterred from breeding at higher elevations by cooler temperatures. Conservationists are concerned that global warming will allow the mosquito to move farther up the mountain and could allow the disease to spread to previously safe i'iwi populations that have no resistance (Loope 1990).

Worldwide, the tropical montane cloud forests of islands are one of the rarest natural habitats, occurring in places such as New Guinea, Sri Lanka, Madagascar, Fiji, Samoa and the Lesser Antilles. Scientists Lloyd Loope and Thomas Giambelluca of **Haleakala National Park** believe that "*island tropical montane cloud forests may be among the most sensitive to climate change.*" Even small changes in climatic conditions could cause major changes in the cloud cover and precipitation regimes that maintain the rain forest of **Haleakala**. The dominant tree species of the cloud forest is *Metrosideros polymorpha*, and the environment is one of the wettest on Earth, with annual rainfall measured as high as 14 meters in 1994 (Loope and Giambelluca in press). Direct precipitation from rainfall is added to by water from the fog that constantly swirls through the dripping vegetation of the cloud forest. On a visit to Hawaii in 1866, Mark Twain marveled at the natural beauty of **Haleakala's** cloud cover as he gazed down on it from above, perched on the volcano's rim. He called it "*the sublimest spectacle I ever witnessed*" and said that as he watched the "*imposing squadrons*" of clouds bank over the forests he "*felt like the Last Man, neglected of the judgement, and left pinnacled in mid-heaven, a forgotten relic of a neglected world.*"

The upper limit of the cloud forest zone is determined by the altitude of the upper cloud zone, which in turn is set by the elevation of the trade wind inversion. Changes in the trade wind inversion are deemed to be highly probable as a result of climate change, and if this occurs it would certainly cause a shift in distribution of cloud forest species. Above the inversion layer, the cloud forest quickly changes to shrubland and grassland. Paleocological evidence from other parts of Hawaii suggests that there have been vertical displacements of the trade wind inversion during cooler and warmer periods during the Holocene (Loope and Giambelluca in press).

Apart from a shift in the precipitation zones necessary for the survival of the montane cloud forest, climate change may have other effects in **Haleakala National Park**. Global warming of between 2°–2.5° C would translate into an elevational shift in species

distribution roughly 360–450m upslope throughout the Hawaiian Islands. If, as some have predicted (Hulme and Viner 1995), climate change brings an increased variability in interannual rainfall conditions in the tropics, this would certainly be harmful to **Haleakala's** cloud forest. Increased drought in tropical moist forests is likely to significantly increase the risk of fire (Goldammer in press, Whitmore in press) in wet forests that are generally unadapted in evolutionary terms to this kind of disturbance. In tropical island forests, fire disturbance can be one of the major mechanisms allowing invasion by non-native species (Cronk in press). The high montane forests of **Haleakala National Park** have so far been relatively free of the takeovers by non-native species that have, by accident or by design, changed the ecosystems of lower elevation forests throughout Hawaii and many other Pacific island chains. If increased frequency or intensity of hurricanes also accompanies global warming, this will greatly exacerbate the problems associated with fire and invasive, alien species (Loope and Giambelluca in press).

Although considerable uncertainty exists about the exact nature of the likely impacts of climate change on the unique ecosystems of **Haleakala National Park**, there is little doubt that in combination with increasing human pressure, the effects of global warming will be negative. Some of the last intact tropical rainforests in the United States, which have for so long been protected by their inaccessibility on the steep, wet slopes of an isolated volcano, may finally succumb to humankind's heavy footprint on the global environment.

APPENDIX 1: Assessing the vulnerability of U. S. protected areas to climate change

INTRODUCTION

Unless greenhouse gas emissions are reduced, the future may be one of enormous climatic and ecosystem change (Houghton et al. 1996). Important properties of ecosystems, including their spatial and temporal distribution, and functional attributes such as productivity and nutrient cycling, are expected to be highly sensitive to the types of climate change predicted by climate models, as was recently highlighted in the Vegetation/Ecosystem Modeling and Analysis Project (VEMAP) (Kittel 1995, VEMAP Members 1995). In turn, these changes in climate and ecosystem properties will affect protected areas, which are often the last refuges for the plant and animal communities that were once widespread. Climate-induced shifts in ecosystem boundaries have long been recognized to have the potential to leave populations in protected areas behind, as necessary habitat types shift elsewhere or disappear entirely (Peters and Darling 1985). Unless populations are able to move with the change or adapt to new conditions, local extinction may result. Several factors influence the ability of a species to track the change, including the extent and rate of the change itself and possibilities for reestablishment and movement in the surrounding landscape (Peters and Darling 1985, Malcolm and Markham 1996). In a general sense, however, we can expect protected areas to be especially vulnerable when they are located in region of high ecosystem change and where currently existing habitats are expected to disappear or become rare.

The VEMAP project offered an excellent opportunity to investigate the potential for greenhouse-induced ecosystem change in the landscapes surrounding protected areas. The project was designed to provide spatially explicit information on the sensitivity of terrestrial ecosystems in the coterminous U. S. to elevated atmospheric CO₂ and associated climatic change. A standardized methodology was designed whereby state-of-the-art climatic, biogeographic, and biogeochemical models could be linked and compared (VEMAP Members 1995). In the Phase I analysis, three "mixed-layer ocean" general circulation models (GCMs) were selected to span a range of possible equilibrium climate changes, from the relatively insensitive Oregon State University model (3.0° C average temperature increase under doubled CO₂) to the more sensitive United Kingdom Meteorological Office model (+ 6.7° C) (the Geophysical Fluid Dynamics Laboratory model was intermediate at +4.3° C). The resulting climate scenarios, plus baseline controls and information on soils, served as input for three biogeographic models (BIOME2, DOLY, and MAPSS) that simulated major vegetation types across the lower 48 U. S. states (VEMAP Members 1995). It was recognized by the VEMAP members that current understanding of ecosystem structure and functioning, or for that matter of global climate, does not yet allow the identification of "best" models or acceptance of correct predictions. However, by providing information from a suite of attempts, the results can be used to provide preliminary information on the general sensitivity of natural ecosystems to greenhouse warming (VEMAP Members 1995).

Our objective was to perform a preliminary analysis of the vulnerability of U.S. protected areas to climate change, by quantifying the degree to which representation of potentially suitable habitats in the landscape surrounding protected areas changed under the suite of VEMAP scenarios. We were especially interested in three aspects of protected areas vulnerability. First, was the overall effect of the climate change positive or negative; that is, did climate change on average lead to deterioration in the landscapes surrounding protected areas, or were the overall effects usually beneficial? Secondly, were some protected areas consistently vulnerable, and if so, where were they? Finally, how did the analysis of landscape vulnerability compare with the more standard analysis of individual pixel change?

MATERIALS AND METHODS

Data sets

We obtained the VEMAP Phase I vegetation classification results for the three biogeographic models and climate scenarios (nine combinations in total). The biogeography models incorporated both climate effects and direct CO₂ concentration effects. Details concerning the models and simulations can be found in VEMAP Members (1995) and Kittel et al. (1995). The biogeographic models predicted dominance of various plant life forms (Table A1) according to ecophysiological constraints and resource limitations. The vegetation classification was developed by considering constraints and requirements of the biogeography models and physiognomic and physiological characteristics of existing maps of potential vegetation of the coterminous U. S. In BIOME2 (Haxeltine et al. 1995), ecophysiological constraints determined which plant types were present at a location, and the model subsequently identified the quantitative combination that maximized whole-system net primary productivity. In DOLY (Woodward et al. 1995), biochemical processes such as photosynthesis and evapotranspiration were calculated, and a discriminant function based on present-day relationships was subsequently used to assign vegetation types. In MAPSS (Neilson 1995), ecophysiological constraints determined potential vegetation at a site, and processed-based growth, competition, and fire models assigned vegetation types. Soils, baseline climate, and climate change scenarios included daily and monthly climate drivers, soil data, and various representations of solar radiation and surface humidity. The three GCMs were from the Geophysical Fluid Dynamics Laboratory (GFDL) [R30 2.22° by 3.75° grid run; Wetherald et al. 1990], Oregon State University (OSU) [Schlesinger and Zhao 1989], and the United Kingdom Meteorological Office (UKMO) [Wilson and Mitchell 1987]. Climate changes from the GCMs under doubled CO₂ (710 vs. 355 ppmv) were represented as differences (for monthly mean temperature) or as change ratios (for monthly precipitation, solar radiation, and vapor pressure). After interpolation to the 0.5 degree grid, the monthly change fields were applied to the VEMAP base climate to generate altered-climate inputs. Respective average annual

temperate and precipitation sensitivities of GFDL, OSU, and UKMO were: +4.3° C and +21%; +3.0° C and +4%; and +6.7° C and +12%.

Names and geographical coordinates were compiled for four types of federally protected areas: 1) National Monuments, 2) National Parks, 3) National Wildlife Refuges, and 4) Wilderness Areas (listed in Table A3). The last group included areas designated by the Bureau of Land Management, the Forest Service, the National Park Service, and the Fish and Wildlife Service.

Protected Area Vulnerability

Because of the coarse level of resolution in the VEMAP analysis (grid cells [pixels] were 0.5° on a side and thus ranged in area from 2037 to 2794 km²), we investigated landscape changes of only one vegetation type for each protected area; namely, the vegetation of the grid cell that contained its geographic center. VEMAP Phase I results were only available for grid cells that were predominantly covered by land and were not dominated by water. As a result, many protected areas were excluded from the analysis, particularly those close to water (see Table A3). Thus, our analysis applied primarily to terrestrial protected areas.

To quantify change in the landscape surrounding a protected area, we quantified representation of the vegetation type of the central pixel in the 112-pixel circle that surrounded it (Fig. A1). We reasoned that areas in the window closer to the protected area would be potentially more accessible to organisms than areas further away; therefore, we weighed representation of the vegetation in a cell according to the reciprocal of the cell's distance from the central pixel. Symbolically, denoting (x_c, y_c) as the coordinates (in pixel units) of the central pixel and (x_i, y_i) as the coordinates of pixel i , we defined S as the set of pixel coordinates within 6 pixel units of the window center (excluding the central pixel): Calling our measure of representation in the surrounding landscape RI , we have where $\lambda = 1$ if pixel i is the same vegetation type as the central pixel, otherwise $\lambda = 0$.

To examine the net effect of climate change on landscape representation, for each we subtracted RI calculated under future conditions from RI calculated under baseline conditions. Student's t -tests were used to test whether average values in the four protected areas classes were significantly different from zero.

In light of the inability to identify correct biogeographic or climate models, we reasoned that a useful measure of overall vulnerability would be the consistency of sign change among the VEMAP models. Thus, for the protected areas we tabulated the number of models that predicted a decline in landscape representation. In addition, to create a map of regional landscape vulnerability for the coterminous U. S., we calculated RI consistency among the models for each pixel in the VEMAP data set. For comparison, we also mapped consistency of pixel change among the scenarios.

RESULTS

The magnitude and direction of change among the nine combinations was consistent within biogeographic models rather than within climate scenarios (Table A2). Interestingly, landscape change appeared to be insensitive to the amount of temperature change predicted by a climate scenario, at least within the range of temperature changes provided by the three scenarios. Irrespective of the climate scenario, vegetation representation in the surrounding landscape declined for all classes of protected areas for BIOME2 and MAPSS (Table A2). For MAPSS, the decline was in all cases highly significant and for BIOME2 it was significant in 9 of 12 cases. Average landscape change for DOLY was not consistent from scenario to scenario, except for National Wildlife Refuges, which showed a highly significant decline under all scenarios and biogeographic models. R^2 values averaged within biogeographic models are shown for National Wildlife Refuges in Fig. A2. Distributions were markedly skewed to the left, especially for BIOME2 and MAPSS, indicating large potential declines in ecosystem representation in the landscapes surrounding these refuges.

The decline in representation in the landscapes surrounding protected areas tended to be consistent among models. Depending on the class of protected area, between 9 and 27% of protected areas exhibited declines in seven or more of the nine scenarios. Five percent of the National Wildlife Refuges showed a decline under all scenarios (Table A3). Protected areas that showed consistent declines tended to be evenly spread among the protected areas in the west and southwest, except for National Wildlife Refuges which were concentrated in the central part of the country (Fig. A3). On a state-by-state basis, consistency of decline averaged greatest for North Dakota, Iowa, Nebraska, Illinois, Montana, Minnesota, Texas, Missouri, Oklahoma, and Wisconsin (Table A4).

Pixel-by-pixel landscape decline similarly showed high consistency in the central part of the country (south from Montana, North Dakota, and Minnesota, into South Dakota, Nebraska, Colorado, Kansas, Oklahoma, New Mexico, and Texas) (Fig. A4). Other foci of consistent declines included the region west and south of Lakes Superior and Michigan (Wisconsin, Iowa, Illinois and Missouri), most of California, and the western flanks of the Rocky Mountains (New Mexico, Arizona, Utah, and Idaho). The map of the consistency of individual pixel change showed the same general spatial pattern (Fig. A4); however, pixel change was not nearly as consistent on average as landscape decline. For example, whereas only 19% of pixels showed change in five or more model runs, more than 60% showed declines in the surrounding landscape (Fig. A5).

DISCUSSION

Typically, analyses based on GCMs show considerable variability among the scenarios themselves. In the VEMAP experiment, temperature sensitivities varied considerably among the scenarios and precipitation varied even more markedly; thus, it came as a surprise to us to find that vegetation cover tended to vary more between biogeographic

models than between climate scenarios. This conclusion was bolstered by other analyses not presented here (correlations tended to be higher within biogeography models than among them; a principal components analysis separated protected areas responses according to biogeographic model, not climate scenario). This discrepancy between biogeographic models is clearly problematic, and indicates that considerable research will be required before ecosystem responses can be realistically modelled.

In light of the uncertainty with respect to both climate scenarios and ecosystem responses, the present analyses must be viewed as exploratory rather than prescriptive, and the identified changes as potential rather than likely. Nevertheless, the analysis paints a bleak picture of greenhouse-induced deterioration in the landscapes surrounding protected areas. Note that, *a priori*, this need not be so. While change is expected under greenhouse warming, one might expect favorable change (i.e. an increase in abundance of suitable ecosystems close to protected areas) as often as unfavorable change. That was clearly not the case in our analysis. For all combinations of biogeographic models and climate scenarios, more protected areas had negative RI values than positive ones, and at least for BIOME2 and MAPSS, the RI values were skewed to the left, indicating severe deterioration in ecosystem representation in many cases. This was clearly indicated for National Wildlife Refuges, which showed highly significant declines under all models. This picture of overall decline was irrespective of the degree of temperature sensitivity among GCMs, at least within the range used in VEMAP.

We attribute this overall decline to both the magnitude of climate change, and hence the magnitude of ecosystem change, and to the spatial complexity of the change, especially in the western part of the country. A high degree of global warming (such as the 3 to 6.7° in VEMAP) means a large potential shift in ecosystem boundaries. Thus, even protected areas well within a large homogenous region may find themselves isolated. Spatial heterogeneity means that even relatively slight climate change can translate into markedly heterogeneous change; for example as new sets of climate interactions are imposed on a topographically diverse terrain (Halpin in press). Marked spatial heterogeneity was evident in the western U. S. for both the 1 × CO₂ and 2 × CO₂ VEMAP scenarios.

In addition to the foci of consistent change in the western and southern part of the U. S., the analyses indicated consistent declines in the central portion of the country. In contrast to the west and southwest, this is an area of relative homogeneity, being dominated by grasslands and temperate savannas. These systems are highly sensitive to climate change, as highlighted in the VEMAP analysis. Under the various 2 × CO₂ scenarios, widespread and homogeneous cover of one vegetation type was usually replaced by another. As a result, ecosystems originally common in an area became rare, and RI values were high and negative. These changes are of particular import for migratory bird populations, especially under scenarios of lower precipitation. Many of the National Wildlife Refuges were originally established to protect populations of migratory waterfowl, a task for which they may be ill-suited in the future.

The analysis presents an unfavorable picture for the future of protected areas in several other ways. The landscape-level analysis we used gave more consistent declines than the usual pixel-change approach, presenting the possibility of more-or-less stable ecosystems within a protected area, but simultaneous deterioration in the surrounding landscape. Vegetation change within a protected area can be expected to have more severe impacts than change outside; however, decreases in ecosystem representation in the surrounding landscape may have insidious effects, for example through increased population fragmentation and concomitant declines in demographic and genetic viability. The consistency of landscape decline adds particular strength to arguments to maintain and improve connectivity among protected areas whenever possible and to set aside large areas of contiguous wilderness (eg. Noss et al. 1996).

Most seriously, the present analysis ignores the change that development has already brought to the lower 48 states. Superimposed on the dynamic of climate and potential vegetation is an evolving pattern of direct human impacts. In the western U. S., large relatively natural areas still exist, and at least some mobility is afforded to natural populations. In many parts of the country, however, protected areas are islands in a sea of agricultural and other development activities. This is particularly true in the agriculturally rich central portion of the country, an area of consistent landscape decline in the present analysis. In these areas, little opportunity exists for movement or establishment in the landscape surrounding landscape.

Finally, the analysis is based on an equilibrium approach that envisions some future stasis between climate and vegetation. In reality, ecosystem change is dynamic and the end result is highly dependent on the path taken. Different rates of climate change may impose different paths, and ultimately different results. Present indications are that the rate of greenhouse warming is higher than anything organisms have experienced in the recent past, and an unresolved question is their ability to keep up with the change. Differing responses may lead to unequal rates of change of key components of a species' habitat. For example, climatic conditions may change faster than vegetation, leaving organisms with new and potentially deadly problems to solve. These disequilibria between climate change and habitat characteristics are expected to be more frequent under high rates of climate change and will be exacerbated by existing human pressures and erosion of biodiversity (Malcolm and Markham 1996).

In conclusion, climate change will significantly worsen prospects for the successful conservation of the native flora and fauna of the coterminous U. S. Change within protected areas will be compounded by change in the surrounding landscape, and against a backdrop of human-induced change, many organisms will be unlikely to keep up. While maintenance of connectivity, diversity, and resilience can improve the possibilities for conservation in the face of change, a more effective strategy long-term strategy will be to eliminate greenhouse warming.

LITERATURE CITED

- Halpin (in press)
- Haxeltine, A., I. C. Prentice, and I. D. Cresswell (1995) A coupled carbon and waterflux model to predict vegetation structure. *J. Veg. Sci.*
- Houghton, et al. (1996) IPCC
- Kittel, T.G.F., N.A. Rosenbloom, T.H. Painter, D.S. Schimel, and VEMAP Modeling Participants2 (1995) The VEMAP integrated database for modeling United States ecosystem/vegetation sensitivity to climate change. *Journal of Biogeography* 22:857-862.
- Malcolm, J. R. and A. Markham (1996) Ecosystem resilience, biodiversity, and climate change: setting limits. *Parks* 6:38-49.
- Neilson, R. P. (1995) A model for predicting continental-scale vegetation distribution and water balance. *Ecol. Appl.* 5: 362-385.
- Noss, R. F. et al. (1996) Conservation biology and carnivore conservation in the Rocky Mountains. *Conserv. Biol.* 10:949-963.
- Peters, R. L. and Darling, J. D. S. (1985) The greenhouse effect and nature reserves. *BioScience* 35: 707-717.
- Schlesinger, M. E. and Z.-C. Zhao (1989) Seasonal climate changes induced by doubled CO₂ as simulated by the OSU atmospheric GCM-mixed layer ocean model. *J. Clim.* 2:459-495.
- VEMAP Members (1995) Vegetation/Ecosystem Modeling and Analysis Project (VEMAP): Comparing biogeography and biogeochemistry models in a continental-scale study of terrestrial ecosystem responses to climate change and CO₂ doubling. *Global Biogeochemical Cycles* 9:407-437.
- Weatherald, R. T., S. Manabe, U. Cubasch, and R. D. Cess (1990) Processes and modelling. In: *Climate Change: The IPCC Scientific Assessment*. (Houghton, J. T., G. J. Jenkins, and J. J. Ephraums, eds.). Pp 69-91, Cambridge University Press, New York.
- Wilson, C. A., and J. F. B. Mitchell (1987) A doubled CO₂ climate sensitivity experiment with a global climate model including a simple ocean. *J. Geophys. Res.* 92(D11): 13315-13343.
- Woodward, F. I., T. M. Smith, W. R. Emanuel (1995) A global land primary productivity and phytogeography model. *Global Biogeochem. Cycles*

Table A1. Vegetation types used in the Phase I VEMAP analysis.

TUNDRA

Tundra

FOREST

Boreal Coniferous Forest (includes Boreal/Temperate Transitional and Temperate Subalpine Forests)

Maritime Temperate Coniferous Forest

Continental Temperate Coniferous Forest

Cool Temperate Mixed Forest

Warm Temperate/Subtropical Mixed Forest

Temperate Deciduous Forest

Tropical Deciduous Forest

Tropical Evergreen Forest

XEROMORPHIC WOODLANDS and FORESTS

Temperate Mixed Xeromorphic Woodland

Temperate Conifer Xeromorphic Woodland

Tropical Thorn Woodland

SAVANNAS

Temperate/Subtropical Deciduous Savanna

Warm Temperate / Subtropical Mixed Savanna

Temperate Conifer Savanna

Tropical Deciduous Savanna

GRASSLANDS

C3 Grasslands (includes Short, Mid-, and Tall C3 Grasslands)

C4 Grasslands (includes Short, Mid-, and Tall C4 Grasslands)

SHRUBLANDS

Mediterranean Shrubland

Temperate Arid Shrubland

Subtropical Arid Shrubland

EXCLUDED SURFACE TYPES

Ice

Inland Water Bodies (includes ocean inlets)

Wetlands (includes floodplains and strands)

Table A2. Average change in the landscapes surrounding protected areas, as quantified by changes in vegetation type representation (RI). Negative values indicate a decrease representation of the protected area vegetation type; positive values indicate an increase.

National Monument						National Park						National Wildlife Refuge						Wilderness					
Model ¹	n ²	Q	SE	Range	P	n	Q	SE	Range	P	n	Q	SE	Range	P	n	Q	SE	Range	P			
BG	45	-2.9	+ 1.0	(1.9 -30.9)	***	17	-3.1	+ 1.9	(1.7 -22.1)	ns	166	-6.5	+ 0.6	(5.4 -31.0)	***	176	-1.1	+ 0.3	(9.2 -24.9)	***			
BO	26	-5.7	+ 2.8	(27.8 -32.7)	~	10	-8.9	+ 4.7	(1.3 -31.2)	~	157	-13.6	+ 1.1	(14.7 -33.7)	***	128	-0.8	+ 0.4	(12.3 -32.3)	~			
BU	45	-4.9	+ 1.5	(10.6 -30.2)	***	16	-7.1	+ 3.1	(1.0 -32.0)	*	187	-12.8	+ 0.9	(8.7 -33.7)	***	206	-0.7	+ 0.3	(12.6 -32.6)	*			
DG	68	0.2	+ 0.3	(8.1 -9.9)	ns	32	-0.2	+ 0.4	(4.9 -7.1)	ns	268	-0.6	+ 0.2	(17.8 -17.8)	***	316	-0.2	+ 0.1	(5.5 -11.6)	~			
DO	68	-1.7	+ 0.5	(6.5 -20.3)	***	32	1.2	+ 0.6	(9.8 -5.0)	~	268	-1.9	+ 0.3	(13.4 -20.2)	***	316	0.0	+ 0.1	(8.8 -10.7)	ns			
DU	68	0.1	+ 0.4	(5.2 -13.1)	ns	32	-0.8	+ 0.5	(4.3 -9.1)	ns	268	-0.7	+ 0.2	(17.5 -13.8)	***	316	0.0	+ 0.1	(9.8 -5.4)	ns			
MG	69	-8.6	+ 0.9	(9.2 -31.6)	***	34	-6.6	+ 1.9	(16.9 -22.8)	***	292	-5.3	+ 0.5	(22.8 -31.1)	***	316	-4.1	+ 0.4	(14.8 -27.9)	***			
MO	69	-3.8	+ 0.8	(13.8 -21.3)	***	34	-2.9	+ 1.1	(10.3 -20.2)	***	292	-2.6	+ 0.4	(15.2 -23.2)	***	316	-1.3	+ 0.3	(17.5 -27.7)	***			
MU	69	-8.5	+ 0.9	(6.3 -32.9)	***	34	-5.9	+ 1.5	(18.6 -20.7)	***	292	-6.2	+ 0.5	(20.6 -33.2)	***	316	-5.8	+ 0.3	(17.6 -28.4)	***			

¹ The first letter indicates the biogeographic model (B=BIOME2, D=DOLY, M=MAPSS); the second letter indicates the climate scenario

(G=GFDL, O=OSU, U=UKMO).

² $\bar{n}$ = number of protected areas; $\bar{Q}$ = mean; $\underline{SE}$ = standard error of mean; $\underline{P}$ = probability (two-tailed t-test of null hypothesis :=0).

Table A3.1 The number of models/scenarios combinations that predict a decrease in ecosystem representation in the landscape surrounding National Monuments. A period identifies protected areas that were excluded from the analysis.

Cabrillo NaM	.
Fort Frederica NaM	.
Fort Jefferson NaM	.
Fort Sumter NaM	.
Grand Portage NaM	.
Muir Woods NaM	.
Organ Pipe Cactus NaM	.
Perrys Victory and Internatl. Peace Memorial NaM	.
Alibates Flint NaM	-8
Capulin Mountain NaM	-8
Effigy Mounds NaM	-8
John Day Fossil Beds (Sheep Rock) NaM	-8
Colorado NaM	-7
El Morro NaM	-7
Fort Union NaM	-7
Hagerman Fossil Beds NaM	-7
Homestead NaM	-7
Hovenweep NaM	-7
Jewel Cave NaM	-7
Oregon Caves NaM	-7
Scotts Bluff NaM	-7
Black Canyon of the Gunnison NaM	-6
Canyon de Chelly NaM	-6
Custer Battlefield NaM	-6
Dinosaur NaM	-6
John Day Fossil Beds (Clarno) NaM	-6
John Day Fossil Beds NaM	-6
Navajo NaM	-6
Pinnacles NaM	-6
Rainbow Bridge NaM	-6
Tumacacori NaM	-6
Wupatki NaM	-6
Yucca House NaM	-6
Casa Grande Ruins NaM	-5
Chaco Canyon NaM	-5
Chiricahua NaM	-5
Craters of the Moon NaM	-5
Death Valley NaM	-5
Devil's Postpile NaM	-5
Dinosaur NaM	-5
Florissant Fossil Beds NaM	-5
Fossil Butte NaM	-5
George Washington Carver NaM	-5
Gila Cliff Dwellings NaM	-5
Great Sand Dunes NaM	-5
Hohokam Pima NaM	-5
Lava Beds NaM	-5
Lehman Caves (Nevada) NaM	-5

Montezuma Castle NaM	-5
Pecos NaM	-5
Saguaro NaM	-5
Timpanogos Cave NaM	-5
Tuzigoot NaM	-5
Agate Fossil Beds NaM	-4
Aztec Ruins NaM	-4
Cedar Breaks NaM	-4
Devil's Tower NaM	-4
Joshua Tree NaM	-4
Mound City Group NaM	-4
Natural Bridges NaM	-4
Ocmulgee NaM	-4
Salinas NaM	-4
Tonto NaM	-4
Bandelier NaM	-3
Booker T. Washington NaM	-3
Castillo de San Marcos NaM	-3
Fort Matanzas NaM	-3
Fort Pulaski NaM	-3
George Washington Birthplace NaM	-3
Pipestone NaM	-3
Sunset Crater NaM	-3
Walnut Canyon NaM	-3
Washington Monument NaM	-3
White Sands NaM	-3
Congaree Swamp NaM	-2
Pipe Spring NaM	-1

Table A3.2. As Table A3.1 except that National Parks are shown.

Acadia NP	.
Biscayne NP	.
Channel Islands NP	.
Everglades NP	.
Isle Royale NP	.
Redwood NP	.
Voyageurs NP	-8
Bryce Canyon NP	-7
Theodore Roosevelt NP	-7
Wind Cave NP	-7
Big Bend NP	-6
Canyonlands NP	-6
Crater Lake NP	-6
Grand Teton NP	-6
Guadalupe Mountains NP	-6
Yosemite NP	-6
Zion NP	-6
Carlsbad Caverns NP	-5
Great Basin NP	-5
Kings Canyon NP	-5
Mount Rainier NP	-5
North Cascades NP	-5
Sequoia NP	-5
Yellowstone NP	-5
Arches NP	-4
Capitol Reef NP	-4
Great Smoky Mountains (North Carolina) NP	-4
Great Smoky Mountains NP	-4
Lassen Volcanic NP	-4
Mesa Verde NP	-4
Rocky Mountain NP	-4
Badlands NP	-3
Shenandoah NP	-3
Glacier NP	-2
Grand Canyon NP	-2
Hot Springs NP	-2
Petrified Forest NP	-2
Olympic NP	-1

Table A3.3 As Table A3.1 except that National Wildlife Refuges are shown.

Alligator River NWR	.
Amagansett NWR	.
Aransas NWR	.
Back Bay NWR	.
Bear River NWR	.
Big Lake NWR	.
Blackwater NWR	.
Block Island NWR	.
Bombay Hook NWR	.
Breton NWR	.
Brigantine NWR	.
Cedar Island NWR	.
Cedar Keys NWR	.
Cedar Point NWR	.
Chassahowitzka NWR	.
Chincoteague NWR	.
Conscience Point NWR	.
Copalis NWR	.
Crocodile Lake NWR	.
Delta NWR	.
Dungeness NWR	.
Elizabeth A. Morton NWR	.
Farallon NWR	.
Felsenthal NWR	.
Fishermen Island NWR	.
Flattery Rocks NWR	.
Gravel Island NWR	.
Great White Heron NWR	.
Green Bay NWR	.
Hillside NWR	.
Humbolt Bay NWR	.
Island Bay NWR	.
J.N. "Ding" Darling NWR	.
Jones Island NWR	.
Key West NWR	.
Lacassine NWR	.
Laguna Atascosa NWR	.
Lower Hatchie NWR	.
Lower Suwannee NWR	.
Loxahatchee NWR	.
Mackay Island NWR	.
Martin NWR	.
Matagordo NWR	.
Matlacha Pass NWR	.
Mattamuskeet NWR	.
Merritt Island NWR	.
Mingo NWR	.
Monomy NWR	.
Moosehorn NWR	.
Morgan Brake NWR	.

Nantucket NWR	.
National Key Deer Refuge NWR	.
Nomans Land Island NWR	.
Okefenokee (Florida) NWR	.
Okefenokee (Georgia) NWR	.
Ottawa NWR	.
Panther Swamp NWR	.
Parker River NWR	.
Pea Island NWR	.
Pelican Island NWR	.
Petit Manan NWR	.
Plum Tree Island NWR	.
Quillayute Needles NWR	.
Sabine NWR	.
Sachuest Point NWR	.
Salt Meadow NWR	.
San Bernard NWR	.
Seal Beach NWR	.
Seal Island NWR	.
Seney NWR	.
Shell Keys NWR	.
St. Johns NWR	.
St. Vincent NWR	.
Swanquarter NWR	.
Thacher Island NWR	.
Wallops Island NWR	.
Wapanocca NWR	.
Wassaw Island NWR	.
West Sister Island NWR	.
White River NWR	.
Wolf Island NWR	.
Yazoo NWR	.
Bowdoin NWR	-9
Charles M. Russel NWR	-9
Hailstone NWR	-9
Hewitt Lake NWR	-9
Lake Alice NWR	-9
Lake George NWR	-9
Lambs Lake NWR	-9
Maxwell NWR	-9
McLean NWR	-9
Optima NWR	-9
Rose Lake NWR	-9
Shell Lake NWR	-9
Sheyenne Lake NWR	-9
Sibley Lake NWR	-9
Silver Lake NWR	-9
Valentine NWR	-9
Appert Lake NWR	-8
Audubon NWR	-8
Black Coulee NWR	-8
Charles M. Russell NWR	-8

Chautaugau NWR	-8
Conboy Lake NWR	-8
Creedman Coulee NWR	-8
Halfbreed Lake NWR	-8
Lake Nettie NWR	-8
Lake Thibadeau NWR	-8
Lake Zahl NWR	-8
Long Lake NWR	-8
Medicine Lake NWR	-8
Meredocia NWR	-8
Pishkun NWR	-8
Sevilleta NWR	-8
Slade NWR	-8
Squaw Creek NWR	-8
Trempealeau NWR	-8
U.L. Bend NWR	-8
Upper Mississippi (Minnesota) NWR	-8
Upper Mississippi (Minnesota) NWR	-8
Upper Mississippi (Wisconsin) NWR	-8
War Horse NWR	-8
Willow Creek NWR	-8
Agassiz NWR	-7
Buffalo Lake (North Dakota) NWR	-7
Cabeza Prieta NWR	-7
Camp Lake NWR	-7
Canfield Lake NWR	-7
Chautauqua NWR	-7
Cottonwood Lake NWR	-7
De Soto (Iowa) NWR	-7
De Soto (Nebraska) NWR	-7
Deer Flat NWR	-7
Florence Lake NWR	-7
La Creek NWR	-7
Lake Ilo NWR	-7
Lake Mason NWR	-7
Lamesteer NWR	-7
Las Vegas NWR	-7
Lost Lake NWR	-7
National Bison Range NWR	-7
Nine-Pipe NWR	-7
North Platte NWR	-7
Pleasant Lake NWR	-7
Pocasse NWR	-7
Rice Lake NWR	-7
Sandstone NWR	-7
School Section Lake NWR	-7
Stewart Lake NWR	-7
Swan Lake NWR	-7
Upper Mississippi River (Illinois) NWR	-7
Upper Mississippi River (Iowa) NWR	-7
White Lake NWR	-7
Willow Lake NWR	-7

Arapahoe NWR	-6
Ardoch NWR	-6
Arrowwood NWR	-6
Bear Lake NWR	-6
Browns Park NWR	-6
Camas NWR	-6
Chase Lake NWR	-6
Crescent Lake NWR	-6
Dakota Lake NWR	-6
Des Lacs NWR	-6
Fallon NWR	-6
Flint Hills NWR	-6
Fort Niobrara NWR	-6
Grolla NWR	-6
Hagerman NWR	-6
Hobart Lake NWR	-6
Horicon NWR	-6
Huron NWR	-6
J. Clark Salyer NWR	-6
Johnson Lake NWR	-6
Lostwood NWR	-6
Malheur NWR	-6
Maple River NWR	-6
Mark Twain NWR	-6
Mille Lacs Lake NWR	-6
Minidoka NWR	-6
Modoc NWR	-6
Muleshoe NWR	-6
National Elk NWR	-6
Oregon Islands NWR	-6
Pablo NWR	-6
Pathfinder NWR	-6
Pixley NWR	-6
Ruby Lake NWR	-6
Salt Plains NWR	-6
San Francisco Bay NWR	-6
San Pablo Bay NWR	-6
Santa Ana NWR	-6
Stillwater NWR	-6
Stoney Slough NWR	-6
Sullys Hill NWR	-6
Tishomingo NWR	-6
Union Slough NWR	-6
Upper Klamath NWR	-6
Upper Souris NWR	-6
Washita NWR	-6
Alamosa NWR	-5
Anahuac NWR	-5
Bamforth NWR	-5
Benton Lake NWR	-5
Bone Hill NWR	-5
Brazoria NWR	-5

Brumba NWR	-5
Buffalo Lake (Texas) NWR	-5
Cibola NWR	-5
Clarence Cannon NWR	-5
Clear Lake NWR	-5
Cold Springs NWR	-5
Crab Orchard NWR	-5
Desert National Wildlife Range NWR	-5
Erie NWR	-5
Fish Springs NWR	-5
Havasu NWR	-5
Hutton Lake NWR	-5
Imperial NWR	-5
Kellys Slough NWR	-5
Kirwin NWR	-5
Klamath Forest NWR	-5
Kofa NWR	-5
Kootenai NWR	-5
Lake Andes NWR	-5
Lee Metcalf NWR	-5
Mark Twain (Illinois) NWR	-5
McNary NWR	-5
Michigan Islands NWR	-5
Pretty Rock NWR	-5
Quivira NWR	-5
Rock Lake NWR	-5
Saddle Mountain NWR	-5
Seedsadee NWR	-5
Snyder Lake NWR	-5
Storm Lake NWR	-5
Tamarac NWR	-5
Tewaukon NWR	-5
Tule Lake NWR	-5
Turnbull NWR	-5
Umatilla (Oregon) NWR	-5
Umatilla (Washington) NWR	-5
Wapack NWR	-5
Waubay NWR	-5
Wild Rice Lake NWR	-5
Ankeny NWR	-4
Ash Meadows NWR	-4
Attwater Prairie Chicken NWR	-4
Baskett Slough NWR	-4
Bear Valley NWR	-4
Catahoula NWR	-4
Columbia NWR	-4
Cross Island NWR	-4
D' Arbonne NWR	-4
Eufaula NWR	-4
Hart Mountain NWR	-4
Karl E. Mundt NWR	-4
Killicoohook NWR	-4

Lower Klamath NWR	-4
McKay Creek NWR	-4
Muscatatuck NWR	-4
Nisqually NWR	-4
Ouray NWR	-4
Paharanagat NWR	-4
Piedmont NWR	-4
Pryor Mts. National Wild Horse Range NWR	-4
Ridgefield NWR	-4
Salton Sea NWR	-4
Sand Lake NWR	-4
Sherburne NWR	-4
Shiawassee NWR	-4
Supawna Meadows NWR	-4
Sutter NWR	-4
Swan River NWR	-4
Upper Ouachita NWR	-4
Wichita Mountains NWR	-4
William L. Finley NWR	-4
Anaho Island NWR	-3
Barnegat NWR	-3
Bitter Lake NWR	-3
Bogue Chitto (Louisiana) NWR	-3
Bogue Chitto (Mississippi) NWR	-3
Caloosahatchee NWR	-3
Cape Meares NWR	-3
Choctaw NWR	-3
Columbian White-Tailed Deer NWR	-3
Colusa NWR	-3
Cross Creeks NWR	-3
Delevan NWR	-3
Eastern Neck NWR	-3
Great Swamp NWR	-3
Lake Isom NWR	-3
Lake Woodruff NWR	-3
Monte Vista NWR	-3
Montezuma NWR	-3
Necedah NWR	-3
Noxubee NWR	-3
Patuxent Wildlife Research Center NWR	-3
Pinckney Island NWR	-3
Prime Hook NWR	-3
Red Rock Lakes NWR	-3
Reelfoot NWR	-3
Sacramento NWR	-3
San Andres NWR	-3
Seatuck NWR	-3
Sheldon National Antelope Refuge NWR	-3
St. Mark's NWR	-3
Susquehanna NWR	-3
Target Rock NWR	-3
Tennessee NWR	-3

Three Arch Rocks NWR	-3
Toppenish NWR	-3
Tybee Island NWR	-3
Wertheim NWR	-3
Wheeler NWR	-3
Wyandotte NWR	-3
Big Stone NWR	-2
Blackbeard Island NWR	-2
Bosque del Apache NWR	-2
Great Meadows NWR	-2
Harris Neck NWR	-2
Iroquois NWR	-2
Kern NWR	-2
Kesterson NWR	-2
Lewis and Clark NWR	-2
Marumsco NWR	-2
Mason Neck NWR	-2
Merced NWR	-2
Missisquoi NWR	-2
Overflow NWR	-2
Oyster Bay NWR	-2
San Juan Islands NWR	-2
San Luis NWR	-2
Santee NWR	-2
Savannah NWR	-2
Sequoiah NWR	-2
Sheldon NWR	-2
Willapa NWR	-2
Cape Romain NWR	-1
Grays Lake NWR	-1
Holla Bend NWR	-1
Little Pend Oreille NWR	-1
Presquile NWR	-1
Rachel Carson NWR	-1
Carolina Sandhills NWR	0
Great Dismal Swamp NWR	0
Hatchie NWR	0
Nansemond NWR	0
Pee Dee NWR	0
Pungo NWR	0

Table A3.4 As Table A3.1 except that Wilderness areas are shown.

Blackbeard Island	.
Boundary Waters Canoe Area NFW	.
Chassahowitzka	.
Cummins Creek	.
J.N. "Ding" Darling	.
Miller Peak	.
Pajarita	.
Rock Creek	.
Ventana NFW	.
Ansel Adams	-8
Badger Creek	-8
Black Canyon	-8
Dinkey Lakes	-8
Gates of the Mountain NFW	-8
Jarbridge NFW	-8
Kaiser	-8
La Garita NFW	-8
Medicine Lake	-8
Platte River	-8
Savage Run NFW	-8
U.L. Bend	-8
Winegar Hole	-8
Absaroka-Beartooth NFW	-7
Arrastra Mountain	-7
Bridge Creek	-7
Great Bear NFW	-7
Harcuvar Mountains	-7
Manzano Mountain NFW	-7
Mount Nutt	-7
North Maricopa Mountains	-7
Organ Pipe	-7
Rainbow Lake NFW	-7
Sandia Mountain NFW	-7
Signal Mountain	-7
Teton NFW	-7
Theodore Roosevelt	-7
Tres Alamos	-7
Wellsville Mountain	-7
Woolsey Peak	-7
Aldo Leopold NFW	-6
Baboquivari Peak	-6
Big Horn Mountains	-6
Bisti	-6
Black Canyon of the Gunnison	-6
Blue Range NFW	-6
Bucks Lake	-6
Cabeza Prieta	-6
Cache La Poudre NFW	-6
Castle Crags	-6
Chiricahua NFW	-6

Columbia	-6
De-Nah-Zin	-6
Desolation NFW	-6
Dolly Sods NFW	-6
Eagles Nest NFW	-6
East Humbolt	-6
Guadalupe Mountains	-6
Harquahala Mountains	-6
Hassayampa River Canyon	-6
Hells Canyon	-6
Hummingbird Springs	-6
Ishi	-6
Jedidiah Smith	-6
Kalmiopsis NFW	-6
Lava Beds	-6
Lostwood	-6
Lye Brook NFW	-6
Marble Mountain NFW	-6
Mill Creek	-6
Mount Rose	-6
Mount Shasta	-6
Mount Wrightson	-6
Mount Zirkel NFW	-6
Mt. Hood NFW	-6
Muggins Mountains	-6
North Fork	-6
Paria Canyon- Vermilion Cliffs	-6
Pine Valley Mountain	-6
Pinnacles	-6
Ruby Mountains	-6
Salmon-Huckleberry	-6
Selway Bitterroot	-6
Shining Rock NFW	-6
Sierra Estrella	-6
Siskiyou	-6
Sky Lakes	-6
Snow Mountain	-6
South Maricopa Mountains	-6
Superstition NFW	-6
Table Top	-6
Trinity Alps	-6
Wabayuma Peak	-6
White Canyon	-6
White Mountain NFW	-6
Yolla Bolly Middle Eel NFW	-6
Yolla Bolly-Middle Eel NFW	-6
Agua Tibia NFW	-5
Anaconda-Pintler NFW	-5
Aravaipa Canyon	-5
Aubrey Peak	-5
Bear Wallow	-5
Boulder Creek	-5

Box-Death Hollow	-5
Carlsbad	-5
Chiricahua NaM Wilderness	-5
Cranberry	-5
Craters of the Moon	-5
Dome Land NFW	-5
Dos Cabezas Mountains	-5
Eagletail Mountains	-5
East Cactus Plain	-5
Escudilla	-5
Fishhooks	-5
Flat Tops NFW	-5
Galiuro	-5
Gearhart Mountain NFW	-5
Gibraltar Mountain	-5
Gila NFW	-5
Glacier Peak NFW	-5
Golden Trout NFW	-5
Gospel Hump NFW	-5
Grant Range	-5
Great Sand Dunes	-5
Gros Ventre	-5
Imperial	-5
Jennie Lakes	-5
Juniper Dunes	-5
Kofa	-5
Machesna Mountain	-5
Minarets	-5
Monarch	-5
Mount Adams NFW	-5
Mount Moriah	-5
Mount Naomi	-5
Mount Timpanogos	-5
Mountain Lakes NFW	-5
Munds Mountain	-5
New Water Mountain	-5
North Fork Umatilla	-5
North Santa Teresa	-5
Otter Creek NFW	-5
Pecos NFW	-5
Peloncillo Mountains	-5
Petrified Forest	-5
Point Reyes	-5
Pusch Ridge NFW	-5
Quinn Canyon	-5
Raggeds NFW	-5
Rawhide Mountains	-5
Red Buttes	-5
Red Buttes	-5
Red Rock- Secret Mountain	-5
Redfield Canyon	-5
Rincon Mountain	-5

Russian	-5
Saguaro	-5
San Jacinto NFW	-5
Santa Lucia	-5
Santa Rosa- Paradise Peak	-5
Santa Teresa	-5
South Sierra	-5
Swansea	-5
Sycamore Canyon NFW	-5
Thousand Lakes NFW	-5
Trigo Mountains	-5
Warm Springs	-5
Welcome Creek NFW	-5
Wenaha-Tucannon (Oreg)NFW	-5
West Clear Creek	-5
West Elk NFW	-5
Wet Beaver	-5
Wild Rogue NFW	-5
Woodchute	-5
Absoraka Beartooth	-4
Alpine Lakes NFW	-4
Alta Toquima	-4
Anaconda-Pintlar NFW	-4
Apache Kid NFW	-4
Arc Dome	-4
Ashdown Gorge	-4
Beaver Creek NFW	-4
Beaver Dam Mountains	-4
Big Blue NFW	-4
Bridger NFW	-4
Bull of the Woods	-4
Cabinet Mountains NFW	-4
Capitan Mountains NFW	-4
Caribou NFW	-4
Castle Creek	-4
Cedar Bench	-4
Citico Creek	-4
Cloud Peak	-4
Collegiate Peaks NFW	-4
Comanche Peak NFW	-4
Cucamonga NFW	-4
Currant Mountain	-4
Dark Canyon	-4
Deseret Peak	-4
Dick Smith	-4
Fitzpatrick NFW	-4
Fossil Springs	-4
Four Peaks	-4
Frank Church-River of No Return NFW	-4
Gee Creek NFW	-4
Goat Rocks NFW	-4
Grand Wash Cliffs	-4

Granite Chief	-4
Grassy Knob	-4
Hells Canyon	-4
High Uintas	-4
Holy Cross NFW	-4
Hoover NFW	-4
Hunter-Fryingpan NFW	-4
Indian Peaks NFW	-4
James River Face NFW	-4
Joshua Tree	-4
Joyce Kilmer-Slickrock (North Carolina) NFW	-4
Joyce Kilmer-Slickrock (Tennessee) NFW	-4
Lassen Volcanic	-4
Lone Peak NFW	-4
Maroon Bells-Snowmass NFW	-4
Mazatzal NFW	-4
Menagerie	-4
Mesa Verde	-4
Middle Santiam	-4
Mokelumne NFW	-4
Monument Rock	-4
Mount Charleston	-4
Mount Olympus	-4
Mount Wilson	-4
Mt. Jefferson NFW	-4
Neota NFW	-4
Never Summer NFW	-4
North Absaroka	-4
Paiute	-4
Pasayten NFW	-4
Pine Mountain NFW	-4
Popo Agie	-4
Rawah NFW	-4
Saddle Mountain	-4
Salome	-4
San Gabriel NFW	-4
San Rafael NFW	-4
Santa Rosa	-4
Sawtooth NFW	-4
Scapegoat NFW	-4
Selway-Bitterroot	-4
Sheep Mountain	-4
South Warner NFW	-4
Table Mountain	-4
Table Rock	-4
Twin Peaks	-4
Weminuche NFW	-4
Wenaha-Tucannon (Wash.) NFW	-4
Withington NFW	-4
Apache Creek	-3
Bandelier	-3
Boundary Peak	-3

Bristol Cliffs NFW	-3
Chanchelulla	-3
Cohutta NFW	-3
Cruces Basin NFW	-3
Dome NFW	-3
Drift Creek	-3
Encampment River	-3
Granite Mountain	-3
Great Gulf NFW	-3
Hellsgate	-3
Huston Park	-3
John Muir NFW	-3
Juniper Mesa	-3
Kachina Peaks	-3
Kendrick Mountain	-3
Lee Metcalf	-3
Lizard Head NFW	-3
Mount Massive NFW	-3
Mount Nebo	-3
Mount Tipton	-3
Mt. Washington NFW	-3
Needle's Eye	-3
North Fork John Day	-3
Red Rock Lakes	-3
Sage Creek	-3
Salt Creek	-3
Salt River Canyon	-3
San Gorgonio NFW	-3
San Mateo Canyon	-3
Sierra Ancha NFW	-3
Sipsey NFW	-3
South San Juan NFW	-3
St. Mark's	-3
Washakie NFW	-3
Bob Marshall NFW	-2
Carson-Iceberg	-2
Chama River Canyon NFW	-2
Chupadera	-2
Coyote Mountains	-2
Diamond Peak NFW	-2
Eagle Cap NFW	-2
Emigrant NFW	-2
Indian Well	-2
Latir Peak NFW	-2
Little San Pascual	-2
Mount Logan	-2
Mount Sneffels NFW	-2
Mount Thielsen	-2
Mount Trumbull	-2
Rogue-Umpqua Divide	-2
San Pedro Parks NFW	-2
Strawberry Crater	-2

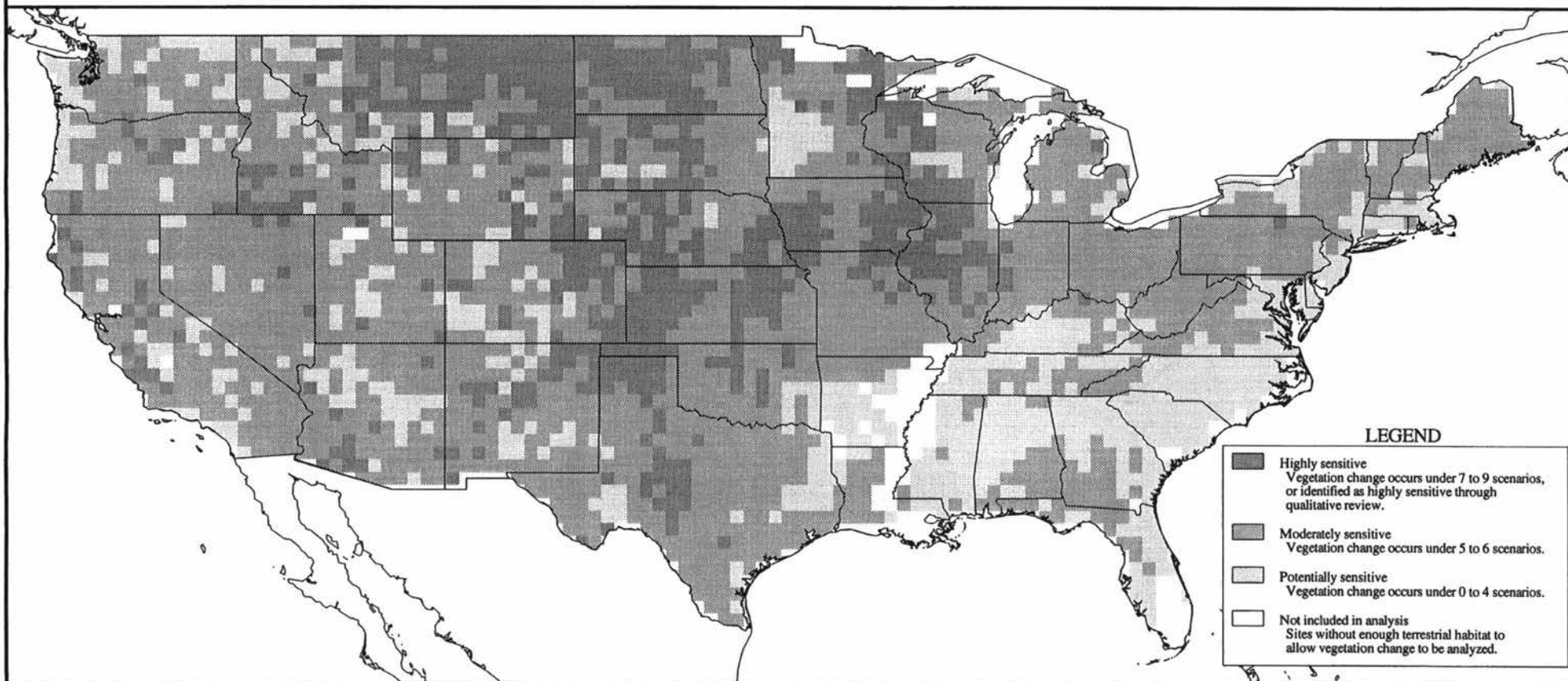
Strawberry Mountain NFW	-2
Upper Burro Creek	-2
Waldo Lake	-2
Wheeler Peak NFW	-2
Cottonwood Point	-1
Hauser	-1
Kanab Creek	-1
Kanab Creek	-1
Lost Creek NFW	-1
Mission Mountains NFW	-1
Mount Baldy NFW	-1
Pine Creek	-1
Rattlesnake NFW	-1
Linville Gorge NFW	0
Mount Evans NFW	0

Table A4. Average number of model/scenario combinations that predicted decreased representation of ecosystems in the landscapes surrounding protected areas.

State	Average number of models/scenarios	Number of protected areas
ND	-6.84	52
IA	-6.80	5
NE	-6.62	8
IL	-6.57	7
MT	-5.97	43
MN	-5.90	11
TX	-5.72	11
MO	-5.60	5
OK	-5.50	6
WI	-5.42	7
KS	-5.33	3
WV	-5.33	3
SD	-5.20	10
WY	-5.08	25
ID	-5.06	15
PA	-5.00	1
UT	-4.86	29
NV	-4.69	26
CA	-4.65	82
AZ	-4.64	109
OR	-4.63	57
CO	-4.59	42
NM	-4.54	42
WA	-4.04	23
IN	-4.00	1
MI	-4.00	6
NH	-4.00	2
VT	-3.66	3
KY	-3.50	2
NJ	-3.50	4
LA	-3.50	6
DE	-3.33	3
AL	-3.25	4
OH	-3.20	5
TN	-3.09	11
FL	-3.00	9
GA	-3.00	10
MD	-3.00	5
	80	

MS	-3.00	6
NY	-2.66	6
ME	-2.50	2
AR	-2.42	7
NC	-2.12	8
MA	-2.00	1
VA	-2.00	9
SC	-1.66	6

Country-Wide Vegetation Change



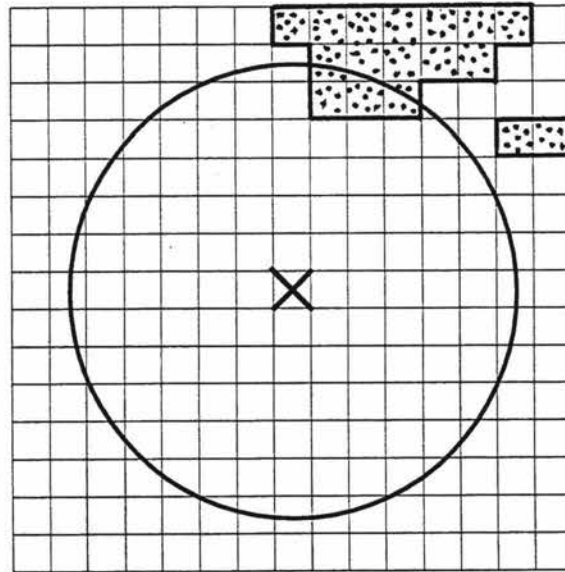
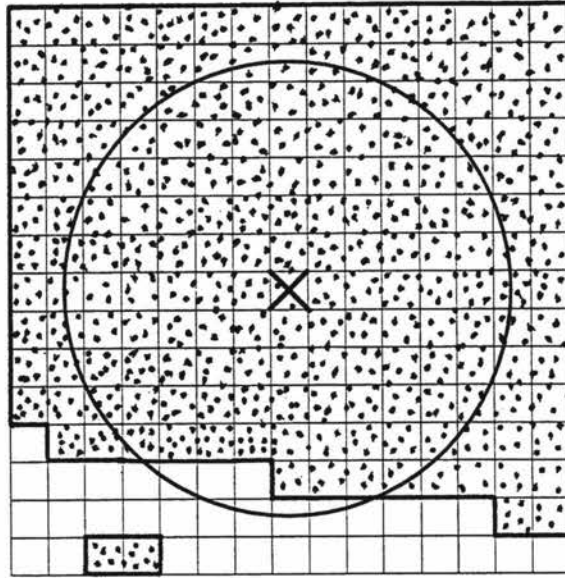


Figure A1. In the method used to quantify landscape change, representation of the vegetation type in the central pixel of a protected area (marked with at "X") is measured in a circular window with a radius of six pixel units. In the upper figure, most of the landscape is the same vegetation as the central pixel. In the lower pixel, that vegetation type is now restricted to the upper left of the window.

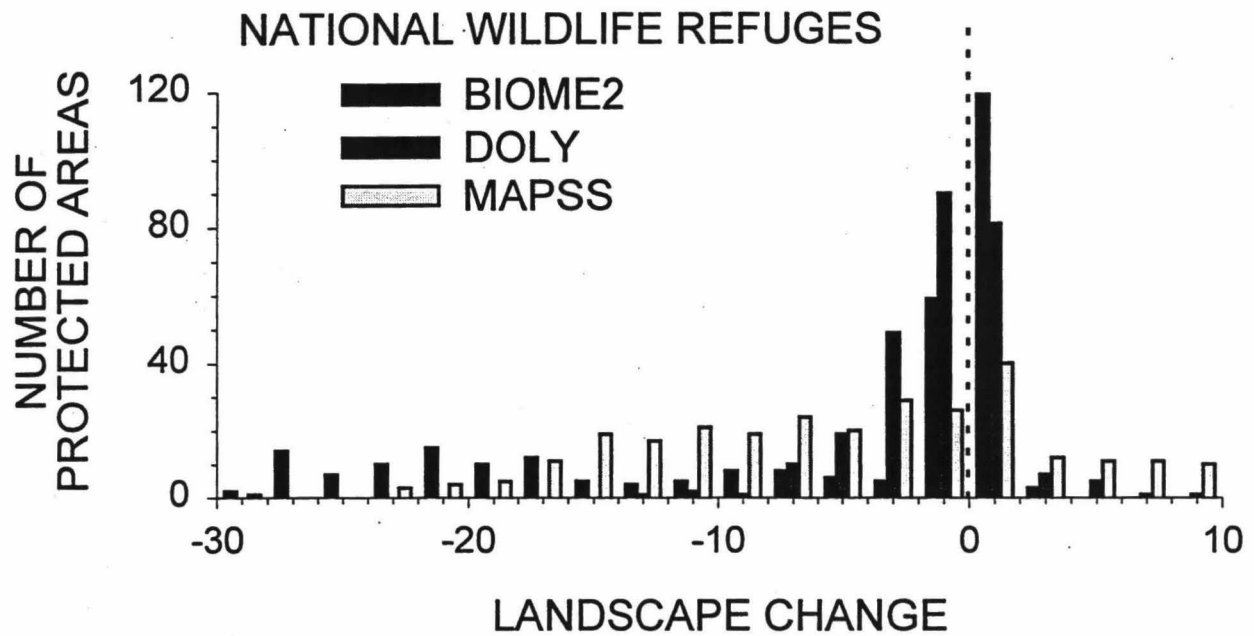


Figure A2. Changes in vegetation representation (RI) in the landscapes surrounding National Wildlife Refuges under three biogeographic models. RI values for each protected area were averaged across three climate scenarios.

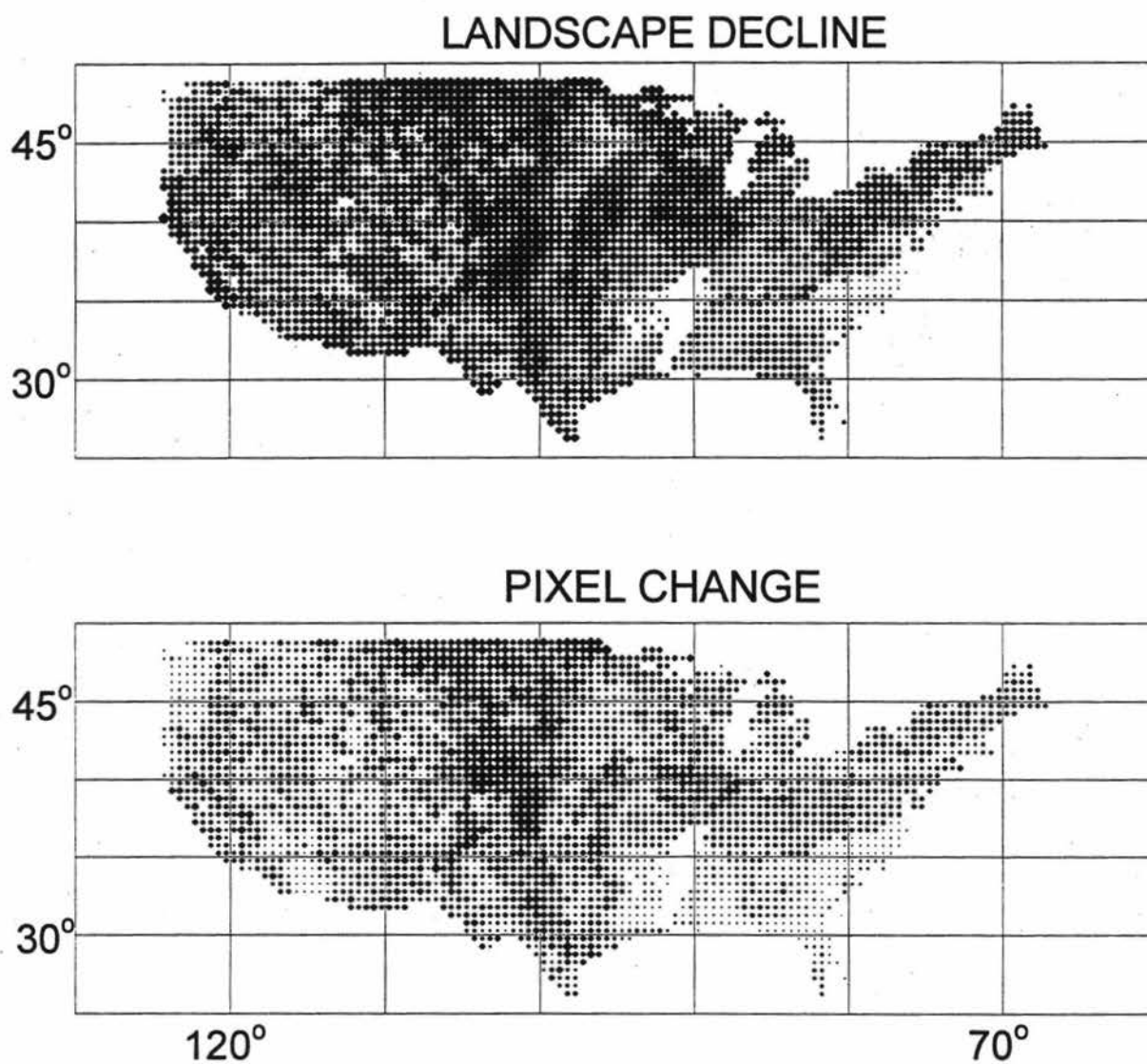


Figure A4. In the upper map, dot size represents the number of models that showed a decrease in vegetation type representation in the landscape surrounding a pixel. In the lower map, dot size represents the number of models that showed a change in the vegetation type of the pixel.

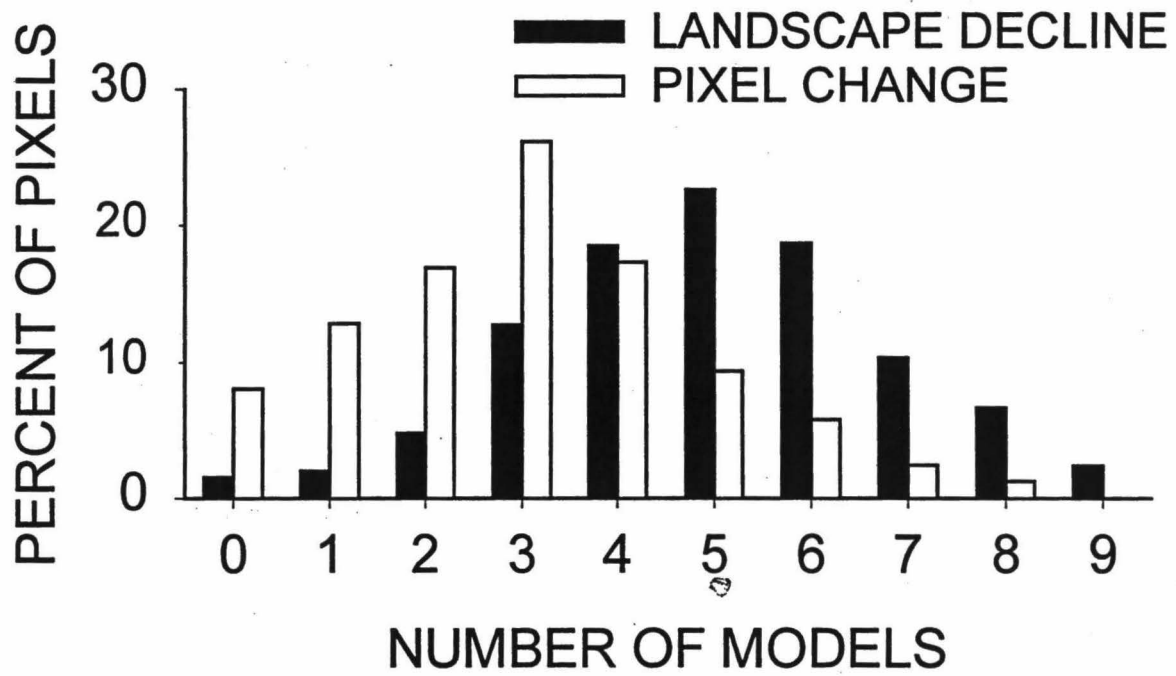
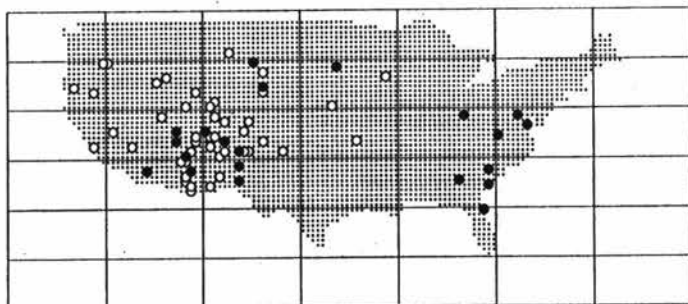
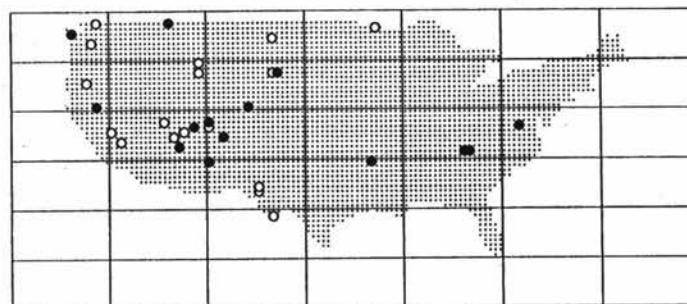


Figure A5. Frequency distributions of decreases in vegetation representation in the landscape surrounding a pixel vs. pixel change.

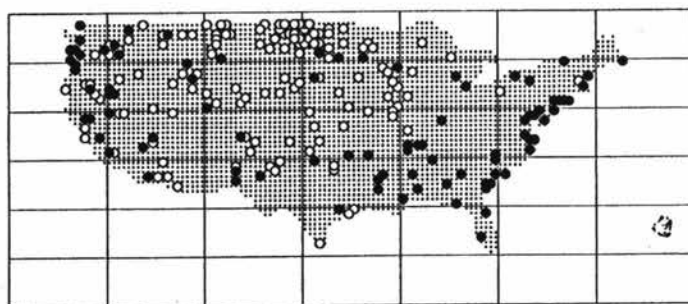
NATIONAL MONUMENTS



NATIONAL PARKS



NATIONAL WILDLIFE REFUGES



WILDERNESSES



Figure A3. Locations of protected areas that showed decreases in ecosystem representation in the surrounding landscape in five or more models (open circles) or four models or less (closed circles).

IV. LITERATURE CITED

- Alaska Conservation Foundation. 1994. Trouble in the North Pacific. *Dispatch*, Spring edition. Anchorage.
- Alcamo, J. and E. Kreileman. 1996. The global climate system: Near term action for long term protection. Background report prepared for the Workshop on Quantified Emission Limitation Reduction Objectives at the Third Meeting of the Ad Hoc Group on the Berlin Mandate Framework Convention on Climate Change, Geneva, 1994. National Institute of Public Health and the Environment (RIVM), Bilthoven.
- Alexander, V. 1992. Arctic marine Ecosystems. Pp 221-232 in Peters, R.L. and T.E. Lovejoy, eds. 1992. *Global Warming and Biological Diversity*. Yale University Press, New Haven.
- Alley, R.B., D.A. Meese, C.A. Shuman, A.T. Gow, K.C. Taylor, P.M. Grootes, T.W. White, M.Ram, E.D. Waddington, P.A. Mayewski, and G.A. Zielinski. 1993. Abrupt increase in Greenland snow accumulation at the end of Younger Dryas event. *Nature* 362:527-529.
- Apps, M.J., W.A. Kurz, R.J. Luxmoore, L.O. Nilsson, R.A. Sedjo, R. Schmidt, L.G. Simpson, and T.S. Vinson, 1993: Boreal forests and tundra. *Water, Air, and Soil Pollution*, 70, 39-53.
- Auclair, A.N.D., J.T. Lill, and C. Revenga, 1996: The role of climate variability and global warming in the dieback of Northern Hardwoods. *Water, Air, and Soil Pollution*, 91, 163-186.
- Babcock, C.A. and C.R. Ely. 1994. Classification of vegetation communities in which geese rear broods on the Yukon-Kuskokwim delta, Alaska. *Canadian Journal of Botany* 72:1294-1301.
- Balling Jr. R.C., G.A. Meyer and S.G. Wells. 1992. Climate change in Yellowstone National Park: Is the drought-related risk of wildfires increasing? *Climatic Change* 22: 35-45.
- Bancroft, G.T. Case Study: United States of America. Pp 199-219 in *Human Population, Biodiversity and Protected Areas: Science and Policy Issues* (Dompka, V. ed.). American Association for the Advancement of Science, Washington D.C.
- Barry, J.P., C.H. Baxter, R.D. Sagarin and S.E. Gilman. 1995. Climate-related, long-term faunal changes in a California rocky intertidal community. *Science* 267: 672-675.
- Beamish, R.J. 1995. Response of anadromous fish to climate change in the North Pacific. Pp 123-136 in *Human Ecology and Climate Change: People and Resources of the Far North* (D.L. Peterson and D.R. Johnson, Eds). Taylor and Francis, Washington D.C.
- Bergsma, B.M., J. Svoboda, and B. Freedman. 1984. Entombed plant communities released by a retreating glacier at central Ellesmere Island, Canada. *Arctic*. 37:49-52.

BESIS. 1997. The impacts of global climate change in the Bering Sea region: An assessment conducted by the International Arctic Science Committee under its Bering Sea Impacts Study (BESIS). BESIS Project Office, Anchorage.

Bethke, R.W. and T.D. Nudds. 1995. Effects of climate change and land use on duck abundance in Canadian prairie-parklands. *Ecological Applications* 5:588-600.

Billings, W. D. 1988. Alpine vegetation. Pages 391-420. *in* Barbour, M. G. and W. D. Billings (eds.). *North American Terrestrial Vegetation*. Cambridge University Press, New York.

Billings, W. D. 1992. Phytogeographic and evolutionary potential of the arctic flora and vegetation in a changing climate. Pages 91-109 *in* Chapin, F.S.III, R.L. Jefferies, J.F. Reynolds, G.R. Shaver, and J. Svoboda (eds.), *Arctic Ecosystems in a Changing Climate: an Ecophysiological Perspective*. Academic Press, San Diego.

Botkin, D.B. and R.A. Nisbet. 1992. Projecting the effects of climate change on biological diversity in forests. *In* *Global Warming and Biological Diversity* (Peters, R.L. and T.E. Lovejoy, eds). Yale University Press, New Haven.

Brassard, G.R. 1976. The mosses of Ellesmere Island, Arctic Canada. III. New or additional records. *The Bryologist* 79:480-487.

Brassard, G.R. 1971. The mosses of Ellesmere Island, Arctic Canada. I. Ecology and phytogeography, with an analysis for the Queen Elizabeth Islands. *The Bryologist* 74:233-281.

Brotton, J., and G. Wall. 1997. Climate change and the Bathurst caribou herd in the Northwest Territories, Canada. *Climatic Change* 35:35-52.

Bryant, D., D. Nielsen, and L. Tangle. 1997. *The last frontier forests: ecosystems and economies on the edge*. World Resources Institute, Washington, D.C.

Cess, R. D., G. L. Potter, J. P. Blanchet, G. J. Boer, S. J. Ghan, J. T. Kiehl, H. Le Treut, Z-X Li, X-Z Liang, J. F. B. Mitchell, J-J Morcrette, D. A. Randall, M. R. Riches, E. Roeckner, U. Schlese, A. Slingo, K. E. Taylor, W. M. Washington, R. T. Wetherald, and I. Yagai. 1989. Interpretation of cloud-climate feedback as produced by 14 atmospheric general circulation models. *Science* 245:513-516.

Chapin, F. S., III, G. R. Shaver, A. E. Giblin, K. J. Nadelhoffer, and J. A. Laundre. 1995. Responses of arctic tundra to experimental and observed changes in climate. *Ecology* 76:694-711.

- Chapman, W.L., and J.E. Walsh. 1993. Recent variations of sea ice and air temperatures in high latitudes. *Bulletin of the American Meteorological Society* 74:33-47.
- Cogley, J.G., W.P. Adams, M.A. Ecclestone, F. Jung-Rothenhauser, and C.S.L. Ommanney. 1995. Mass balance of Axel Heiberg Island Glaciers 1960-1991. NHRI Science Report No. 6. Environment Canada, National Hydrology Institute, Saskatoon, Sask.
- Cohen, S.J. 1997. Mackenzie Basin impact study final report. Environment Canada and University of British Columbia, Vancouver, BC.
- Constantz, G (1994). *Hollows, Peepers and Highlanders: An Appalachian Mountain Ecology*. Mountain Press Publishing Co. Missoula.
- Cronk, Q.C.B. In press. Interaction of global climate change with global change due to alien plant invasion. *Climatic Change*.
- Crowell, A. 1996. Archeology in a mythical landscape: Glacier Bay National Park. Arctic Studies Center Web Site. Smithsonian, Washington D.C.
- Crowley, T. J., and K.-Y. Kim. 1995. Comparison of longterm greenhouse projections with the geologic record. *Geophysical Research Letters* 22:933-936.
- Cumming, H.G. and D.B. Beange. 1993. Survival of woodland caribou in commercial forests northern Ontario. *Forestry Chronicle* 69:579-587.
- D'Arrigo, R. D., and G. C. Jacoby. 1993. Secular trends in high northern latitude temperature reconstructions based on tree rings. *Climatic Change* 25:163-177.
- Davis, M.B. 1986. Climatic instability, time lags, and community disequilibrium. In: Diamond, J. & Case, T.J. (eds) *Community Ecology*. Harper & Row, New York. 269-284.
- DeMaster, D. P., and I. Stirling. 1981. *Ursus maritimus*. *Mammalian Species* No.145:1-7.
- Diamond, A.W. and R.K. Brace. 1991. Climate and waterfowl populations. pp. 245-257 in *Symposium on the impacts of climatic change and variability on the Great Plains*. Department of Geography Publication Series, Occasional Paper No. 12, University of Waterloo.
- Dobson, A., Jolly, A. & Rubenstein, D. 1989. The greenhouse effect and biological diversity. *Trends in Ecology and Evolution* 4:64-68.
- Douglas, M.S.V., J.P. Smol and W. Blake Jr. 1994. Marked post-18th Century environmental Change in High-Arctic Ecosystems. *Science* 266: 416-419.

Elliott, K.J. and W.T. Swank, 1994: Impacts of drought on tree mortality and growth in a mixed hardwood forest. *Journal of Vegetation Science*, 5:229-236.

Fagre, D.B. In press. Understanding climate change effects on Glacier National Park's natural resources. *In* The Status and Trends of the Nation's Biological Resources. USGS, Washington D.C.

Fagre, D.B. In press. Understanding climate change impacts on Glacier National Park's natural resources. *In* Mac, M. and P. Opler, eds. Status and Trends. National Biological Service. Washington D.C.

Fagre, D.B., P.L. Comanor, J.D. White, F.R. Hauer and S.W. Running. In press. Watershed responses to climate change at Glacier National Park.

Findlay, B. F., and A. Deptuch-Stapf. 1991. Colder than normal temperatures over north eastern Canada during the 1980's. *Climatic Perspectives* 13:9-12.

Flannigan, M.D. and C.E. Van Wagner, 1991: Climate change and wildfire in Canada. *Canadian Journal of Forest Research*, 21:66-72.

Fosberg, M.A., 1990: Global change--a challenge to modeling. Pp. 3-8. *in* Process Modeling of Forest Growth Responses to Environmental Stress (Dixon, R.K., R.S. Meldahl, G.A. Ruark, and W.G. Warren , eds.). Timber Press, Inc., Portland, OR.

Fosberg, M.A., B.J. Stocks, and T.J. Lynham. 1996. Risk analysis in strategic planning: fire and climate change in the boreal forest. Pp. 495-504 *in* Fire in Ecosystems of Boreal Eurasia (Goldammer, J.G. and V.V. Furyaev, eds.). Kluwer Academic Publishers, Netherlands.

Galen, C., and M.L. Stanton. 1993. Short-term responses of alpine buttercups to experimental manipulations of growing season length. *Ecology*, 74(4), 1052-1058.

Goldammer, J.G. and C. Price. In Press. Potential impacts of climate change on fire regimes in the tropics based on MAGICC and a GISS GCM-derived lightening model. *Climatic Change*.

Groisman, P., T.R. Karl, and T.W. Knight. 1994. Observed impact of snow cover on the heat balance and the rise of continental spring temperatures. *Science* 263:198-200.

Guffey, S.Z., G.F. McCracken, S.E. Moore and C.R. Parker. In Press. Management of isolated populations: Native southern Appalachian brook trout. *In* Ecosystem Management for Sustainability: Principles and practices illustrated by the Southern Appalachian Man and Biosphere Cooperative.

Gunn, A. 1995. Responses of arctic ungulates to climate change. Pp. 89-104 *in* Human ecology and climate change: people and resources in the far north (Peterson, D. L., and D. R. Johnson, eds.). Taylor & Francis, Washington, D.C.

- Halpin, P. N. 1995. Modeling potential impacts of climate change on northern landscapes. Pp. 57-74 in *Human ecology and climate change: people and resources in the Far North* (Peterson, D. L., and D. R. Johnson, eds.), Taylor & Francis, Washington, D.C.
- Halsey, L. A., D. H. Vitt, and S. C. Zoltai. 1995. Disequilibrium response of permafrost in boreal continental western Canada to climate change. *Climatic Change* 30:57-73.
- Havström, M., T.V. Callaghan, S. Jonasson, and S. Svoboda. 1995. Little Ice Age temperature estimated by growth and flowering differences between subfossil and extant shoots of *Cassiope tetragona*, an arctic heather. *Functional Ecology*. 9:650-654.
- Halpin, P.N. In press. Global change and natural area protection: Management responses and research directions.
- Harris, L.D. and W.P. Cropper, Jr. 1992. Between the devil and the deep blue sea: Implications of climate change for Florida's fauna. In *Global Warming and Biological Diversity* (Peters, R.L. and T.E. Lovejoy, eds). Yale University Press, New Haven.
- Heath, L.S., P.E. Kauppi, P. Burschel, H.D. Gregor, R. Guderian, G.H. Kohlmaier, S. Lorenz, D. Overdieck, F. Scholz, H. Thomasius, and M. Weber. 1993. Contribution of temperate forests to the world's carbon budget. *Water, Air, and Soil Pollution* 70, 55-69.
- Houghton, J.T. et al. 1996. *Climate Change 1995: the science of climate change*. University of Cambridge, Cambridge, U.K.
- Houghton, J.T., L.G. Meira Filho, B.A. Callander, N. Harris, A. Kattenberg and K. Maskell. 1996. *Climate Change 1995: The Science of Climate Change*. Cambridge University Press, Cambridge.
- Hulme, M., and D. Viner. 1995. A climate scenario for assessing the impact of climate change on tropical rain forests. Unpublished report. World Wildlife Fund, Washington D.C.
- Inouye, D.W. and A.D. McGuire. 1991. Effects of snowpack on timing and abundance of flowering in *Delphinium nelsonii* (*Ranunculaceae*): Implications for climate change. *American Journal of Botany* 78(7): 997-1001.
- International Porcupine Caribou Board 1995. Fourth annual report. U.S. Fish & Wildlife Service, Anchorage, AK.
- International Porcupine Caribou Board. 1993. Sensitive habitats of the Porcupine Caribou herd. U.S. Fish & Wildlife Service, Anchorage, AK.

ICC. 1996. Media backgrounder: Climate change and the circumpolar region. Inuit Circumpolar Conference (ICC), Ottawa.

Jacoby, G. C., R. D. D'Arrigo, and T. Davaajamts. 1996. Mongolian tree rings and 20th century warming. *Science* 273:771-773.

Jacoby, G. C., and R. D'Arrigo. 1989. Reconstructed northern hemisphere annual temperature since 1671 based on high-altitude tree-ring data from North America. *Climatic Change* 14:39-59.

Jefferies, R. L., F. L. Gadallah, D. S. Srivastava, and D. J. Wilson. 1995. Desertification and trophic cascades in arctic coastal ecosystems: a potential climatic change scenario? Pp. 201-206 in *Global change and arctic terrestrial ecosystems: proceedings of papers contributed to the International Conference*, (Callaghan, T. V., ed.). 21-26 August 1993, Oppdahl, Norway. Office for Official Publications of the European Union, Luxembourg.

Jones, E.A., D.D. Reed, G.D. Mroz, H. O. Liechty and P.J. Cattellino. 1993. *Canadian Journal of Forest Research* 23: 229-233.

Karl, T.R., N. Nicholls and J. Gregory. 1997. The coming climate. *Scientific American*, May: 78-82.

Keane, R.E., C.C. Hardy, K.C. Ryan and M.A. Finney. In press. Simulating effects of fire on gaseous emissions from future landscapes of Glacier National Park, Montana, U.S.A. *World Resources Review*.

Kerr, R. A. 1996. Sky-high findings drop new hints of greenhouse warming. *Science* 273:34.

Kerr, R. A. 1995. It's official: first glimmer of greenhouse warming seen. *Science* 270:1565-1567.

King, G.A. and R.P. Neilson, 1992: The transient response of vegetation to climate change: a potential source of CO₂ to the atmosphere. *Water, Air and Soil Pollution* 64:365-383.

Knight, D.H. 1991. The Yellowstone fire controversy. Pp 87-103 in *The Greater Yellowstone Ecosystem: Redefining America's Wilderness Heritage* (Keiter, R.B. and M.S. Boyce, eds.). Yale University Press, New Haven.

Kukla, G.T., and E. Went. (eds.) 1992. Start of a glacial (NATO ASI Series/NATO Advanced Research Workshop Vol. 3.). Springer-Verlag, Berlin.

Kwong, Y. T. J., and T. Y. Gan. 1994. Northward migration of permafrost along the Mackenzie highway and climatic warming. *Climatic Change* 26:399-419.

- Langdon, S.J. 1995. Increments, ranges and thresholds: Human population responses to climate change in northern Alaska. Pp 139-154 *in* Human Ecology and Climate Change: People and Resources of the Far North (D.L. Peterson and D.R. Johnson, Eds). Taylor and Francis, Washington D.C.
- Larson, D.L. 1995. Effects of climate on numbers of northern prairie wetlands. *Climatic Change* 30:169-180.
- Leader-Williams, N. 1988. Reindeer and South Georgia: the ecology of an introduced population. Cambridge University Press, Cambridge, U.K.
- Leatherman, S.P. 1989. National assessment of beach nourishment requirements associated with accelerated sea level rise. *In* The Potential Effects of Global Climate Change on the United States (Smith, J.B., and D.Tirpak, eds.). United States Environmental Protection Agency, Washington, D.C.
- Lloyd, A.H. and L.J. Graumlich. 1997. Holocene dynamics of tree line forests in the Sierra Nevada. *Ecology* 78,4: 1199-1210.
- Loope, L.L. 1990. A capability and interest statement for Haleakala National Park for participation in the NPS Global Climate Change Research Program. Unpublished report.
- Loope, L.L. and T.W. Giambelluca. In press. Vulnerability of island tropical montane cloud forests to climate change, with special reference to east Maui, Hawaii. *Climatic Change*.
- Maarouf, A. R., J. D. Jacobs, and E. A. Perkins. 1994. An analysis of the recent instrumental record of climate for northern Labrador and Quebec for conditions unfavourable to caribou. George River Caribou Workshop, January 27-29, 1994. Labrador Institute for Northern Studies, Labrador City, Labrador.
- MacDonald, K.A. and J.H. Brown. 1992. Using montane mammals to model extinctions due to global change. *Conservation Biology* 6:409-415.
- Malcolm, J. R., and R.J. Brooks. 1993. The adaptive value of photoperiod-induced shape changes in the collared lemming. Pp. 311-328 *in* The biology of lemmings (Stenseth, N. C., and R. A. Ims, eds.). Academic Press, London.
- Malcolm, J. R., and A. Markham. 1996. Ecosystem resilience, biodiversity and climate change: setting limits. *Parks* 6:38-49.
- Markham, A. 1996. Potential impacts of climate change on ecosystems: a review of implications for policymakers and conservation biologists. *Climate Research* 6:179-191.
- Markham, A., and J. Malcolm. 1996. Biodiversity and wildlife conservation: adaptation to climate change. Pp 384-401 *in* Adaptation to Climate Change: Assessment and Issues (Smith, J.,

- N. Bhatti, G. Menzhulin, R. Benioff, M. Campos, B. Jallow, and F. Rijsberman, eds.). Springer-Verlag, New York.
- Martin, C. 1992. Climatic Perturbation as a General Mechanism of Forest Dieback. Pp. 38-58 *in* Forest decline concepts (P.D. Manion and D. Lachance, eds.). APS Press, St. Paul, Minnesota.
- Matson, D.J., and M.W. Reid. 1991. Conservation of the Yellowstone grizzly bear. *Conservation Biology* 5,3.
- Maxwell, B. 1992. Arctic climate: potential for change under global warming. Pp. 11-34 *in* Arctic ecosystems in a changing climate: an ecophysiological perspective (Chapin, F. S., III, R. L. Jefferies, J. F. Reynolds, G. R. Shaver, and J. Svoboda, eds.). Academic Press, San Diego.
- Miller, F.L. 1991. Peary Caribou -- a Status Report. Canadian Wildlife Service, Ottawa.
- Miller, B., G. Ceballos, and R. Reading. 1994. The prairie dog and biotic diversity. *Conserv. Biol.* 8:677-681.
- Myneni, R.B., C.D. Keeling, C.J. Tucker, G. Asrar, and R.R. Nemani. 1997. Increased plant growth in the northern high latitudes from 1981-1991. *Nature*. ***
- Myneni, R.B., F.G. Hall, P.J. Sellers, and A.L. Marshak. 1995. The interpretation of spectral vegetation indexes. *IEEE Trans. Geosci. Remote Sens.* 33:481-486.
- Norse, E.A. 1990. Ancient Forests of the Pacific Northwest. Island Press, Washington D.C.
- O'Brien, S., B.P. Hayden and H.H. Shugart. 1992. Global climate change, hurricanes and a tropical forest. *Climatic Change* 22: 175-190.
- Ono, K.A. 1995. Effects of climate change on marine mammals in the Far North. Pp 105-121 *in* Human Ecology and Climate Change: People and Resources of the Far North (D.L. Peterson and D.R. Johnson, Eds). Taylor and Francis, Washington D.C.
- Osterkamp, T.E. and V.E. Romanovsky. 1996. Thawing of Discontinuous Permafrost as a result of climatic warming: Impacts. Presentation to AAAS/ASC Workshop on the Impacts of Global Change in the Bering Sea Region. Anchorage.
- Park, R.A., M.S. Trehan, P.W. Mausel, and R.C. Howe. 1989. The effects of sea level rise on U.S. coastal wetlands. *In* The Potential Effects of Global Climate Change on the United States (Smith, J.B., and D.Tirpak, eds.). United States Environmental Protection Agency, Washington. D.C.
- Pastor, J., Dewey, B., Naiman, R. J., McInnes, P. F. and Cohen, Y. 1993. Moose browsing and soil fertility in the boreal forests of the Isle Royale National Park. *Ecology* 74:467-480.

Peine, J.D and C. Berish. In prep. Climate change: Potential effects in the Southern Appalachians. In Ecosystem management for sustainability: Principles and practices illustrated by the Southern Appalachian Man and Biosphere Cooperative.

Peine, J.D., and C.J. Martinka. 1994. Impacts of climate change on mountain protected areas: Implications for management. In Impacts of Climate Change on Ecosystems and Species (Pernetta and Elder, eds). IUCN, Gland.

Peters, R.L. and T.E. Lovejoy, eds. 1992. Global Warming and Biological Diversity. Yale University Press, New Haven.

Peters, R.L. 1992. Conservation of biological diversity in the face of climate change. In Global Warming and Biological Diversity (Peters, R.L. and T.E. Lovejoy, eds). Yale University Press, New Haven.

Peters, R.L., and J.D.S. Darling. 1985. The greenhouse effect and nature reserves. *BioScience* 35,1: 707-716.

Peterson, D.L. 1994. Recent changes in the growth and establishment of subalpine conifers in western North America. Pp 234-243 in Mountain Environments in Changing Climates (Beniston, M. Ed.). Routledge, London.

Peterson, D.L. and D.R. Johnson 1995. Human ecology and climate change at northern latitudes. Pp 3-13 in Human Ecology and Climate Change: People and Resources of the Far North (D.L. Peterson and D.R. Johnson, Eds). Taylor and Francis, Washington D.C.

Peterson, R. O. 1977. Wolf ecology and prey relationships on Isle Royale. Scientific Monograph Series No. 11, National Park Service, Washington, DC

Peterson, R. O., Page, R. E. and Dodge, K. M. 1984. Wolves, moose, and the allometry of population cycles. *Science*, 224:1350-1352.

Pielke, R.A., J. Baron, T. Chase, J. Copeland, T.G.F. Kittle, T.J. Lee, R. Walko, X. Zeng. 1993. Use of mesoscale models for simulation of seasonal weather and climate change for Rocky Mountain states. Proceedings, Second International Conference/Workshop on Integrating GIS and Environmental Modeling, Breckenridge, CO.

Poiani, K.A. and W.C. Johnson. 1993. Potential effects of climate change on a semi-permanent prairie wetland. *Climatic Change* 24:213-232.

Poiani, K.A. and W.C. Johnson. 1991. Global warming and prairie wetlands. *BioScience* 41:611-618.

Porcupine Caribou Management Board 1996. 1996 Porcupine Caribou Review. Porcupine Caribou Management Board, Whitehorse, YT.

Price, C. and D. Rind, 1994: Possible implications of global climate change on global lightning distributions and frequencies. *Journal of Geophysical Research* 99: 10823. ***

Price, J.T. 1995. Potential impacts of global climate change on the summer distributions of some North American grassland birds. Ph.D. Dissertation, Wayne State University, Detroit, Michigan.

Price, J., S. Droege, and A. Price. 1995. The summer atlas of North American birds. Academic Press, London.

Reid, W. V., and M.C. Trexler. 1991. Drowning the National Heritage: Climate Change and U.S. Coastal Biodiversity. World Resources Institute, Washington D.C.

Riley, L. and T. Riley. 1992. Guide to the national wildlife refuges, (second edition). Collier Books, New York.

Rocheftort, R.M., R.L. Little, A. Woodward and D.L. Peterson. 1994. Changes in sub-alpine tree distribution in western North America: a review of climatic and other causal factors. *The Holocene* 4,1: 89-100.

Roemmich, D. and J. McGowan. 1995. Climatic warming and the decline of zooplankton in the California Current. *Science*: 267, 1324-1326.

Romme, W.H. and M.G. Turner. 1990. Implications of global change for biogeographic patterns in the Greater Yellowstone Ecosystem. *Conservation Biology* 5,3:373-386.

Rouse, W.R., M.S.V. Douglas, R.E. Hecky, A.E. Hershey, G.W.Kling, L. Lesack, Philip Marsh, M. McDonald, B. J. Nicholson, N.T. Roulet and J.P. Smol. Effects of climate change on the freshwaters of Arctic and Subarctic North America. In Prep.

Russell, D. E. 1993. Effects of global warming on the biology and management of the Porcupine Caribou herd. Pp. 91-97 *in* Impacts of Climate Change on Resource Management in the North. Department of Geography Publication Series, Occasional Paper No. 16, University of Waterloo.

Sampson, R.N., M. Apps, S. Brown, C.V. Cole, J. Downing, L.S. Heath, D.S. Ojima, T.M. Smith, A.M. Solomon, and J. Wisniewski, 1993: Workshop summary statement: terrestrial biospheric carbon fluxes -- quantification of sinks and sources of CO₂. *Water, Air, and Soil Pollution* 70:3-15.

Schaaf, J. 1995. Understanding northern environments and human populations through cooperative research: A case study in Beringia. Pp 229-244 *in* Human Ecology and Climate

Change: People and Resources of the Far North (D.L. Peterson and D.R. Johnson, Eds). Taylor and Francis, Washington D.C.

Sedinger, J.S., P.L. Flint. and M.S. Lindberg. 1995. Environmental influence on life-history traits: growth, survival, and fecundity in black brant (*Branta bernicla*). *Ecology* 76:2404-2414.

Sedinger, J.S. and P.L. Flint. 1991. Growth rate is negatively correlated with hatch date in black brant. *Ecology* 72:496-502.

Smith, T.M. and H.H. Shugart, 1993: The transient response of terrestrial carbon storage to a perturbed climate. *Nature* 361: 523-526.

Sohngen, B. and R. Mendelsohn, in press: A dynamic model of carbon storage in the United States during climate change. *Critical Reviews of Environmental Science and Technology*.

Solbrig, O. T. (ed). 1991. From Genes to Ecosystems: a Research Agenda for Biodiversity. International Union of Biological Sciences, Cambridge, MA.

Solomon, A.M., 1986: Transient response of forests to CO₂-induced climate change: simulation modeling experiments in eastern North America. *Oecologia* 68: 567-579.

Southern Appalachian Man and the Biosphere Cooperative. 1996. USDA, Wasington D.C.

Stirling, I., and A. E. Derocher. 1992. Possible impacts of climate warming on polar bears. Abstract presented at Canadian Arctic Global Change Research. Biological Implications of Global Change: Northern Perspectives. Workshop co-sponsored by Royal Society of Canada, Canadian Global Change Program, & Association of Canadian Universities for Northern Studies. October 22-23, 1992, University of Alberta, Edmonton.

Stocks, B.J., B.S. Lee and D.L. Martell, 1996: Some potential carbon budget implications of fire management in the boreal forest. Pp. 89-96 in Forest ecosystems, forest management and the global carbon cycle (Apps, M.J. and D.T. Price, eds.). NATO ASI Series, Subseries 1, Global Environmental Change, Vol. 40, Springer-Verlag, Berlin, Germany.

Stohlgren, T.J., J. Baron, T.G.F. Kittel and D. Brinkley. 1995. Ecosystem trends in the Colorado Rockies. pp. 310-312 in Our living resources, 1995: a report to the nation on the distribution, abundance, and health of U.S. plants, animals, and ecosystems. National Biological Service, Washington, D.C.

Stohlgren, T.J. et al. 1995. The National Biological Service Global Change Research Program in the Colorado Rockies biogeographical area: third year report (1994-1995). Rocky Mountain Field Station, National Biological Service, Ft. Collins, CO.

Svoboda, J. 1995. Could the eastern Canadian arctic and Greenland be prone to neoglaciation even under the global warming scenario? pp. 89-92 *in* Wadati Conference on Global Change and the Polar Climate. Tsukuba Science City, Japan.

United States Environmental Protection Agency. 1995. Ecological impacts from climate change: An economic analysis of freshwater recreational fishing. U.S. EPA, Washington D.C.

Varley, J.D. and P. Schullery. 1991. Reality and opportunity in the Yellowstone fires of 1988. Pp105-121 *in* The Greater Yellowstone Ecosystem: Redefining America's Wilderness Heritage (Keiter, R.B. and M.S. Boyce, eds.). Yale University Press, New Haven.

Veit, R.R., P. Pyle and J.A. McGowan. 1996. Ocean warming and long-term change in pelagic bird abundance within the California current system. *Marine Ecology Progress Series* 139: 11-18.

Veit, R.R., J.A. McGowan, D.G. Ainsley, T.R. Wahls and P. Pyle. 1997. Apex marine predator declines ninety percent in association with changing oceanic climate. *Global Change Biology* 3: 23-28.

Vitousek, P. M. 1990. Biological invasions and ecosystem processes: towards an integration of population biology and ecosystem studies. *Oikos* 57:7-13.

Vose, J., B.D. Clinton, and W.T. Swank, 1993. Fire, drought, and forest management influences on pine/hardwood ecosystems in the southern Appalachians. Pp. 232-238 *in* Proceedings of the 12th International Conference on Fire and Forest Meteorology. Society of American Foresters, Bethesda, MD.

Wedeles, C. H. R., and Van Damme, L. 1995. Effects of clear-cutting and alternative silvicultural systems on wildlife in Ontario's boreal mixedwoods. NODA/NFP Technical Report TR-19, Northern Forestry Program, Ministry of Natural Resources, Ontario.

Weller, G., A. Lynch, T. Osterkamp and G. Wendler. 1995. Climate change and its effects on the physical environment of Alaska. Pp 5-13 *in* Proceedings - Preparing for an uncertain future: Impacts of short- and long-term climate change on Alaska. The Center for Global Change and Arctic System Research, Anchorage.

Wenzel, G.W. 1995. Warming the Arctic: Environmentalism and Canadian Inuit. Pp 169-184 *in* Human Ecology and Climate Change: People and Resources of the Far North (D.L. Peterson and D.R. Johnson, Eds). Taylor and Francis, Washington D.C.

West, P.C. 1995. Global Warming, protected areas and the right to live off the land. Pp 281-287 *in* Human Ecology and Climate Change: People and Resources of the Far North (D.L. Peterson and D.R. Johnson, Eds). Taylor and Francis, Washington D.C.

- White, J.D. and S.W. Running. 1994. Testing scale dependent assumptions in regional ecosystem simulations. *Journal of Vegetation Science* 5:687-702.
- White, J.D., S.W. Running, P.E. Thornton, R.E. Keane, K.C. Ryan, D.B. Fagre and C.H. Key. In press. Assessing regional ecosystem simulations of carbon and water budgets for climate change research at Glacier National Park, U.S.A. *Ecological Applications*.
- White, R. G., and J. Trudell. 1980. Habitat preference and forage consumption by reindeer and caribou near Atkasook, Alaska. *Arctic and Alpine Research* 12:511-529.
- Whitmore, T.C. In press. Potential impacts of climatic change on tropical rain forest seedlings and forest regeneration. *Climatic Change*.
- Wiens, J.A. and A.H. Farmer. In press. Population and community energetics. *in* Avian energetics. (C. Carey, ed.). Chapman and Hall, Inc.
- Zolbrod, A.N., and D.L. Peterson. In Press. The effects of climate change on high elevation forests of the Olympic Mountains, Washington, U.S.A.
- Zullo, V., T. Agardy and A. Markham. 1995. WWF rapid assessment mission to the U.S. Virgin Islands. Unpublished report, World Wildlife Fund, Washington D.C.
- Wotton, B.M. and M.D. Flannigan, 1993. Length of fire season in a changing climate. *The Forestry Chronicle* 69:187-192.

North American Parks

national park boundaries provide no barrier to climate change

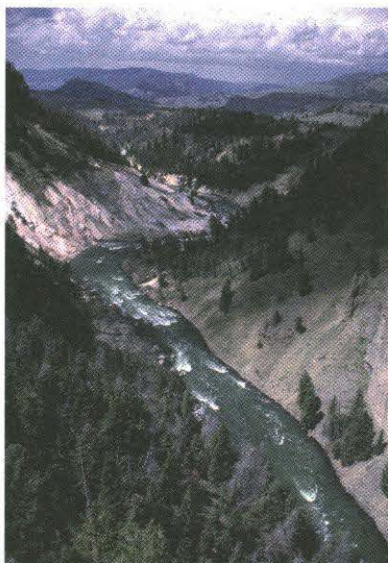
BY ADAM MARKHAM AND JAY MALCOLM



Many of North America's most treasured national parks are now at risk from global warming. A new analysis carried out by World Wildlife Fund (WWF) examines potential threats from climate change and leaves no doubt that national parks and protected areas in many states now face serious ecosystem damage and even the extinction of some protected species.

A New Invisible Danger

In 1872, when Congress turned two million western acres into Yellowstone, the world's first national park, it was envisioned that this great wilderness would last forever. Now, Yellowstone, like many other national parks and protected areas, is becoming an island of nature isolated in a sea of suburban and agricultural development. Worse yet, wonderful spaces like Yellowstone are facing the new threat of global warming.



yellowstone

Park boundaries cannot protect the habitats and species within them from the invisible and insidious threat posed by global climate change. More than 2,500 of the world's top scientists are in agreement that the Earth's atmosphere is already warming up because of air pollution from the burning of coal, oil, and gas by power stations and automobiles.

Global warming is changing and destabilizing world weather patterns, causing sea levels to rise, and creating an unprecedented new environmental threat. The current warming trend is faster than at any time in the past 10,000 years, and the 10 hottest years on record have occurred in the last two decades. This rapid climate change threatens national parks, national wildlife refuges, national seashores, and wilderness areas throughout the U.S. and Canada.

Parks At Risk

A new WWF study reveals that mountain protected areas, as well as those in the Great Plains and in the Arctic are the most vulnerable to global warming. The

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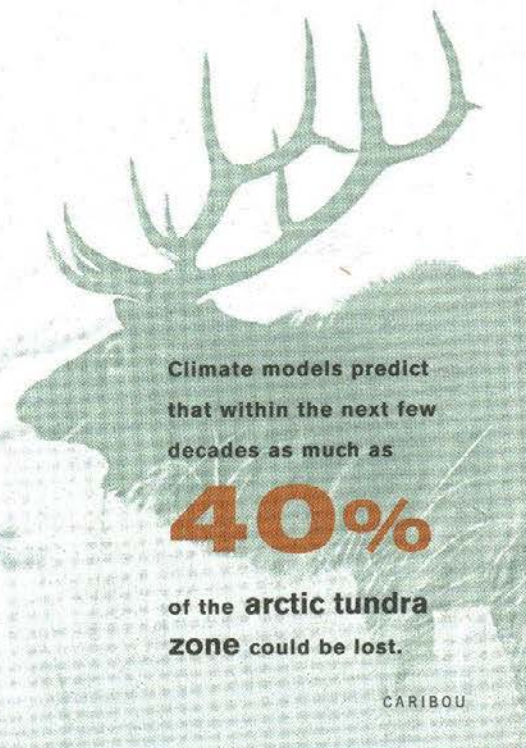
and other energy use.

report identifies Yellowstone, California's Yosemite, Florida's Everglades, Hawaii's Haleakala, Theodore Roosevelt National Park in North Dakota, the Arctic National Wildlife Refuge and Canada's Ellesmere Island, among many others, as particularly under threat.

North America's national parks are the jewels in a splendid conservation crown. From the tropical delights of the Florida Everglades to the high Arctic wilderness of Canada's Ellesmere Island, national parks are meant to be preserved forever for everyone to enjoy. National parks in the United States and Canada are famous throughout the world, attracting millions of visitors and helping to preserve this continent's incredible natural bounty of wild species and wild places.

A grizzly bear and her cubs emerging from Yellowstone's morning mists to frolic

in a mountain meadow; the sun rising over the tropical forests of Hawaii's Haleakala National Park; the stunning fall colors of the maple, birch, and beech forest comprising Quebec's La Mauricie National Park; the startling tints of bright, darting fish swimming among the under-sea corals of the Virgin Islands National Park — these are just some of the sights that make our national parks and protected areas of such value to us. Yet all of these spectacles now face the added peril of global warming.

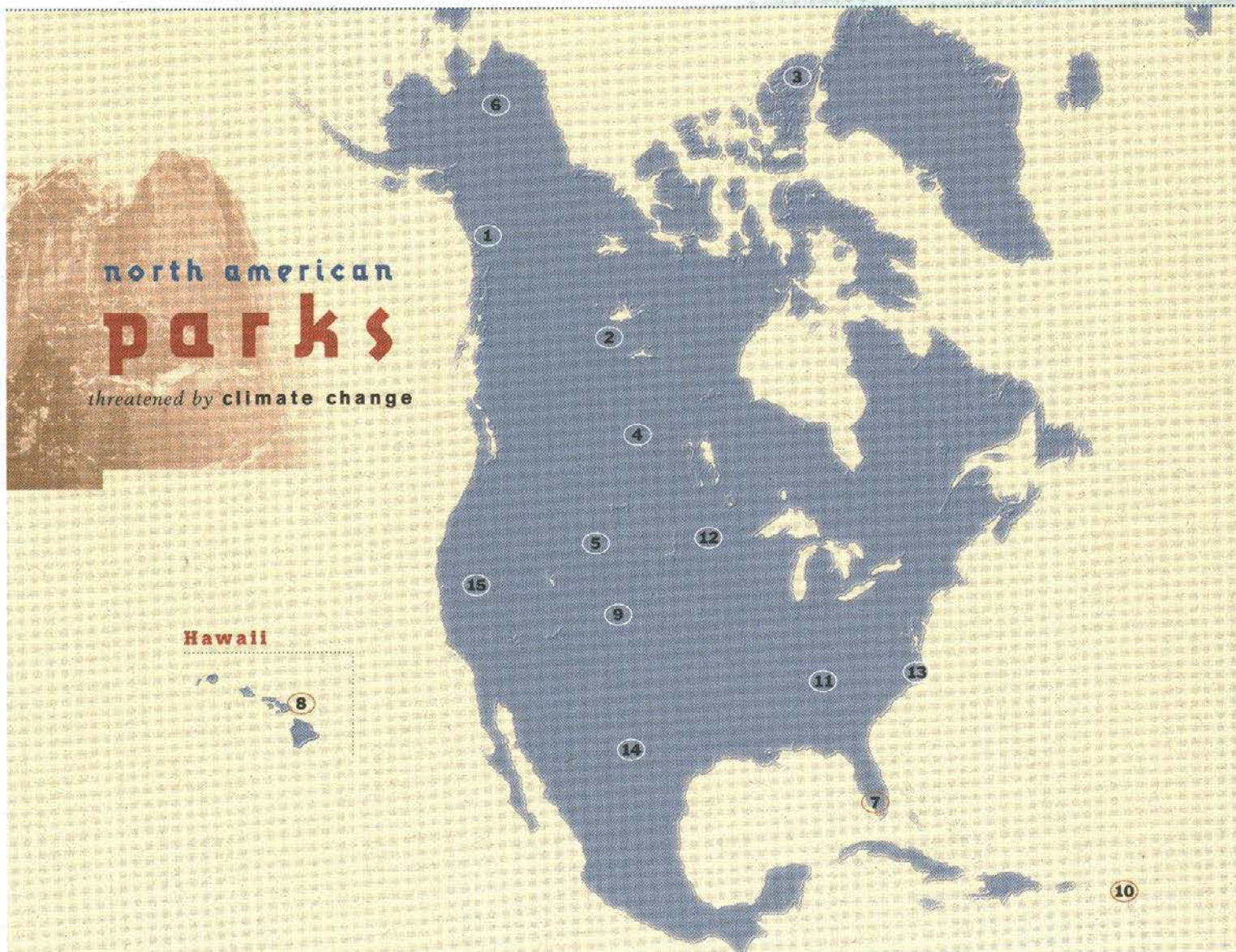


Climate models predict that within the next few decades as much as

40%

of the **arctic tundra zone** could be lost.

CARIBOU



Latest Facts Reveal Disturbing Trends

Physical evidence of this peril can be seen in the way glaciers the world over are beginning to recede at alarming rates. Neither Glacier Bay National Park in Alaska nor Glacier National Park in Montana have been immune to this trend. Perhaps even more alarming is the widespread melting of the permafrost (permanently frozen ground) that underlies the tundra in the most northerly latitudes. (Tundra is a treeless area located between the ice cap and the northern tree line of the Arctic region.) Climate models predict that within the next few decades

as much as 40 percent of the tundra zone could be lost as permafrost melts and southern tree species, like the aspen, are able to grow farther north and invade areas that were previously too cold for their survival. Already, significant melting of the permafrost has been recorded at Denali National Park in Alaska and threatens many areas that are essential habitats for vast caribou (reindeer) herds including the Arctic National Wildlife Refuge.

Climate change also is affecting the oceans. Sea levels are rising in many parts of the world as a result of warmer waters and the melting of glaciers and snow pack. Many important wildlife areas in the United States are at risk, and in some the effects can already be seen. Blackwater National Wildlife Refuge, a critical site for the Chesapeake Bay's bald eagle population and many species of wildfowl, has already lost so much land to permanent flooding as a result of sea-level rise that scientists and conservation managers predict the refuge may have only a few useful decades left. Coastal flooding and erosion are likely to have particularly severe impact on Florida's Everglades, the Chincoteague National Wildlife Refuge in Maryland and Virginia, Cape Hatteras in North Carolina, the Gulf Islands National Seashore of Alabama and Mississippi, and Padre Island National Seashore in Texas.

Where evidence of the recent warming of the seas is strongest, as in the California Current that runs along the West Coast as far as southern Alaska, alarming ecological changes have occurred. Strong

declines in marine plankton have been linked to the warming trend, and the effects of this have moved up the food chain. For example, the albatross-like sooty shearwater, a seabird that migrates annually from the Antarctic to the North Pacific, has experienced a 90 percent decline in population in the past 20 years. The shearwaters normally can be seen off places such as California's Point Reyes National Seashore and Channel Islands National Park at different times of the year, but recent surveys show more than four million birds have disappeared.



ELLESMERE ISLAND NATIONAL PARK
NORTHWEST TERRITORIES



EVERGLADES NATIONAL PARK
FLORIDA

CANADA

- ① Kluane National Park, Yukon Territory
- ② Wood Buffalo National Park, Alberta
- ③ Ellesmere Island Nat'l Park, N.W. Territories
- ④ Prince Albert National Park, Saskatchewan

USA

- ⑤ Yellowstone National Park, Wyoming
- ⑥ Arctic National Wildlife Refuge
- ⑦ Everglades National Park, Florida
- ⑧ Haleakala National Park, Hawaii
- ⑨ Rocky Mountain National Park, Colorado
- ⑩ Virgin Islands Nat'l Park, Virgin Islands
- ⑪ Great Smoky Mountains Nat'l Park, Tennessee
- ⑫ Theodore Roosevelt Nat'l Park, N. Dakota
- ⑬ Cape Hatteras Nat'l Seashore, N. Carolina
- ⑭ Big Bend National Park, Texas
- ⑮ Yosemite National Park, California

A grizzly bear
and her cub emerging from
Yellowstone's morning mists to
frolic in a mountain meadow now
threatened by climate change.



Increased Risk of Wildfires

Scientists suggest that the increased risk of wildfire in Yellowstone National Park seems to be related to a warming and drying trend in recent decades. The same is almost certainly true in Colorado's Rocky Mountain National Park, Yosemite, and several other fire-prone parks such as Jasper and Banff in Canada. The warmer, drier scenario is also predicted to reduce whitebark pine and alpine habitats in Yellowstone, causing stress to species such as the grizzly bear, the rosy finch, and the arctic gentian flower. New research shows that the unique fraser fir and red spruce forest of the Great Smoky Mountains National Park is likely to be wiped out by global warming. The Smokies also would lose rare brook trout, salamanders and several species of alpine plant. In Washington's Olympic National Park and Mount Rainier, the warming trend appears to already be causing changes in the mountain wildflower meadows.

The Final Straw

Many national parks and protected areas are already under tremendous pressure from environmental problems such as



encroaching development, overcrowding with cars and visitors, and water and air pollution. The additional stress of climate change may be enough to tip the balance and cause serious damage to ecosystems and the extinction of some of the species these magnificent parks were set up to protect.

WWF believes that it is critical that the governments of the United States and Canada take a leadership role in the ongoing international negotiations to curb greenhouse gas emissions. Major reductions of carbon dioxide emissions by the year 2005 are needed. In addition to pre-

venting atmospheric pollution, it is essential that we act now and invest more in conserving our last remaining wildernesses. Better management of the areas surrounding parks, greater connectivity of habitat areas between them, and reduction of existing environmental threats such as habitat fragmentation, wetland drainage, and road building may help our national parks and protected areas to withstand some of the coming climate changes. It is paramount, however, that we try to prevent further increase in the rate of warming by reducing greenhouse gas emissions.



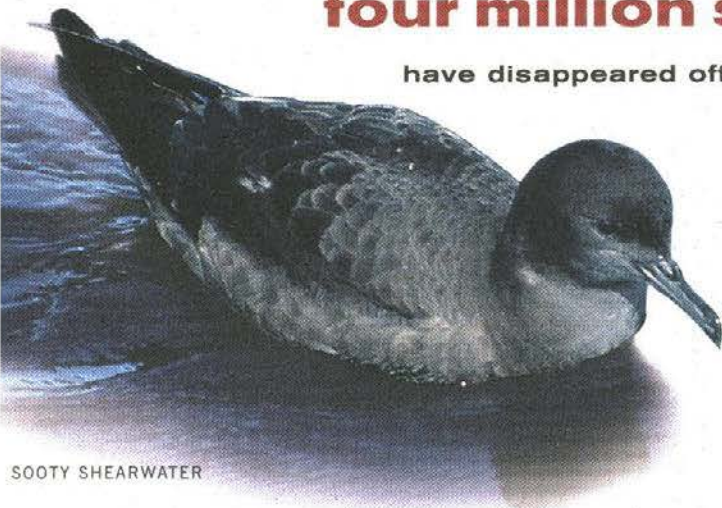
WWF leads international efforts to protect the diversity of life on Earth. The WWF Climate Change Campaign is working in over 25 countries to raise awareness of the threats of climate change to wildlife and natural ecosystems, pressure governments into taking action to prevent climate change, and to build partnerships with business and industry to find solutions to the problem.

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Recent surveys show more than
four million seabirds
have disappeared off the West Coast.



SOOTY SHEARWATER

To find out more about how climate change will affect the national parks and national wildlife refuges in your area go to WWF's new interactive parks web site. You can access it through the WWF US web site.



<http://www.worldwildlife.org>

*The National Science Foundation
invites you to a reception
immediately following this event
in the Indian Treaty Room*

