Global Climate Change and Wildlife in North America

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Foreword

Presidents of The Wildlife Society occasionally appoint ad hoc committees to study and report on select conservation issues. The reports ordinarily appear as either a Technical Review or a Position Statement. Review papers present technical information and the views of the appointed committee members, but not necessarily the views of their employers. Position statements are based on the review papers, and the preliminary versions are published in *The Wildlifer* for comment by Society members. Following the comment period, revision, and Council's approval, the statements are published as official positions of The Wildlife Society.

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It is not the strongest
of the species that survive,
nor the most intelligent,
but the most responsive
to change.

—*Charles Darwin (1835)*

SYNOPSIS

It is widely accepted by the scientific community that the earth, which has always experienced climate variation, is now undergoing a period of rapid climate change that is enhanced by anthropogenic atmospheric carbon enrichment during the past 100 years. These climatic changes are accelerating and projections for the next 100 years indicate extensive warming in most (but not all) areas, changing patterns of precipitation, and a significant acceleration of sea level rise. Other likely components of ongoing climate change include changes in season lengths, decreasing range of nighttime versus daytime temperatures, declining snowpack, and increasing frequency and intensity of severe weather events. The many components of climate change, and especially the unprecedented rapid rate of change, are just as important as increasing temperatures.

Wildlife species are closely adapted to their environments and readily respond to climate variation. However, as discussed in this technical review, the climate change now underway has extensive potential to affect wildlife throughout North America, either directly or indirectly through responses to changing habitat conditions. When considered in combination with other factors (e.g., pollution, ozone depletion, urbanization, etc.), the potential effect is even greater. The effects of climate change on populations and range distributions of wildlife are expected to be species specific and highly variable, with some effects considered negative and others considered positive. In North America the ranges of habitats and wildlife are predicted to generally move northward as temperatures increase. Variations in this overall pattern will be dependent upon specific local conditions, changing precipitation patterns, and the response of different species to different components of climate change. It follows that the structure of plant–animal communities will also change.

Ignoring climate change is likely to increasingly result in failure to reach wildlife management objectives. Wildlife managers need to become knowledgeable about climate change, ways to cope with it, and ways to take advantage of it. Management options currently available include protecting coastal wetlands to allow for sea level rise, reducing the risks to wildlife from potential catastrophic events, adjusting yield and harvest models, accounting for known climatic variations, and taking climate change into consideration when selecting the location and other characteristics of conservation areas. Wildlife managers also need to expect the unexpected and reduce nonclimate stressors on ecosystems. Overall, wildlife managers can minimize negative impacts to wildlife and take advantage of positive aspects by planning ahead and employing adaptive management.

INTRODUCTION

Society values North America's fish and wildlife and the habitats they require. The benefits that wildlife and their habitats provide to humans include food, fiber, medicines, ecosystem stability, spirituality, recreation, a source of income and jobs, and much more. Accordingly, citizens have created many state and federal laws to conserve wildlife and have charged wildlife management professionals with maintaining and restoring wildlife populations and their habitats.

Wildlife professionals, and society as a whole, are challenged by the need to accommodate the growing human population, which has affected wildlife in many ways. The loss of wildlife habitat to urban sprawl, agriculture, and industrial development is readily apparent in North America. Other significant anthropogenic impacts to wildlife occur from air and water pollution, ozone depletion, exotic species, disease, and many other factors. These challenges have existed for some time, we are familiar with them, and we are learning how to cope with them.

The Intergovernmental Panel on Climate Change (IPCC), a team of leading scientists from throughout the world sponsored by the United Nations, has concluded that in the past two decades climate research has definitively shown that large-scale worldwide changes in climate, enhanced by anthropogenic sources, have occurred and will continue to occur for decades (IPCC 1996, 2001*c,d*). These findings, corroborated by the National Research Council (2001) of the National Academy of Sciences, present new challenges for wildlife conservation, as well as for society as a whole. Biodiversity has already been affected by recent climate change and projected climate change for the 21st century is expected to affect all aspects of biodiversity (IPCC 2002).

This technical review first describes climate changes underway, including how markedly different they are from historical climate variability due to the magnitude of change over a short period of time. We review the wildlife research providing evidence of climate change effects on wildlife and wildlife habitats and describe possible major habitat changes in North America, including likely effects on wildlife species. In particular, we highlight known and probable effects on amphibians, waterfowl, Neotropical migrant birds, and caribou. These examples demonstrate that the effects of global climate change and variability on wildlife simply cannot be ignored.

Although the challenges of global climate change to our natural ecosystems are great, there are actions that wildlife managers can take to minimize negative effects on wildlife

and their habitats, as well as make best use of positive changes for wildlife and their habitats. We conclude with recommended actions for wildlife managers and government agencies to account for climate change and variability when conserving our wildlife heritage.

CLIMATES ARE CHANGING

Natural Climate Variation

Variability is a natural part of the climate system and has occurred throughout earth's history, long before humans had any role in changing the climate. Driven by complex interactions among the earth's solar orbit, atmospheric CO_2 concentrations, continental ice sheets, ocean circulation (Imbrie et al. 1992, 1993), and other factors, climate variation is evident on many different scales and has many different patterns.

Currently, the earth is in an interglacial period that began approximately 14,000 years ago. During the last glacial maximum, just 21,000 years ago, ice advanced so far south that temperatures were over 10°C colder in northern parts of the U.S. (Thompson et al. 1993, Webb et al. 1993, IPCC 2001*b*) and 5°C colder near the equator (Guilderson et al. 1994, Colinvaux et al. 1996). Within the most recent glacial period (74,000 to 14,000 years bp), the earth experienced 1500-year cold–warm cycles, resulting in temperature fluctuations up to 5°C (Bond et al. 1993, IPCC 2001*b*).

On shorter cycles of several years to several decades there are more familiar weather phenomena such as the El Niño–Southern Oscillation that has a period of 2–7 years. The warm phase (El Niño) causes cooler and wetter conditions in the southeastern U.S. (although fewer Atlantic hurricanes), warmer temperatures in northwestern and northeastern North America (Glantz 1996), drier conditions in the Pacific Northwest, and wetter conditions in Alaska and California. The cool phase (La Niña) has opposite effects (NAST 2001). Recent patterns have suggested a tendency toward more El Niño events and fewer La Niña events (Trenberth and Hoar 1997).

Other documented cycles of climate variability are the Pacific Decadal Oscillation, affecting western North America and the North Atlantic Oscillation, affecting the eastern U.S. These events cycle over several decades, affecting both temperature and rainfall (Hurrell 1995, Thompson and Wallace 1998).

The Past 100 Years

Despite the enormous complexities of climate, significant changes in climate in the past 100 years have been documented (Table 1). Warming during the 20th century (Mann et al. 1998, 1999) has resulted in the warmest period during the past 1000 years, with global surface temperatures increasing by 0.6°C (IPCC 2001*a,e*). The warming is manifested in many ways. Nighttime temperatures have increased more than daytime temperatures (thereby decreasing the diurnal range) (Karl et al. 1991), and land surface temperatures have warmed more than sea surface temperatures. Since the 1950s, there have been fewer days of extreme low temperatures and more days of extreme high temperatures in the U.S. (Karl et al. 1996). From 1976 to 2000, most parts of North America have warmed, with only a few exceptions along coastal Alaska and the eastern Canadian Arctic. Other parts of high-latitude Canada have exhibited as much as 1°C/decade warming, consistent with the trend of greater warming at higher latitudes. Warming is more pronounced during winter than summer. During the entire 20th century, only the period from 1946 to 1976 exhibited a cooling trend (IPCC 2001*b*). Rising temperatures have reduced snow cover, mountain glaciers, and Arctic sea ice. Sea level rise resulting from thermal expansion of the ocean and freshwater input was 0.1–0.2 m for the 20th century (IPCC 2001*a*).

This warming is at least partly the result of an enhanced greenhouse effect (IPCC 2001*c,d*). The greenhouse effect occurs when atmospheric gases such as carbon dioxide (CO_2), water (H_2O), methane (CH_4), and nitrous oxide (N_2O) absorb infrared radiation emitted by the earth and, as a result, emit some infrared radiation back toward the surface of the earth. The greenhouse effect is a natural

Table 1. Changes in general climate trends in North America during the past 100 years.

Climate factor Trend
Temperature
Global surface temperature increases
Increase in nighttime low temperatures
Greater warming on land than on water
Greater warming at higher latitudes
Fewer days of extreme low temperatures
More days of extreme high temperatures
Greater warming in winter than in summer
Precipitation
Increased frequency of precipitation events
Increased intensity of extreme precipitation events
More areas with increased precipitation than decreased
Other climate factors
Increased cloud cover
Sea level rise
Reduced snow cover
Receding glaciers
Thinner and less areal coverage of Arctic sea ice

phenomenon that maintains livable temperature on the earth. However, there has been an approximate one-third increase in atmospheric CO_2 concentrations since the beginning of the Industrial Revolution, and essentially all of that increase is attributable to fossil fuel burning (IPCC 2001*a,* National Research Council 2001).

Increased levels of CO_2 also lead to important positive feedbacks that further increase the warming, such as increased atmospheric water vapor and reduced sea ice in the Arctic. Carbon dioxide levels have increased as much since the 1860s as they did for a period of 10,000 years after the most recent advance of glaciers. This rapid rate of change is unprecedented in the earth's recent history.

In addition to fossil fuel emissions, land-use changes (especially tropical deforestation) contribute to global warming (Pielke et al. 2002). This contribution is a direct effect of changing albedo (reflected light) and evapotranspiration on the climate system, as well as other factors (see Houghton et al. 1999).

During the 20th century precipitation has increased by 0.5%–1% per decade in the mid- to high latitudes of the Northern Hemisphere, although it decreased by 0.3% per decade in the Northern Hemisphere subtropics. Heavy precipitation events have increased by 2%–4% and cloud cover has increased by 2% (which is the cause of the decrease in diurnal temperature range) in mid- to high latitudes of the Northern Hemisphere (IPCC 2001*b*). In North America, precipitation increased in most areas from 1976 to 1999. During the 20th century these increases in the U.S. resulted from increased intensity of extreme precipitation events (Karl and Knight 1998). Although some regions of the U.S. have experienced increased droughts (in part due to increased evaporation), a greater portion of the U.S. has most recently experienced increasing moisture (Karl et al. 1996).

The IPCC (2001*d*:4) concluded that "the earth's climate system has demonstrably changed on both global and regional scales since the pre-Industrial era, with some of these changes attributable to human activities." They specifically state "there is new and stronger evidence that most of the warming observed over the past 50 years is attributable to human activities" (IPCC 2001*d*:5) and that "changes in sea level, snow cover, ice extent, and precipitation are consistent with a warming climate near the earth's surface" (IPCC 2001*d*:6).

The Next 100 Years

The IPCC (2001*d*:8) concludes "carbon dioxide concentrations, globally averaged surface temperature, and sea level are projected to increase under all IPCC emissions scenarios during the 21st century" and "an increase in climate variability and some extreme events is projected" (IPCC 2001*d*:14).

Complex computer climate models have been developed, incorporating factors such as atmospheric gas concentrations, ocean effects, the cryosphere (snow cover and sea ice), land surface, solar variability, and elements of the biosphere (e.g., vegetation and soils). Founded on the equations of motion and the laws of thermodynamics, these models are able to reproduce large-scale present-day climatic patterns and are used to project future climatic variations. These models can help identify likely climatic changes based on various emission levels of greenhouse gases.

Although climate is impossible to accurately predict, the comparison of various climate models and extensive analysis has led to some generally accepted climate projections for the next 100 years. (Some of the major climate modeling centers include the United Kingdom's Hadley Center for Climate Prediction and Research, Germany's Max Planck Institute/Das Deutsche Klimarechenzentrum, the U.S. National Center for Atmospheric Research, Geophysical Fluid Dynamics Laboratory, Goddard Institute for Space Studies, and the Canadian Centre for Climate Modelling and Analysis.) Two widely used future global scenarios project warming throughout all of North America (Figure 1), with most warming occurring during the Arctic winter and greater than average warming occurring throughout the U.S. and Canada. In North America, only Mexico shows an inconsistent level of warming. Modeling projects 1.4–5.8°C warming from 1990 to 2100, which is 2–10 times greater than observed warming during the 20th century. Globally, warming is expected to produce sea level rise of 0.09 to 0.88 m by 2100 (IPCC 2001*a,d*) compared to 0.1–0.2 m recorded for the 20th century (IPCC 2001*a*).

There is greater variability among models for projected precipitation changes (Figure 2). However, there is general agreement on increased precipitation in northern Canada and Alaska. There is also some consistency for small increases in precipitation during the winter months in the eastern and western U.S. and for reduced precipitation in Mexico. But significant regions, including the U.S. Great Plains and summer precipitation throughout the U.S., show no consistent patterns of projected change.

Potentially more important for ecosystems and wildlife than mean climate change are changes in variability and extremes. Model projections (Table 1) include more hot extremes and fewer cold extremes, reduced diurnal temperature ranges as nighttime temperatures rise more than daytime temperatures, and increased heat indices (a measure

of temperature and humidity intended to describe the discomfort level felt by humans).

Model projections include increased intensity of extreme precipitation events and more summer droughts. There may be fewer (but more intense) extratropical storms due to reduced pole-to-equator temperature gradients (Carnell and Senior 1998), although there are no current trends to support this conclusion (Hayden 1999). Tropical cyclones will likely be more intense. However, if the trend toward increased El Niño events continues (Trenberth and Hoar 1997), Atlantic hurricanes would be less frequent (Bengtsson et al. 1996). Other changes in phases of the North Atlantic Oscillation and Pacific Decadal Oscillation may also bring significant changes to the climate of particular regions of North America, but there are not yet reliable model estimates of this type of variability.

Climate and Wildlife

The complexities of climate change described above are likely to affect wildlife and ecosystems in equally complex ways, and vary tremendously. For example, increased nighttime temperatures could markedly influence range patterns of species with life histories especially influenced by ice cover, or other species that require certain minimum temperatures to induce key physiological changes (seed germination, for example). These same species could be largely unaffected by increased daytime temperatures.

It is certain that various wildlife species and ecosystems will be affected by changes to both the mean and variable state of the climate system and the rapid rate of these projected changes in the coming century. The IPCC (2001*d*:9) notes that "projected climate change will have beneficial and adverse effects on both environmental and socioeconomic systems, but the larger the changes and rate of change in climate, the more the adverse effects predominate." Further, "adaptation has the potential to reduce adverse effects of climate change and can often produce immediate ancillary benefits, but will not prevent all damages" (IPCC 2001*d*:12).

HABITATS AND WILDLIFE

In response to projected climate changes in the next 100 years, the geographic ranges of North American flora and fauna are expected to shift upwards in elevation and northward (IPCC 2002). Temperature, rainfall, soil moisture, and the specific physiological requirements of each species are expected to be driving forces in these shifts. Overall, range shifts in plants are likely to depend upon factors such as soil types, migratory pathways, seed dispersal mechanisms, and pollinator availability. Range shifts of wildlife are likely to depend upon factors such as the availability of migration corridors, suitable habitats, and the concurrent movement of forage and prey. Further complicating potential range shifts will be other landscape changes such as roads, cities, and habitat fragmentation, all of which can present significant barriers to species range shifts.

As temperature and rainfall patterns change, some species will likely benefit and some will likely decline. However, precise predictions of ecological change are not possible due to the scale and accuracy of current climate models. Predicting effects on plants and animals is further confounded by a lack of information concerning species-level response, interactions among biotic and abiotic components of ecosystems, and uncertainties related to nonclimate stresses on ecosystems. Climate effects are sometimes difficult to distinguish from the more striking effects of human development. Nonetheless and as discussed in this technical review, there is sufficient evidence to indicate that many species have responded to climate change of the past 100 years. In a review of published studies, Root et al. (2003) concluded that animals and plants are already exhibiting discernible range changes consistent with changing temperatures.

Individual physiological responses of plant and animal species to temperature and moisture make it unlikely that species will respond in the same manner to climate change. This diverse response by species could cause significant restructuring of existing plant and animal communities. For example, changing climate could decouple population cycles of eastern spruce budworm (*Choristoneura fumiferana*) and its parasitoid and avian predators (Mattson and Haack 1987, Price 2002). In the absence of significant mortality factors, budworm populations could become epidemic, causing large-scale ecosystem change through extensive spruce mortality.

The difficulties inherent in projecting a single species change, let alone the many species in an ecosystem, makes projecting community restructuring very challenging. However, modeling of potential ecosystem shifts based on best available climate change projections and the physiological requirements of existing ecosystems is useful. Simulation of vegetation response to future climatic change suggests major changes in the geography of existing biomes (Figure 3). Some generalizations can be made regarding major shifts in habitats. For example, the range of dominant southeastern pine and hardwood species is projected to expand northward (NAST 2000). In addition, the conifer forests of the New England states and much of the northeastern mixed forests are expected to gradually change to a temperate deciduous forest similar to that found today in

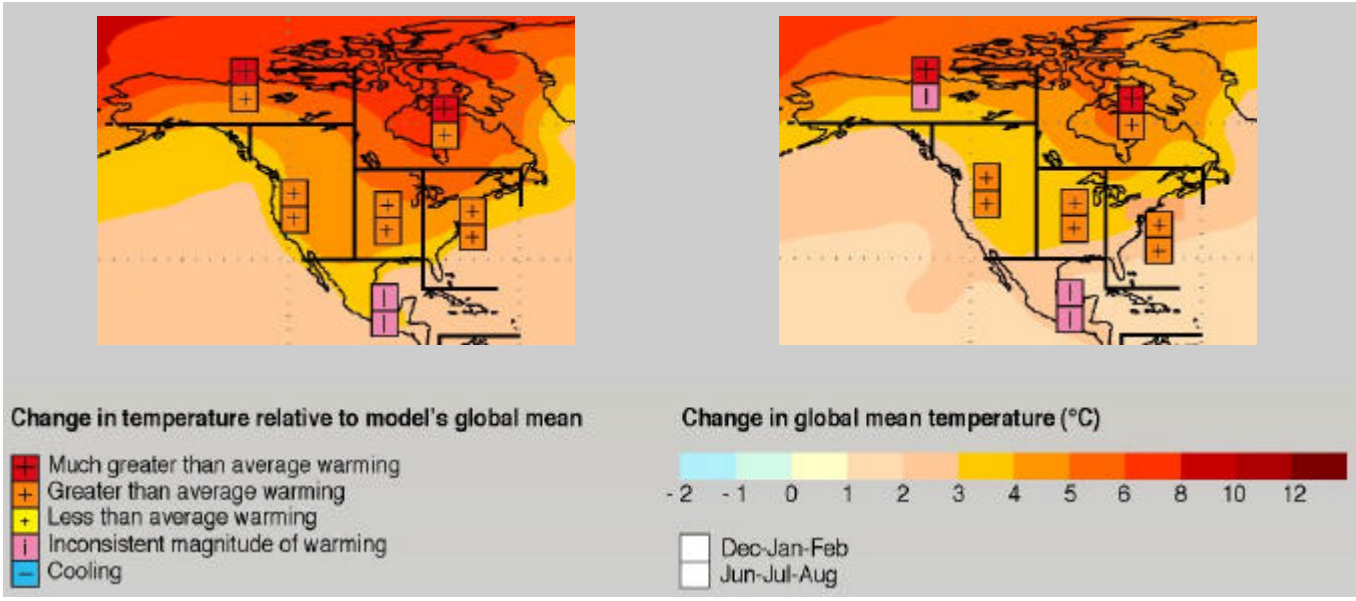

Figure 1. Possible changes in temperatures in North America during the next 100 years. Each of the two different but widely used future scenarios is derived from the results of nine different climate models (modified and reprinted with permission from IPCC 2001*c*).

southeastern Pennsylvania and northern Virginia. Some forest species such as sugar maple (*Acer saccharum*) are projected to disappear entirely from the United States over the next century (NAST 2000). North American biogeography models consistently project that the northern edge of the boreal forest in Canada and Alaska could advance into the present tundra region (Parson 2001).

Some of the most well understood mechanisms and effects of climate change on habitats and wildlife species are described below. Our intent in describing both known and possible influences of climate change on habitat and wildlife is not to provide specific management information, but instead to reveal the extreme complexities involved in climate change and the many different mechanisms by which climate change could influence habitats and wildlife. The fact that species are and will continue to be affected by climate change is evident.

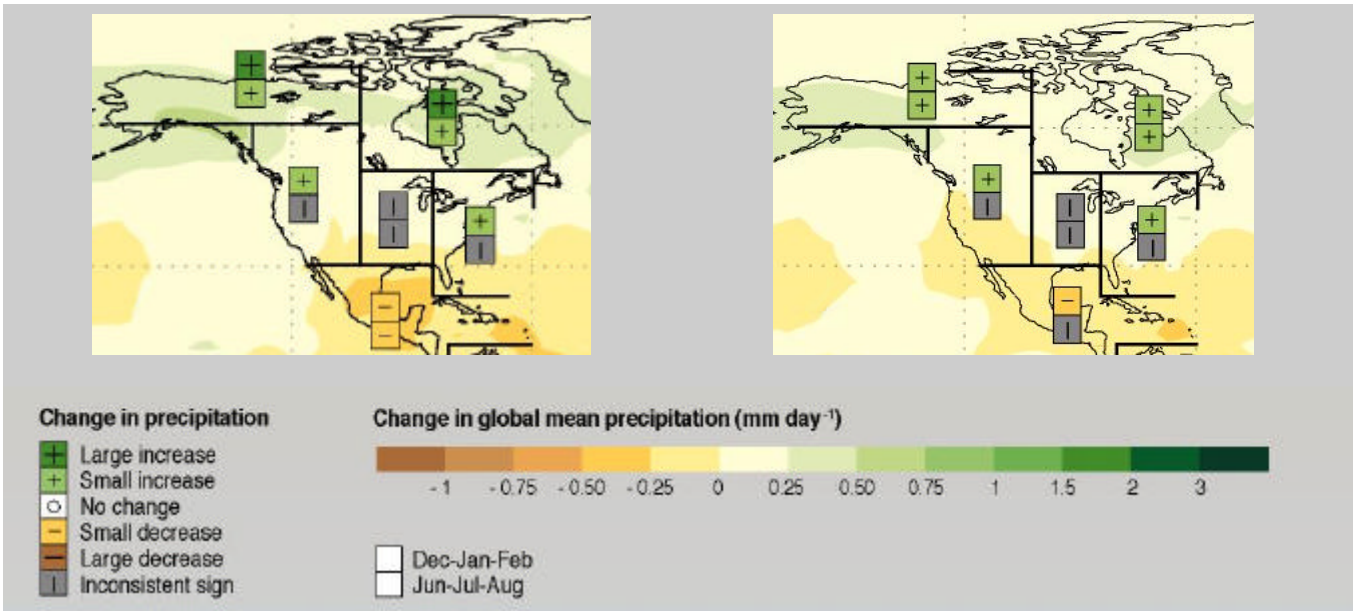

Figure 2. Possible changes in precipitation in North America during the next 100 years. Each of the two different but widely used future scenarios is derived from the results of nine different climate models (modified and reprinted with permission from IPCC 2001*c*).

Changes in Primary Productivity

Current climate change is complex because it includes simultaneous increases in atmospheric CO_2 and temperature (IPCC 2001*b*, Beier 2004). These two factors are directly involved in regulating biological and chemical processes at scales ranging from the individual to the ecosystem. Atmospheric CO_2 enrichment tends to have a fertilizing effect on agricultural plants by enhancing photosynthesis and water use efficiency (Acock et al. 1985, Nijs et al. 1988, Allen et al. 1989, Rabbinge et al. 1993, IPCC 1996). Growth in woody species is also stimulated by increases in CO_2, but there is a wide range of responses among deciduous and coniferous species (Eamus and Jarvis 1989, Nance 1995). Virtually all plants have a threshold at which further CO_2 enrichment will not continue to increase photosynthesis due to other limiting factors. Despite the potential benefits of CO_2 enrichment, limited soil nutrients and water may offset potential gains in productivity (Lockwood 1999). Temperature, plant pests, air pollution, and light availability can also constrain the potential enhancement of growth by elevated CO_2 (Nance 1995).

Differences in carbon-fixation pathways may explain some differences in species response to CO_2 enrichment. In general, plants that use the C_3 photosynthetic pathway (most trees and shrubs and some grasses and sedges) may be enhanced by atmospheric CO_2 enrichment more than those with C_4 systems (many tallgrass prairie species) (Drake

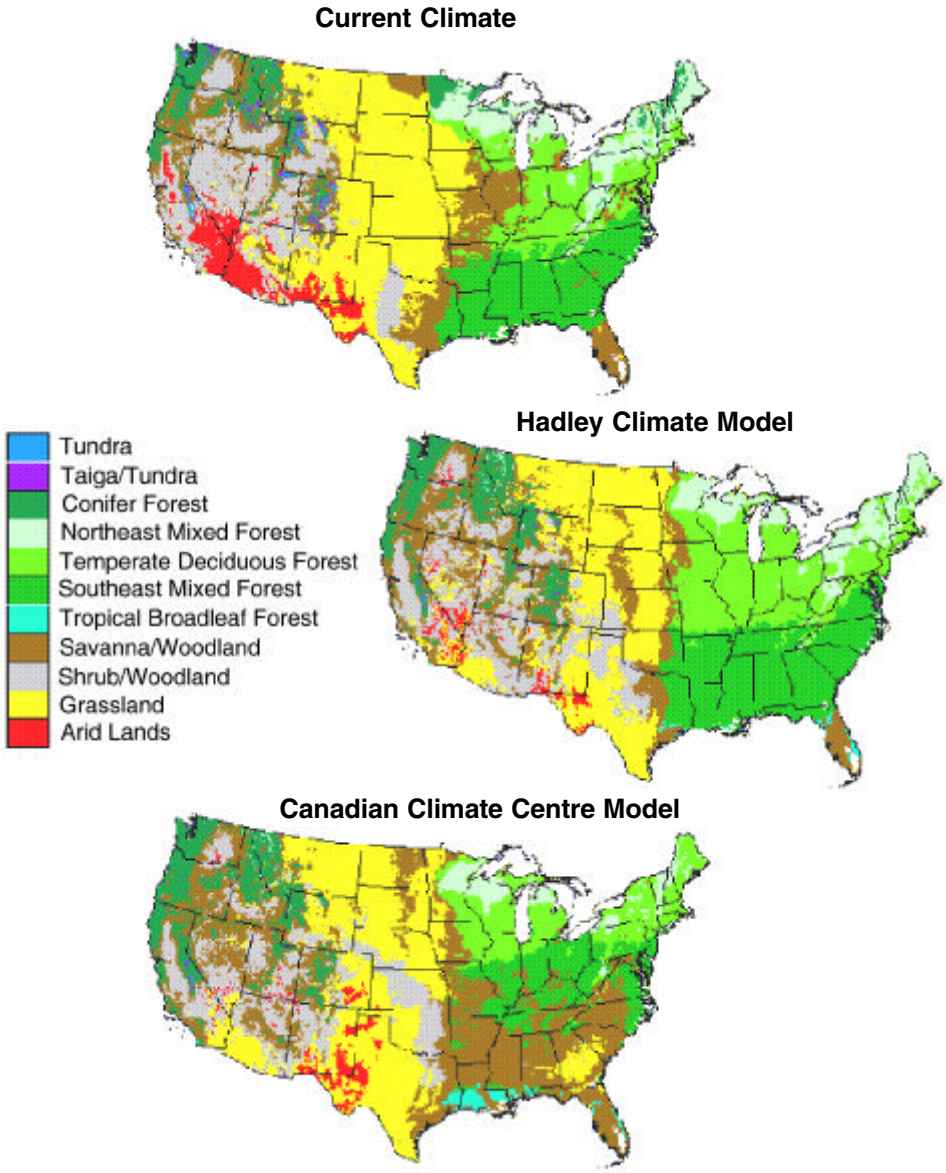

Figure 3. Simulations of vegetation response by 2070–2099 to different climate change models (U.S. Forest Service 2004).

1992, Drake et al. 1996, IPCC 1996, Marsh 1999). Southwestern semidesert rangeland, dominated by C_4 grasses, may benefit less from elevated CO_2 than cooler semidesert rangeland of the Great Plains, dominated by C_3 grasses and C_4 shrubs (IPCC 1996).

Coastal herbivores such as muskrat (*Ondatra zibethicus*) and nutria (*Myocastor coypus,* an invasive exotic species) that preferentially forage upon C_3 sedges may be favored more than wildlife species that depend upon C_4 marsh grasses. This example demonstrates the potential for differential photosynthetic responses to elevated CO_2 among plant species to alter plant community productivity and structure and subsequently relationships among species at higher trophic levels.

Net photosynthesis also usually increases with rising temperature up to a threshold temperature level at which it begins to decline rapidly (Kramer and Koslowski 1979). For this reason, most ecosystem climate models suggest a general increase in ecosystem productivity in North America in areas where rainfall is not expected to decline. However, species assemblages and plant-community dynamics will likely change.

Both of the primary models used to project climate changes in North America (NAST 2001) suggest minimum temperatures will increase significantly in all major regions over the next 100 years. Increased temperatures would expand the growing season across North America, most significantly at higher latitudes where growing-season length is an important limiting factor. Twentieth-century warming increased the average number of growing degree-days by 20% in Alaska (Weller et al. 1999). The cumulative effects of increasing growing-season temperature, decreasing days below freezing, and increased atmospheric CO_2 will likely have a positive effect on net primary productivity and the accumulation of carbon in many plant communities. Increased aboveground biomass increases the potential for wildfires, which can lead to rapid restructuring of ecosystems (VEMAP 1995, NAST 2000).

Changes in Plant Chemical and Nutrient Composition

Atmospheric CO_2 levels influence plant physiology and nutrient content in complex ways (Nowak et al. 2004). Several studies have shown protein content of grains such as wheat and rice decreased as CO_2 levels increased (IPCC 2001*a*), and native herbaceous species consistently had reduced leaf-N content under elevated CO_2 compared to woody species (Nowak et al. 2004). Carbon:nitrogen ratios could increase in many grasses (Gregory et al. 1999). However, elevated CO_2 has been shown to enhance nitrogen uptake in some temperate grassland species (Jones and Jongen 1996, Coughenour and Chen 1997).

The implications for wildlife of these and other changes in plant composition are poorly understood. A large increase in water-soluble carbohydrates of grass species grown under elevated CO_2 levels could lead to faster digestion in ruminants, whereas declines in nitrogen content would reduce the protein value of forage (IPCC 2001*a*).

Changes in Seasonality

Changes in climate can influence the timing and length of seasons, which in turn can have a direct effect on plants and animals. Root and Schneider (2002) summarize evidence from 45 studies that indicate significant changes in the timing of life-cycle events for a wide range of plant and animal species in response to 20th-century climate warming. These changes included trees coming into leaf sooner, grasses and forbs flowering earlier, the abundance of many insects peaking earlier, and some birds and butterflies migrating earlier. Most (80%) of the changes appeared to be linked with species' physiological tolerances.

Differences in responses of species to seasonality can lead to an uncoupling of the migration of birds, for example, with the availability of essential food sources such as invertebrates and plant seeds (Visser et al. 1998). Hellmann (2002) found links between the timing of emergence of bay checkerspot butterfly (*Euphydryas editha bayensis*) larvae and the growth and abundance of two larval host plants (*Plantago erecta* and *Castilleja* spp.). If seasonality changes cause closely interacting species to become out of phase, essential ecological processes such as pollination, seed dispersal, and insect control (by birds) can be disrupted (Price 2002).

Sea Level Rise

Accelerated sea level rise is regarded as one of the most costly and certain consequences of increasing global temperature. Average global sea level rose 10–25 cm during the past 100 years, and is projected to increase 2- to 4-fold in the next 100 years. The midrange estimate of sea level rise by 2100 is 48 cm (IPCC 2001*a*). If sea level rises at the high end of the projected range, thousands of square miles of U.S. coastal land could be inundated. New coastlines further inland may eventually create wildlife habitats if roads, buildings, levees, seawalls, and bulkheads do not impede landward migration of wetlands, barrier shorelines, and wildlife species associated with them.

As seas rise, impacts on coastal landforms could be exacerbated if tropical storm severity increases, as indicated by some climate models (Knutson et al. 1999, Timmerman et al. 1999). Even if storms do not increase in severity, storm surge effects could intensify as sea levels rise and natural coastal defenses deteriorate. Coastal islands could

tend to "roll over" toward the mainland if human activities and changes in storm patterns do not affect this natural landward migration (Burkett 2002, Scavia et al. 2002).

Sea level rise could increase tidal flushing in estuaries and storm surge over coastal landforms. Increased storm surge and mean tide levels could alter disturbance regimes in shallow coastal waters, thereby influencing the composition and productivity of seagrasses and benthic fauna that are vulnerable to changes in sedimentation patterns, current velocity, and turbidity. Both average and peak salinity levels could increase in estuaries and adjacent habitats, thereby altering the zonation of vegetation and other biota. Some wildlife species could be displaced inland or disappear entirely if their low-lying coastal wetlands are rapidly inundated. Sea level rise could also flood many critical mudflats used by migrating shorebirds.

Submergence of coastal marshes is expected to be most severe along the U.S. Gulf and Atlantic coasts. Some coastal marshes and mangrove systems along these coasts are presently accumulating sufficient mineral and/or organic sediment at rates that will likely compensate for predicted increases in the rate of sea level rise. In southern Louisiana, however, approximately 1 million acres of coastal marsh have been converted to open water since 1940 (Burkett et al. 2001). Natural subsidence and a variety of human activities (drainage projects, dredge and fill, groundwater withdrawals, and levee construction on the Mississippi River) have contributed to these losses.

Snow, Permafrost, and Sea Ice Decline

Historical trends and projections of declining snow cover during this century portend many changes in boreal and alpine ecosystems. For example, duration and depth of snow cover are key variables determining the hydrology of alpine wetlands. If air temperatures increase at projected rates, alpine snow cover will likely recede 100–400 m upslope in some alpine regions during the next century (IPCC 1996). Unless precipitation increases, alpine wetlands could disappear. Even small amounts of warming may eliminate some wetland plant and animal species in alpine regions because there is little opportunity to disperse among these isolated habitats (Burkett and Kusler 2000).

As permafrost thaws in alpine areas and Arctic regions, changes in groundwater mobility and increased slumping and flooding may occur, converting forests to grasslands and bogs (Parson 2001). Very little documentation of the effects of permafrost thawing on habitats and wildlife has been published (Vitt et al. 1994), and there is much uncertainty about the fate of present ecosystems that rest on permafrost. In Siberia, where large-scale thawing of ground ice has already occurred, the landscape has been altered through mudslides and formation of flat-bottomed valleys and melt ponds (IPCC 1996).

In addition to the effects of sea level rise, ice-bonded coasts are susceptible to increased erosion and shoreline retreat due to declining sea ice cover (which increases open-water fetch and wave energy) and declining frozen ground (permafrost) at the shoreline. Rapid coastal erosion is already occurring along the Canadian coast of the Beaufort Sea (Dallimore et al. 1996) and Alaska (Parson 2001). Changes in energy regimes and stability of Canadian and Alaskan coastal habitats will likely affect coastal shorebirds and marine mammals.

Arctic sea ice thickness decreased 1–2 m (about 40%) at the end of the melt season during the past few decades (Rothrock et al. 1999) and further large-scale reductions in sea ice thickness and extent are projected (Parson 2001). Loss of sea ice will likely directly affect marine mammals and seabirds dependent upon ice shelves and floes as platforms for reproduction, pupping, nesting, and migration (Boesch et al. 2000). Walrus (*Odobenus rosmarus*), polar bears (*Ursus maritimus*), ringed seals (*Phoca hispida*), and bearded seals (*Erignathus barbatus*) are considered particularly vulnerable to loss of sea ice.

Increased Invasive Species, Pests, and Pathogens

Effects of climate change on invasive species, pests, and pathogens are expected to be important determinants of future ecosystem structure and productivity. For example, the exotic and invasive Chinese tallow (*Triadica sebifera* [*Sapium sebiferum*]), a freeze-intolerant nonnative tree species, increased 30-fold in southeastern Texas in 14 years (1981–1995), often outcompeting native species (Harcombe et al. 1998). As freeze-free zones shift northward, expansion of Chinese tallow is expected to continue.

Interactions and changes in forest dynamics due to disease and insects are very likely in areas where warming is greater. Concomitant with rapid Arctic warming from 1992 through 1996, a sustained outbreak of spruce bark beetles (*Ips typographus*) caused over 2.3 million acres of tree mortality in Alaska. This was the largest loss by spruce bark beetles ever recorded in North America (Werner 1996). Defoliating insects are also affecting boreal forest habitats. Outbreaks of spruce budworm, fir coneworm (*Dioryctria abietivorella*), and arch sawfly (*Pikonema alaskensis*) increased over the past decade, affecting approximately 800,000 acres in Alaska (Holsten and Burnside 1997). However, insect outbreaks and ecological effects are inconsistent across the Arctic ecosystem. Some bird species may benefit from increases in insect forage, but descriptive studies are lacking.

Warming could also influence the southern pine beetle (*Dendroctonus frontalis*). Warmer winter air temperatures are likely to increase overwintering southern pine beetle larval survival rate, and warmer annual air temperatures could allow beetles to produce more generations per year (McNulty et al. 1998). Both of these factors could increase southern pine beetle populations. Although moderate drought stress can increase pine resin production thereby reducing beetle colonization success rates, severe drought stress reduces resin production and therefore increases susceptibility of trees to beetle infestation. Data are insufficient to predict how these factors will affect future beetle populations in southern pine forests (McNulty et al. 1998).

Similarly, pathogens are also expected to respond to climate change. Warming and increased moisture in mid-latitudes could provide ready environs for tropical and subtropical diseases to move northward. Although not linked directly to climate change, the rapid expansion of West Nile Virus in North America demonstrates the potential for various diseases to spread when environmental conditions suit a disease's particular life-history requirements and physiological tolerances.

Wildlife Impacts by Taxonomic Group

In addition to investigating potential effects of climate change on habitats and individual species, it is instructive to examine potential impacts on major vertebrate groups, which are discussed below.

Amphibians

The range and abundance of amphibians are closely tied to environmental variables affecting development, reproduction, and survival (Cooke 1972, Osborne 1989, Pancharatna and Patil 1997, Donnelly and Crump 1998). Chorusing behavior, an indication of breeding activities, appears to be triggered by rain and temperature conditions in some frogs (Busby and Brecheisen 1997). The activity of some North American toads near the northern limit of their ranges is also positively correlated with temperature (Bider and Morrison 1981). Movement of salamanders during the breeding season in Florida was found to be positively correlated with precipitation and minimum air temperature (Palis 1997). The importance of moisture is indicated by rapid responses of amphibians to availability of temporary ponds and adjustments in development rates that vary with the risk of pond desiccation (Griffiths 1997). In one study, the date of spring calling for frogs and toads occurred earlier over time and was positively correlated with spring temperature (Sparks and Carey 1995). Based on these and other studies, amphibian populations and distributions are likely to change significantly as air and water temperatures change (Elmberg 1991). Species inhabiting high-altitude areas would be at particular risk (Hamilton 1995, Pounds et al. 1999).

As amphibians respond to changing climates, ecosystem dynamics are also likely to change. For example, changes in thermal environments can alter the outcome of predator–prey interactions (Manjarrez 1996, Moore and Townsend 1998). Reductions in larval-period length, which occur because of increased growth rates in warmer waters (Ryan 1941), may reduce the risk of predation for young amphibians (Martof 1956, Wilbur and Collins 1973, Smith-Gill and Berven 1979). However, larvae in warmer habitats often metamorphose at smaller sizes (Werner 1986, Smith 1987). Smaller adult body size may lead to reduced mating success for males (Berven 1981) or reduced fecundity for females (Berven 1982).

Reptiles

Because they are poikilothermic, it is not surprising that physiology of reptiles is temperature sensitive. Painted turtles (*Chrysemys picta*) grow larger in warmer years. During warm sets of years turtles reach sexual maturity faster (Frazer et al. 1993). However, a warmed climate may also be a threat. Hibernating painted turtle hatchlings are normally protected from the killing effects of rapid ambient temperature changes by overwintering in snow-covered burrows. Temperature increases can lead to a lack of snow cover, resulting in dead hatchlings (Breitenback et al. 1984).

Reptile ranges are often correlated with temperature (Nix 1986, Owen and Dixon 1989, Yom Tov and Werner 1996), suggesting that ranges may shift with temperature change. Additionally, temperature changes may influence the range of operative temperatures for lizard species, possibly altering thermoregulation behavior patterns (Dunham 1993, Christian et al. 1996). Using an individual-based physiological model, Dunham (1993) predicts that, for one lizard species in Texas, a 2°C warming could lead to a reduction from current patterns of 2.5–5.25 active hours a day to less than 2–4.1 active hours per day. This reduction in active time could lead to reduced ability to obtain food or mates. Further modeling suggests that, with a 2°C warming, female lizards would have a 16%–22% reduction in age-specific fecundity, possibly leading to extinction of the study populations (Dunham and Overall 1994).

Physiological effects of temperature can occur while reptiles are still within their eggs. Female leopard geckos (*Eublepharis macularius*) produced from eggs incubated at higher temperatures were possibly sterile, and during reproduction they tended to behave more like males (Gutzke and Crews 1988). Increases in temperature might also alter sex ratios in some reptiles.

Birds

The overall ranges of many bird species are now thought to be as much influenced directly by climate as by availability of particular habitats. For example, the spring range of barnacle geese (*Branta leucopsis*) expanded north along the Norwegian coast, correlated with a significant increase in the number of April and May days with temperatures above 6°C (Prop et al. 1998). Similarly, the average latitude of occurrence for many North American wood warblers (Parulidae) shifted significantly farther north in the past 24 years (Price and Root 2001). The migration route of sooty shearwaters (*Puffinus griseus*) shifted toward cooler northwestern areas of the Pacific, apparently in response to changing sea surface temperatures (Spear and Ainley 1999).

Studies have shown the influence of climate on both migration timing and reproduction of birds. For example, some spring migrants in the U.S. now have earlier arrival dates (Ball 1983, Price and Root 2001) and breeding times (Brown et al. 1999, Dunn and Winkler 1999). Schiegg et al. (2002) followed the parentage of individual red-cockaded woodpeckers (*Picoides borealis*) in a long-term study. They found inbred females were not laying their eggs any earlier and thus their time of breeding is apparently not associated with the warming trend. However, females that are not inbred do track ambient temperature and are laying eggs earlier than they did previously. Thus, there are implications for possible interactions between climate change and the response of threatened and endangered species with a small gene pool.

Climate change may cause a mismatch in the timing of breeding between birds and their prey. For example, one European study (Visser et al. 1998) found that the seasonal development of plants and some animals occurred earlier over a 23-year period whereas breeding timing of the birds did not. This decoupling could lead to eggs hatching when food supplies may be low in abundance (Visser et al. 1998).

Mammals

Mammals are able to inhabit colder habitats than reptiles and amphibians because of their homeothermic capabilities. Nevertheless change in the ranges and abundances of mammals in response to climate change have been documented. In central Canada a warming-associated poleward shift in the tree line seems to be causing northern extensions of the porcupine's (*Erethizon dorsatum*) range (Payette 1987). Climate-linked fluctuations in abundances have been noted for musk oxen (*Ovibos moschatus*) in Greenland (Forchhammer and Boertmann 1993) and for various other mammals in North America (Arditi 1979, Brown et al. 1997).

The implication of possible climate-induced poleward range shifts for arctic and subarctic mammals is interesting. The Arctic Ocean is an obstacle to northerly range extensions for 25 species of Canadian mammals (Kerr and Packer 1998). The collared lemming (*Dicrostonyx groenlandicus*), a keystone species in arctic ecosystems, could lose at least 60% of its available habitat if its range shifts northward with climate warming (Kerr and Packer 1998). Either these species will adapt to warmer climates or their ranges will shift northward toward the Arctic Ocean.

In addition to potential range shifts, climate change may affect the growth and size of mammals. The body weights of wood rats (*Neotoma* spp.) were observed to decline as temperatures increased over an 8-year period (Smith et al. 1998). Body size has potential implications for reproductive success. In Scotland, juvenile red deer (*Cervus elaphus*) grew faster in warm springs, leading to increased adult body size, which was positively correlated with adult reproductive success (Albon et al. 1987, Albon and Clutton-Brock 1988).

CASE STUDIES

The following case studies illustrate the complexity and potential effects of climate change, yet also demonstrate the uncertainty. The amphibian case study is illustrative in that this class is so sensitive to moisture conditions. Unique among these case studies, the potential effects of climate change are complicated by degradation of the ozone layer by chlorofluorocarbons, which has significantly increased the exposure of living organisms to the destructive effects of ultraviolet radiation, to which amphibians are particularly vulnerable.

The close association of waterfowl with wetlands, including shallow seasonal wetlands, suggests their susceptibility to changes in precipitation and temperature, both of which affect water conditions. The waterfowl case study reveals the complexity of climate change as potential effects vary by species and even within species depending upon geographic location.

The annual migration of Neotropical migrant birds exposes them to climate change in both their wintering and breeding habitats, as well as in migration corridors. The Neotropical migrants case study reveals that the breeding range of many species is closely tied to climatic conditions, suggesting significant breeding range shifts are likely as climate continues to change.

The caribou case study demonstrates the strong relationship between caribou life history and local climatic conditions. The study is particularly revealing in that climate change has

already increased temperatures in some high-latitude areas where temperature increases are expected to be the greatest. Also, the future effects of climate change may be easier to assess for caribou than for other species because of the relative lack of other disturbance factors in their annual and seasonal ranges.

Case Study—Amphibians

Amphibians, like other organisms, have survived numerous environmental changes over millions of years. Yet recently amphibian populations have been declining throughout the world (Alford and Richards 1999, Houlahan et al. 2000), prompting consideration of global environmental change as the primary cause. Studies, such as those by Pounds et al. (1999) and Kiesecker et al. (2001), strongly suggest complex global processes affect local populations and may contribute to amphibian declines. These global processes likely include regional climate change and increased ultraviolet radiation from ozone depletion caused by chlorofluorocarbon emissions (Cockell and Blaustein 2001; Reaser and Blaustein, in press). The permeable, relatively unprotected skin of amphibians makes them particularly vulnerable to cell-damaging ultraviolet radiation, airborne pollutants, and changes in moisture conditions (influenced by both precipitation and temperature).

Gibbs and Breisch (2001) showed that daily temperatures increased near Ithaca, New York, during the last century, and several species of anurans shifted their breeding patterns accordingly. Specifically, four species of anurans vocalized 10–13 days earlier, two were unchanged, and none called later (from 1990 to 1999, compared with calling dates between 1900 and 1912).

Blaustein et al. (2001) reported considerable variation in environmental variability and the onset of breeding in anurans. At one site in Oregon, there was a nonsignificant trend for western toads (*Bufo boreas*) to breed increasingly earlier that was associated with increasing temperature. However, at four other sites neither western toads nor Cascades frogs (*Rana cascadae*) showed statistically significant positive trends toward earlier breeding. At three out of four of these sites, breeding earlier was associated with warmer temperatures. The spring peeper (*Pseudacris crucifer*) in Michigan did not show a statistically significant trend toward breeding earlier, but did exhibit a significant positive relationship between breeding timing and temperature. Fowler's toads (*Bufo fowleri*) in eastern Canada showed neither a trend for breeding earlier nor a positive relationship between breeding timing and temperature.

A recent study in the tropics (Pounds et al. 1999) also illustrates complex interrelationships among environmental changes and amphibian population declines. The study found changes in water availability associated with changes in large-scale climate processes, such as the El Niño–Southern Oscillation, may significantly affect amphibians (and other vertebrates) in the Monte Verde cloud forest of Costa Rica. Pounds et al. (1999) showed dry periods associated with global warming correlated with amphibian declines. In Costa Rica and potentially other high-altitude tropical sites, climate change appears to have caused a decrease in mist precipitation received in the forest due to increased altitude of cloud banks.

The potential direct and indirect effects of climate change present challenges for conservation of declining amphibian populations (Carey and Alexander 2003), especially given amphibian sensitivity to other environmental factors. Although worldwide production of chlorofluorocarbons has declined, there will be a significant time lag before ozone depletion is reversed. Local factors (e.g., habitat loss and toxic pollutants) associated with amphibian declines must be assessed to effectively maintain local populations as effects of climate change likely increase in the coming century. It will be important for biologists to minimize these other stressors to reduce effects of climate change.

Case Study—Waterfowl

North America's wetlands support a rich abundance and diversity of waterfowl and other wildlife that have many important economic, ecological, recreational, and aesthetic values. But changes in wetland ecosystems may profoundly affect future waterfowl populations and other wetland-dependent species.

Demands of our growing human population have led to the loss of >50% of wetlands in the conterminous United States (Dahl 1990). Dahl (2000) reported continued net losses of wetlands and open water habitats at nearly 60,000 acres per year. Similar losses, though less well documented, have occurred in Canada and Mexico. Models project that further loss of prairie wetlands, the most important ecosystem for breeding ducks, could lead to significant redistributions and possibly reductions in prairie waterfowl breeding populations (Bethke and Nudds 1995, Sorenson et al. 1998). The ephemeral nature of many wetlands makes them and associated wildlife particular susceptible to climate change. However, potential climate change impacts to ecosystems important to waterfowl are extremely variable, and depend upon locality.

<u>Regional Effects</u>

Prairie Potholes. The Prairie Pothole Region is a 780,000-km^2 arc of glaciated lands stretching from northern Iowa to central Alberta. This landscape of grasslands, croplands,

aspen forest, and wetlands supports more breeding ducks than any other geographic region in North America (Batt et al. 1989). Dabbling ducks (mallard [*Anas platyrhynchos*], northern pintail [*Anas acuta*], northern shoveler [*Anas clypeata*], gadwall [*Anas strepera*], blue-winged teal [*Anas discors*]), pochards (canvasback [*Aythya valisineria*], redhead [*Aythya americana*], lesser scaup [*Aythya affinis*]), and the ruddy duck (*Oxyura jamaicensis*) are the most common breeding species in this region. Two primary factors have affected the dynamics of these waterfowl populations. First, annual variations in precipitation (e.g., Stoudt 1971, 1982; Johnson and Grier 1988) dramatically affected wetland conditions which, in turn, affected breeding propensity and reproductive rates of ducks (Sorenson et al. 1998). Second, extensive loss of perennial nesting cover and altered predator communities resulted in a long-term decline in nesting success (Beauchamp et al. 1996).

All global climate change models for this region predict substantial warming under a doubling of atmospheric CO_2, but precipitation changes for this region are less certain (slight decreases to slight increases). Mean annual and March–May temperatures have increased in this region over the past 50 years (L. G. Sorenson, R. Goldberg, T. L. Root, and M. G. Anderson, unpublished data). Because of temperature-sensitive evapotranspiration, however, nearly all future scenarios predict decreases in soil moisture, which is highly correlated with the abundance of small wetlands (Clair et al. 1998, Sorenson et al. 1998). Expected accompanying ecological changes include fewer wetlands on average; shorter hydroperiods for nonpermanent wetlands; greater annual variability in surface water; and changes to water depth, salinity, temperature, macrophytes, and aquatic food webs (Poiani and Johnson 1991, Larsen 1995, Poiani et al. 1995, Clair et al. 1998). For many waterfowl species, decreased wetland abundance or shortened hydroperiods have been linked to decreased reproductive effort, reduced clutch sizes, lower renesting propensity, lower nesting success, lower brood survival, and reduced recruitment probability for the subsequent year (Dzus and Clark 1998, Anderson et al. 2001).

Sorenson et al. (1998) used model projections of future drought conditions in the Prairie Pothole Region to project trends in wetland and duck abundance during the 21st century. Most scenarios and models projected significant declines in wetlands (no change to –91%), and thus declines in the abundance of breeding ducks (–9% to –69%) in this region by the 2080s.

Because upland nesting ducks are strongly affected by human land-use practices, future changes in agriculture brought about by climate change may have an important influence on waterfowl populations. For instance, if drying of southwestern portions of the region favors conversion of annual cropland to grassland, ducks could benefit in occasional wet years when the normally dry prairies attract breeding ducks. Milder winters may enhance survival of fall-seeded crops (e.g., winter wheat and fall rye) that provide more attractive and secure nesting cover than spring-seeded crops (Duebbert and Kantrud 1987). Conversely, warmer and wetter conditions in eastern parts of the region could favor expansion of corn, soybeans, and other row crops largely incompatible with waterfowl nesting.

Arctic Coastal Plain. Several species of geese and sea ducks, tundra swans (*Cygnus columbianus*), and a few species of dabbling ducks breed across the Arctic Coastal Plain. Relative sea level rise during this century will likely be minimal in important goose breeding areas like the Hudson Bay Lowlands because of continuing rebound of the land surface from past glaciation (Shaw et al. 1998). In other areas, such as northern river deltas or the Beaufort Sea, loss of lowland breeding habitat is probable. Milder springs may enhance average reproductive success in some colonial breeding geese (Boyd and Diamond 1994, Alisauskas 2002), leading to further degradation of northern pastures already degraded from overabundant geese (Batt 1996, 1998).

Western Boreal Forest. Scoters (*Melanitta* spp.), scaup, American wigeon (*Anas americana*), green-winged teal (*Anas crecca*), mallard, and many other waterbirds breed throughout the Western Boreal Forest. This region is second only to the Prairie Pothole Region in importance to breeding ducks, supporting on average 14 million waterfowl (U.S. Fish and Wildlife Service 2002).

The Western Boreal Forest has warmed by some 2–2.5°C during the past century, making it one of the fastest-changing climates in North America (Saporta et al. 1998), and further temperature changes are expected (Anderson et al. 1998, NAST 2000). Concurrently, human development in the area is rapidly increasing. Oil and gas development, forestry, and mining are cumulatively impacting the forest ecosystem, especially in northern Alberta (Schmiegelow and Mönkkönen 2002, Stelfox and Farr 2002). In the southern areas of this region where mineral soils rather than rock underlies the forest, lands are being cleared and drained for small-grain and oilseed production (Hobson et al. 2002).

As the Western Boreal Forest has been affected by human development, scaup and scoter populations have declined markedly since the late 1980s (Austin et al. 2000, Sea Duck Joint Venture Management Board 2000, Afton and Anderson

2001). Unfortunately the ecology of boreal wetlands and breeding ducks is poorly understood, which has hampered assessing the effects of changes in the area, including climate change and variability, and their potential links to declining scaup and scoter populations. Estimation of vital rates such as nest success and female survival, studies of food web relationships, and research on the ecology of these birds outside the breeding season are all required to test working hypotheses about their continuous decline.

Great Lakes–St. Lawrence Basin. The Great Lakes–St. Lawrence Basin region comprises an area of more than 1 million km^2 (Mortsch et al. 2000). Coastal marshes and associated wetlands provide important staging, breeding, and wintering habitat for waterfowl. Most climate model simulations project reduced runoff and lower lake levels later this century (Lofgren et al. 2000, Mortsch et al. 2000, Kling et al. 2003), although one model predicts a very small increase in water levels (Sousounis and Bisanz 2000).

Loss of coastal wetlands around the Great Lakes has already been extensive (Bookhout et al. 1989), and reduced water availability could threaten remnant coastal marshes by reducing the extent and/or duration of flooding, or by adversely affecting water quality (Fuller et al. 1995, Price and Root 2000). Wetlands most at risk are those which would be impeded from adapting to new water levels by artificial structures or geomorphic conditions (Mortsch 1998). As water levels drop, however, there may be new opportunities for wetland conservation.

Mississippi Alluvial Valley. The Mississippi Alluvial Valley is the single most important wintering area for midcontinent mallards. Wintering wood ducks (*Aix sponsa*), gadwall, green-winged teal, Canada geese, and lesser snow geese (*Chen caerulescens caerulescens*) rely on the lower valley (Bellrose 1980), while the upper basin provides important habitat for other dabbling ducks, pochards, and tundra swans (Havera 1999).

Aquatic ecosystems in this area have already been greatly modified or destroyed. Once abundant bottomland hardwood forests have declined by 80% due to logging and conversion to agriculture. Rivers have been channeled, contained within levees, or otherwise managed (Reinecke et al. 1989). Natural winter flooding in the valley, which benefits mallard body condition and winter survival, has been greatly reduced. How climate will change in the valley and interact with other factors affecting waterfowl is difficult to assess because of inconsistent projections among various models. However, the frequency and severity of storm events may be important in determining future frequency and extent of flooding in the watershed.

Gulf Coast. Gulf Coast wetlands of Louisiana and Texas are one of the two most important wintering areas for North American waterfowl (Chabreck et al. 1989, Hobaugh et al. 1989, Stutzenbaker and Weller 1989), especially for redhead and pintail ducks. Approximately 40% of the United States' coastal wetlands are in Louisiana and were created by seasonal flooding of the Mississippi River. During the last century, however, dam and levee construction and channelization have altered channel flow, causing little sediment to settle out where it can build new marshes (Boesch et al. 1994). The Texas coastal prairies recently supported a large area of rice agriculture that provided winter habitat for geese and ducks, but rice farming there is declining, resulting in greater demand on shrinking coastal marsh.

Louisiana alone has lost nearly 8 million acres of wetlands (Dahl 1990). Land subsidence from natural sediment dewatering and compaction, accompanied by subsurface fluid withdrawals in some areas (Boesch et al. 2000) has flooded marshes and made them more vulnerable to storms. Global sea level rise of 10–20 cm during the past century, due mostly to thermal expansion of the oceans and widespread melting of land ice (IPCC 2001*b*), has contributed to this loss. For the coastal U.S., relative sea level rise has been greatest in Louisiana and high in Texas (Titus 1998). As sea level continues to rise due to climate change, loss of Gulf Coast wetlands and their associated values for wintering waterfowl will continue. Restoration of historic wetland–creating hydrology may be the best hope for minimizing negative impacts of global warming on the Gulf Coast.

Mid-Atlantic Coast. The Mid-Atlantic Coast historically wintered large numbers of waterfowl, although changes in these estuaries reduced their attractiveness to ducks during the 1900s (Perry and Deller 1996). The trend continues because Chesapeake Bay salt marshes receive insufficient sediment and organic matter to keep pace with current rates of sea level rise (Kearney and Stevenson 1991). Najjar et al. (2000) predict sea level rise of 19 cm by 2030, and 66 cm by 2095 for this region. Sea level rise is likely to further reduce suitable shallow water habitat available for wintering waterfowl (Sorenson 2000).

California Central Valley. The Central Valley of California historically supported the greatest concentration of wintering waterfowl on the continent (Heitmeyer et al. 1989). Since the mid-1800s, however, more than 95% of California's wetlands have been destroyed or highly modified (Gilmer et al. 1982).

Some climate models for the Central Valley project dryer conditions, but others project more rain, more rapid runoff,

and earlier snowmelt that will lead to higher winter flows and reduced summer flows in most California streams (Field et al. 1999, NAST 2000). More winter water could benefit birds in the Central Valley because shallow flooding of additional farmland could increase foraging and resting habitats and disperse birds, thereby lowering the risk of contagious diseases. The value of winter flooding, however, depends on land use. If the extent of rice culture in the Central Valley is reduced in the future (e.g., if irrigation water becomes too costly), winter flooding of agricultural land will be much less beneficial for waterfowl than it is currently.

Most wetlands in the Central Valley depend on human-delivered water at some time during the year. Increasing human populations, coupled with decreased summer stream flows, would intensify competition for water. Any negative impact of changing climate on waterfowl in the Central Valley is likely to occur via changes in availability of water for rice culture or wetland management.

Pacific Coast. Sea level rise is expected to have minor impacts on waterfowl habitats along much of the Pacific Coast because of the abrupt topography of the coastline and continuing tectonic movements that counteract sea level rise (Shaw et al. 1998). Exceptions of concern include the major river deltas that provide substantial waterfowl habitat (e.g., Suisun Marsh, Fraser River delta, and Skagit River). Where landform or human development prevent the shoreward movement of coastal wetlands, the threat of loss is greater (Boesch et al. 2000). Protection of remaining shoreline lowlands from further development should be a high priority in regions such as the lower mainland of British Columbia.

Changes in seasonal flow patterns of major rivers could affect salinity patterns in estuaries such as San Francisco Bay (Field et al. 1999). Concomitant changes in aquatic food webs are likely, although difficult to predict (Boesch et al. 2000). Because diving duck habitats are generally more limited along the Pacific Coast than the Atlantic Coast, deterioration of habitat quality for these species anywhere in the Pacific Flyway is a concern.

Demographic Considerations

Understanding effects of climate change on waterfowl is complicated by continent-wide migrations wherein climate change will likely vary considerably across a species' range. The influences of climate change could vary dramatically between breeding and wintering areas. How vital rates (e.g., mortality, recruitment, etc.) affect populations, coupled with knowledge of species' distributions and ecosystem vulnerability to climate change, should allow better assessments of the types of species which might be especially vulnerable to changing climate.

Variation in population growth rate for midcontinent mallards is primarily affected by variation in nest success and other breeding-season vital rates (Hoekman et al. 2002). In the study by Hoekman et al. (2002), the combined effects of nest success, duckling survival, female summer survival, and renesting intensity accounted for more than 81% of the variation in population growth rate. Although the relative importance of nonbreeding survival could increase if something were to change drastically on wintering areas, it appears that midcontinent mallards are likely to be most sensitive to climate change on their breeding grounds. Thus, for mallards, projections of decreased habitat suitability in the Prairie Pothole Region (Larson 1995, Sorenson et al. 1998) should be of greatest concern.

Similar to mallards, 71% of the variation in population growth rate of lesser scaup has been associated with variation in breeding ground vital rates (J. Rotella, Montana State University, personal communication). It follows that lesser scaup, already declining in numbers for more than 20 years (Afton and Anderson 2001), may be particularly vulnerable to climate change in its breeding habitats (the Western Boreal Forest and Prairie Pothole Region).

In contrast to mallards and lesser scaup, population growth rates of northern pintails in coastal Alaska (Flint et al. 1998), lesser snow geese (Rockwell et al. 1996, Cooch et al. 2001), greater snow geese (*Chen caerulescens atlantica*) (Gauthier and Brault 1998), Wrangel Island snow geese (Brault et al. 1994), and emperor geese (*Chen canagica*) (Schmutz et al. 1997) were most sensitive to adult female survival. Canvasback population growth rates were affected by both breeding season vital rates and female survival (Anderson et al. 1997). Little is known, however, about ecological covariates associated with female survival or how these might be affected by changing climate.

Minimizing Impacts

Anderson and Sorenson (2001) identified several immediate actions that could help conserve waterfowl and their habitats in the Prairie Pothole Region given the potential impacts of climate change. Some with continent-wide applicability to conserving wetlands include 1) reducing existing anthropogenic stressors on wetlands (e.g., drainage, filling, road impacts) and associated uplands (e.g., overgrazing, intensive tillage); 2) developing contingency plans for large, managed wetlands and wetland complexes (e.g., securing long-term water rights, engineering modifications); and 3) including climate-change scenarios in regional conservation planning at the finest spatial resolution available from climate models.

Case Study—Neotropical Migrants

The implications of global climate change for migratory birds are quite different from those of most other vertebrates. Unlike most amphibians, reptiles, and mammals (with the notable exception of bats), Neotropical migrant birds are adept at traveling long distances. Thus, in terms of mobility, Neotropical migrants appear pre-adapted to shifting range distributions as climates change. But Neotropical migrants pose an additional conservation challenge. Rather than being able to focus on conserving relatively small areas, habitat ranging from breeding areas in the United States and Canada all the way south along migration routes to wintering area in Mexico, Central America, and portions of South America must be conserved.

Neotropical migrant species are often assumed to be primarily associated with specific habitats—for example, Kirtland's warbler (*Dendroica kirtlandii*) breeding in jack pines (*Pinus banksiana*) and golden-cheeked warblers (*Dendroica chrysoparia*) in Ashe junipers (*Juniperus ashei*). However, other Neotropical migrants may be found in a particular habitat throughout their breeding ranges but not in apparently equivalent habitat north or south of their current distributions (Price and Root 2001). Some species may be found in different habitats across their breeding ranges. While habitat selection, food availability, and competition may all play a role in influencing local distribution of a given bird species, climatic conditions are correlated with breeding ranges of many Neotropical migrants (Price 1995, in press; Price and Root 2001).

Projections of potential changes in the breeding ranges of Neotropical migrants caused by climate change can be made by coupling models of the associations between bird distribution and climate, with predictive models of climate change. Price and Root (2001) suggest climate change–induced range shifts will greatly influence the species composition of breeding Neotropical migrants in various regions. Gross changes depict the loss of Neotropical migrant species currently found in areas whereas net changes also take into account species moving into an area from outside of the region (Table 2). For example, the Great Lakes Region could have a potential gross loss of 53% of the Neotropical migrant species. These losses might be partially offset by other Neotropical migrant species colonizing from outside the region, so the net change might approach 29% fewer species than currently found there. Different climate models may yield somewhat different results, although it is clear Neotropical migrant breeding ranges could change markedly as climates change.

How quickly a species' breeding range shifts is unknown, but seems largely dependent on whether a given species' distributional limits are most closely linked with climate or other factors such as vegetation. Range shifts should also be affected by the rate of climate change itself, although there could be a significant lag period if climate changes faster than a species can adjust. One study concluded that the average latitude of occurrence of some Neotropical migrants has already shifted significantly northward in the last 20 years by an average distance of almost 100 km (J. Price, unpublished data). In another study, arrival dates of 20 species of migratory birds were 21 days earlier in 1994 than in 1965 (Price and Root 2000).

Table 2. Possible changes in percentages of breeding Neotropical migrant species in the next 100 years (Price and Root 2001).

	Possible change (%)	
	Gross	Net
California	–29	–6
Eastern Midwest	–57	–30
Great Lakes	–53	–29
Great Plains—Central	–44	–8
Great Plains—Northern	–44	–10
Great Plains—Southern	–32	–14
Mid-Atlantic	–45	–23
New England	–44	–15
Pacific Northwest	–32	–16
Rocky Mountains	–39	–10
Southeast	–37	–22
Southwest	–29	–4

Birds have critical functions in natural ecosystems, including seed dispersal, nutrient cycling, natural pest control, pollination, and more. But identifying appropriate conservation actions for Neotropical migrants will be very challenging as climates change. Further complicating the picture are habitat loss, pollution, and invasive species. Monitoring and research will be important, especially because of the likely synergism of several stressors acting together. Conservation measures must be considered throughout a species' range, necessitating international cooperation due to the long migrations of Neotropical migrant birds.

Case Study—Caribou

Barren-ground caribou (*Rangifer tarandus granti*) that calve in the North American Arctic currently consist of 3–4 million animals in 13 herds and are extremely important to the subsistence and cultural identity of indigenous peoples. These herds migrate long distances between fall–winter

ranges in taiga and their traditional calving grounds above tree line near the Arctic coast. Across the range of these migrating caribou herds there is substantial heterogeneity in the direction and degree of regional climate change. Western herds have been exposed to a warming climate while the climate has been cooling in the range of eastern herds (Serreze et al. 2000).

The internationally migratory Porcupine caribou herd is the most studied of the North American herds. The herd's annual range encompasses 300,000 km^2 (larger than the state of Nevada) along the northern Alaska–Yukon Territory border and the average adult female travels about 4400 km annually (Fancy et al. 1989). Even within this one herd, the large area used and near-continual movement exposes caribou to numerous ecosystems that may be differentially affected by climate change.

Caribou arrive on Arctic coastal calving areas in late May, give birth to calves during the first week of June when snow is typically melting, increase their daily movements as calves mature and insects become abundant, then depart the calving ground by early July for dispersed fall ranges. Winter storms typically restrict caribou to winter ranges in southern mountainous areas until mid-April when they return to the calving grounds.

During calving caribou energy and protein reserves are at a minimum (Chan-McLeod et al. 1999), and females are dependent on the timely emergence of new plant growth to satisfy the near doubling of energy requirements that accompany peak lactation demand in late June (White and Luick 1984, Parker et al. 1990). In winter, access to forage is affected by the distribution, depth, and properties of snow that caribou must excavate to obtain their typical winter diet of lichens (Thompson and McCourt 1981). Climate warming may affect the availability of resources to caribou throughout the year via its influence on the timing of plant emergence and growth in spring and summer and through its influence on snow properties in late fall through late spring. Long-term climate records from summer and winter ranges, remotely sensed estimates of the timing and rate of vegetation green-up on the calving ground, and locations of radio-collared animals have all contributed to an understanding of variable effects of climate warming on summer and winter ranges on the behavior and performance of the herd (Griffith et al. 2002).

Although there has been substantial interannual variability, since the late 1970s summer temperatures have increased by about 1°C while winter temperatures have increased by about 2°C within the range of the Porcupine herd (Houghton et al. 1996). During this recent warming, all four Arctic calving herds in Alaska have increased in size, but only the Porcupine herd has increased and decreased. The Porcupine herd varied slightly less than 2-fold during the past two decades, ranging from 100,000 to 180,000 animals, while increasing at about 4.5% per year during the 1980s, then declining at about 3.5% per year during the 1990s. Other Arctic calving herds in Alaska increased 5- to 7-fold throughout the past two decades.

The Arctic Oscillation, with a warm positive phase and a cool negative phase, affects climate broadly in the Arctic (Thompson and Wallace 1998, 2001) and is positively correlated with the North Atlantic Oscillation. Population size of the Porcupine caribou herd began an extended decline once the Arctic Oscillation entered a predominantly positive phase in the early 1990s. A similar decline, however, has not been evident for other herds that calve in the Alaskan Arctic and winter much farther west than the Porcupine herd. It is conceivable that regional-scale climate indicators may be more important to the performance of Alaska's western herds.

The historical extent of the calving grounds encompasses about 12% of the annual range, but they are consistently used. The center of annual high-density calving has varied about 350 km east to west and 85 km north to south. Typically, in warmer years with earlier green-up, caribou are more likely to calve farther west and closer to the coast as green-up generally proceeds from southeast to northwest. The Arctic Oscillation has provided some degree of predictability to these annual shifts in calving ground location (Griffith et al. 2002). Specifically, caribou were more likely to calve on the Alaskan, rather than Canadian, portion of the coastal plain in years following positive values of the winter Arctic Oscillation. The mechanism of this lagged relationship may be related to the weak correlation between the winter Arctic Oscillation and the amount of green forage available at calving.

Warming advanced green-up in the northern hemisphere during the past two decades (Myneni et al. 1998, Zhou et al. 2001), and this same trend was evident locally on the calving ground of the Porcupine herd. The relative amount of green plant biomass available to caribou in late June, when energetic demands of lactation are high and well before plant biomass peaks, increased approximately 50% from 1985 to 1999. Notwithstanding the trend, within this period there have been years with substantial variation. For example, aerosols from the eruption of Mount Pinatubo in the Philippines in 1991 reached the Arctic in 1992 (Minnis et al. 1993), causing a late spring, cool summer, and particularly severe winter conditions counter to the overall warming trend.

Annually, caribou select calving grounds with high rates of green-up. Within annual calving grounds, which are quite variable in location, the highest density of caribou occurs where plant biomass is high (Griffith et al. 2002). This response to the distribution of green biomass causes substantial variation in selection of annual calving grounds. Because predators (wolves [*Canis lupus*], grizzly bears [*Ursus arctos*], and nesting golden eagles [*Aquila chrysaetos*]) are found predominantly in the foothills and mountains rather than on the coastal plain, caribou selection of climate-mediated habitats causes annual variability in predation risk. In years with early green-up, when forage for lactating females is "high," caribou tend to calve on the coastal plain where predation risk may be reduced.

In addition to selection of calving areas in response to climate-driven habitat variability, there is also a response to habitats in terms of calf survival during June. About 85% of the annual variance in June calf survival (1983–2001) was explained by forage availability in late June that increased during this period of warming. At a smaller local scale (i.e., within the annual calving grounds), forage availability in late June remained important, but predation risk also became a significant predictor of calf survival.

Climate effects on habitat influenced the location of annual calving grounds which in turn apparently influenced predation risk. Thus, during the springs and early summers of the 1980s and 1990s, increasingly warmer years yielded more forage during peak lactation demand, shifted calving to the north and west, simultaneously reduced predation risk, and increased calf survival on the calving grounds during June. At the local scale, spring and early summer climate warming positively affected caribou performance.

Even though the warming trend on calving grounds was consistent throughout the 1980s and 1990s, the population began to decline after 1989. Because there was essentially no adult mortality on the calving ground, spring–summer habitat conditions were unlikely to be directly responsible for the population decline. Warmer temperatures may increase harassment of caribou by insects (Nixon 1990), increase caribou energetic demands, and potentially delay fattening prior to the rut and delay, or reduce conception (White et al. 1975, Russell et al. 1993). However, no differences in parturition rates or calf birth weights were evident between the increase and decrease phases of the herd.

Although increased winter storm frequency has been associated with climate warming (Serreze et al. 2000) and the potentially detrimental influence of major icing events on caribou has been noted (Gunn and Skogland 1996), there have been no such events identified for the winter range of the Porcupine herd. Snow extent has generally declined on the winter range (Brown and Braaten 1998), but warmer temperatures influence snow properties in subtle ways. Daily temperature excursions above freezing in spring and fall can create crusty snow conditions that may increase the energetic costs of traveling and foraging and increase the ability of wolves to capture caribou. These mechanisms would be expected to increase winter mortality rates of caribou, and small changes in mortality would be sufficient to initiate a decline in the Porcupine herd.

Increased frequency of daily temperature excursions above freezing, particularly in spring, was observed during the decrease phase as compared to the increase phase of the herd (Griffith et al. 2002). No such change in potential icing frequency was observed on the spring and fall ranges of the other three Alaskan Arctic calving herds during the 1990s. These herds continued to increase while the Porcupine herd declined. Thus, winter warming may have had a negative effect on herd performance that overwhelmed the positive effects of warming on calving grounds.

The effects of climate change on habitats and subsequent habitat use and population responses of caribou are complex and apparently counteracting for this caribou herd. Within Alaska, correlations between climate and herd size were not consistent. Considering the heterogeneity of climate trends across North America, there is very little reason to expect that the same patterns and relative strengths of climate effects identified in the Porcupine herd would be consistent among herds. However, it is clear that climate does contribute to long-term dynamics of Arctic caribou and must be considered for effective management. Potential energy development on the calving grounds, which currently are essentially undisturbed, would further complicate management.

RECOMMENDATIONS

The pervasiveness, magnitude, and complexity of global climate change and variability are so daunting that taking advantage of positive effects and preventing or minimizing negative effects may initially appear futile. Further, given the difficulties of simply predicting the scale of broad climate changes underway and projected for the decades ahead, climate change may seem totally irrelevant in our daily lives or even in our lifetimes. Nothing could be further from the truth.

The adverse effects of climate change on wildlife and their habitats may be minimized or prevented in some cases through management actions initiated now. Likewise,

positive or desirable effects that occur may be enhanced if anticipated. Herein we present a set of recommendations or actions to assist wildlife biologists in coping with the challenges of global climate change to help ensure a brighter future for wildlife.

To plan and respond effectively, managers must first understand the nature of climatic and ecological changes that are likely to occur in their regions. Numerous adaptations and combinations of approaches should emerge as experienced resource managers gain a better understanding of the changes that are likely to occur to habitats and species. The following 18 recommendations should assist managers in meeting the challenges of climate change when working to conserve our wildlife resources.

1) Recognize global climate change as a factor in wildlife conservation

Adaptation starts with recognition that climate change is occurring. Planners and managers should become better informed about the consequences of climate change and variability on the resources they work with. This technical review provides an introduction of the basics and should act as a springboard for learning more. Although further research is needed, some data on changes in regional climates, biomes, individual species, and potential faunal composition are available.

2) Manage for diverse conditions

Given the uncertainties inherent in projecting the extent and rate of climate change, one management approach is to develop what are known as "no regrets" management strategies. These are sound wildlife management strategies under current conditions, yet remain viable as the climate warms. Restated, the better you can manage under unusual weather conditions today (e.g., drought and flood), the better prepared you may be for future climate change and variability.

3) Do not rely solely on historical weather and species data for future projections without taking into account climate change

Managers must be aware that historical climate, habitat and wildlife conditions are less reliable predictors as climate changes. For example, some migratory birds are returning as much as 3 weeks earlier than previously observed (Root et al. 2003). If bird population surveys continue to be conducted the same week each year based on historic observations, they could be significantly biased. The problem is considerably more complex for surveys such as the national Breeding Bird Survey that survey many avian species, some of which may change migration timing and some of which may not. Similarly, conducting hunting seasons in the same time period each year may mean that harvest levels are either over- or underachieved if the timing and/or pattern of seasonal movements changes.

4) Expect surprises, including extreme events

Surprises in climate change and the wildlife and habitat responses to it could occur. For example, "100-year" floods may become much more frequent because the precipitation cycle changes. Another surprise may be an insect pest suddenly switching from one generation per year to two generations per year—with increased habitat damage as a result. Flexibility in natural resource budget processes will give managers better capability of dealing with surprises as they occur.

5) Reduce nonclimate stressors on ecosystems

The reduction of stressors caused by human activities may increase the resiliency of habitats and species to the effects of climate change and variability. In essence, this situation is what good management already seeks to accomplish. However, a changing climate amplifies the need for managers to minimize effects these stressors have on wildlife populations.

6) Maintain healthy, connected, genetically diverse populations

Small populations and/or more isolated populations are more prone to local extirpations than larger, more widespread populations. Healthier or more robust species and habitats should be better able to adapt to climate change as an additional stress. Although these are goals managers already strive to accomplish, climate change increases their importance.

In addition to government resource agencies, various entities focusing on conservation of specific taxa must include global climate change in their thinking and planning. For example, these groups should include the North American Bird Conservation Initiative, Partners in Flight, North American Waterfowl Management Plan, Partners in Reptile and Amphibian Conservation, North American Shorebird Plan, and Western Hemisphere Shorebird Reserve Network.

7) Translocate individuals

In some cases, it may be necessary to physically move wildlife from one area to another to maintain species viability. However, translocation is not only expensive but it introduces its own potential problems (e.g., disease transmission) to wildlife management. Introduction of exotic species can have devastating effects on host ecosystems, including the extinction of native fauna (McKnight 1993). The unpredictable consequences of species introductions mean that translocation should be

severely limited as a conservation strategy to deal with climate change.

8) Protect coastal wetlands and accommodate sea level rise
Impacts of sea level rise can be ameliorated with conservation easements and acquisition of inland buffer zones to provide an opportunity for habitats and wildlife to migrate inland. Setback lines for coastal development can be effective at establishing zones for natural coastal migration based on projected sea level rise and subsidence projections that include local land movements. Storm surge should be considered in establishing buffer zones and setback boundaries. In other cases, restoration of natural hydrology could facilitate sediment accretion and building of deltaic coastal wetlands.

9) Reduce the risk of catastrophic fires
Fire is a natural part of many ecosystems; however, climate change could lead to more frequent fires and/or a greater probability of catastrophic fires. For instance, in areas that experience lower precipitation from climate change, reductions in soil moisture can increase drought stress on plants, making them more vulnerable to disease and pest outbreaks, thereby increasing mortality. This factor, in turn, could lead to more frequent fires or a greater probability of catastrophic fires. Managers can use prescribed fires and other techniques to reduce fuel load and the potential for catastrophic fires.

10) Reduce likelihood of catastrophic events affecting populations
Increased intensity of severe weather places wildlife at risk. Although it is not possible to avoid the disturbance itself, it may be possible to minimize the effect of the event. For example, securing water rights to maintain water levels through a drought or having an infrastructure capable of surviving floods should minimize impacts. Maintaining widely dispersed and viable populations of individual species also minimizes the probability that localized catastrophic events will cause significant negative effects. Having multiple, widely spaced populations may offset some of the population losses attributable to widespread events such as hurricanes.

11) Prevent and control invasive species
Rapidly changing climates and habitats may increase opportunities for invasive species to spread because of their adaptability to disturbance. Already a very significant problem (McNight 1993) for native plants and wildlife, invasive species control efforts will be essential, including extensive monitoring and spot control to preclude larger impacts. Existing invasive species in southern regions should be monitored and aggressively controlled to preclude northward movements as climates warm.

12) Adjust yield and harvest models
As fish and wildlife populations respond both directly to climate and indirectly to climate through changes in habitats, their productivity and sustainability may increase or decrease. Drought may require increased harvest to reduce the impact of the species on its habitat. Alternatively, stressed populations may need to be protected from harvest so that the population remains large enough to recover once the stress has been removed. Managers may need to adapt yield and harvest regulations, perhaps well beyond historic parameters, in response to climate variability and change. This could be aided greatly by a better understanding of sources of variation in vital rates, especially for exploited populations, coupled with monitoring programs to detect trends in those vital rates most influential in population change.

13) Account for known climatic oscillations
Short-term periodic weather phenomena, such as El Niño, should be closely monitored and predictable. By understanding effects of periodic oscillations on habitats and wildlife, management options can be fine-tuned. For example, restoration of native plants during the wet phase of oscillations could make the difference between success and failure.

14) Conduct medium- and long-range planning
Climate change and variability should be considerations in all medium- and long-range planning exercises. Plans longer than 10 years should take into account potential climate change and variability as part of the planning process. This planning should also apply to National Environmental Policy Act-mandated Environmental Impact Statements. If climate change and variability are not proactively taken into account, the potential for conservation plans to succeed will likely be much reduced.

15) Select and manage conservation areas appropriately
As wildlife and habitats have declined across North America, the establishment of refuges, parks, and reserves has been used as a conservation strategy. However, placement of conservation areas has rarely taken into account potential climate change and variability, even though the problems of climate change and conservation area placement were pointed out in the mid-1980s (Peters and Darling 1985). In highly fragmented habitats, the placement of conservation areas on a north–south axis may enhance movements of habitats and wildlife by in essence providing northward migration corridors. Efforts to conserve habitats for single, or small numbers of species, should be concentrated in northern portions of their range(s), where suitable climate is more likely to be sustained.

Managers of existing conservation areas should consider climate change and variability in developing future

management plans (Solomon 1994, Halpin 1997). Specifically, this planning should include assessing the vulnerability of key taxa in the preserve (Herman and Scott 1994) and monitoring potential effects related to climate change (Solomon 1994). Reintroductions of native species should be more likely to succeed in more northerly areas within a species historic range.

16) Ensure ecosystem processes

Ultimately, managers may need to enhance or replace diminished or lost ecosystem processes. This could mean manual seed dispersal or reintroducing pollinators for some plant species. In the case of pest outbreaks, increased pesticide use with accompanying potential health risks (human and wildlife) and economic costs (Colborn et al. 1996, Kirk et al. 1996, Herremans 1998) may be required. Enhancing or replacing other services, such as contributions to nutrient cycling, ecosystem stability, and ecosystem biodiversity are much harder to imagine. The loss or reduced capacity of ecosystem services may be one of the major sources of surprise from climate change and variability.

17) Look for new opportunities

Managers must be continually alert to anticipate and take advantage of new opportunities that arise. For example, if climatic conditions render existing agricultural areas unusable for agriculture, they could become important wildlife conservation areas with appropriate management. As a means of mitigating global climate change, some industries are investing in carbon sequestration programs by planting trees. In some regions, grassland and wetland conservation may benefit similarly, but more research is needed on carbon cycling in these systems. Collaborating with industry to invest in restoration of habitats has significant potential to offset impacts from global climate change.

18) Employ monitoring and adaptive management

Uncertainty concerning climate change means we should monitor climate and its effects on wildlife and their habitats. Wildlife managers must try to anticipate impacts to wildlife and use monitoring data to quickly adjust management techniques and strategies. Relying on traditional, long-practiced methods and strategies will most likely be less effective as environmental conditions change. In a given area, adaptive management could be as diverse as adjusting regulations, being more proactive in habitat management, and/or changing management objectives altogether.

CONCLUSIONS

Climate has been varying ever since the earth was formed. However, the unprecedented recent and rapid climate warming, which is enhanced by anthropogenic greenhouse gases (IPCC 2001*b*, National Research Council 2001), has significant consequences for wildlife and their habitats. Its effects depend upon the adaptability of wildlife and their habitats. Species with small and/or isolated populations and low genetic variability will be least likely to withstand impacts of climate change. Species with broader habitat ranges, wider niches, and greater genetic diversity should fare better or may even benefit. Wildlife managers can enhance a species' ability to withstand global climate change by ensuring widespread habitat availability and managing for self-sustaining populations.

In addition to the effects of climate change and variability on wildlife and their habitats, cumulative and synergistic effects of climate change coupled with other stressors (e.g., urbanization, pollution, ozone depletion, unregulated exploitation, etc.) on wildlife will be important. Minimization of stressors should improve the ability of wildlife and their habitats to cope with and endure the effects of climate change and variability.

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