Chapter 2: Impacts of Climate Change and Ocean Acidification on Fish, Wildlife and Plants

This chapter discusses current and projected impacts of increasing GHGs on fish, wildlife, and plant species, and then provides more detailed information on impacts within eight major types of ecosystems in the United States: forest, shrubland, grassland, desert, Arctic tundra, inland water, coastal, and marine ecosystems.

2.1 GHG-induced Changes to the Climate and Ocean

The United States has already experienced major changes in climate and ocean acidification and additional changes are expected over time. The magnitude and pace of these changes will depend on the rate of GHG emissions and the resulting atmospheric GHG levels (USGCRP 2009). These changes are already having significant impacts on the nation's natural resources, the valuable services they provide, and the communities and economies that depend on them. These impacts may be driven by a combination of GHG and climate-related factors.

Increases in atmospheric and ocean CO_2

- The concentration of CO_2 in the atmosphere has increased by roughly 35 percent since the start of the industrial revolution (USGCRP 2009).
- The oceans absorb large amounts of CO_2 from the atmosphere and as atmospheric CO_2 has increased, so has the concentration of CO_2 in the oceans. As a result, the pH of seawater has decreased an average of 0.1 units since 1750 (IPCC AR4 2007), which represents a 30 percent increase in acidity. Ocean pH is projected to drop as much as another 0.3 to 0.4 units by the end of the century (Orr et al. 2005).
- As a result of human activities, the level of CO_2 in the atmosphere has been rapidly increasing. The present level of approximately 390 parts per million (Tans and Keeling 2011) is more than 30 percent above its highest level over at least the last 800,000 years (USGCRP 2009). In the absence of strong control measures, emissions projected for this century would result in a CO_2 concentration approximately two to three times the current level (USGCRP 2009).

Changes in air and water temperatures:

- Average temperatures have increased more than 2 °F in the United States over the last 50 years (more in higher latitudes) and are projected to increase further (USGCRP 2009).
- Global ocean temperatures rose 0.2 °F between 1961 and 2003 (IPCC WGI 2007).
- Arctic sea ice extent has fallen at a rate of three to four percent per decade over the last 30 years. Further sea ice loss, as well as reduced snowpack, earlier snow melt, and widespread thawing of permafrost, are projected (USGCRP 2009).
- Global sea level rose by roughly eight inches over the past century, and has risen twice as fast since 1993 as the rate observed over the past 100 years (IPCC WGI 2007). However, local rates of sea level change vary across different regions of the coastal United States. Changes in

air and water temperatures affect sea level through thermal expansion of sea water and melting of glaciers, ice caps, and ice sheets.

Changes in temperature can lead to a variety of ecologically important impacts, affecting our nation's fish, wildlife, and plant species. For example, a recent analysis showed that many rivers and streams in the United States have warmed over the past 50 to100 years (Kaushal et al. 2010), and will continue to warm 0.4 °F per decade (IPCC AR4 2007). The increasing magnitude and duration of high summer water temperatures will increase thermal stratification in rivers, lakes, and oceans, may cause depletion of oxygen for some periods and enhance the toxicity of contaminants, adversely impacting coldwater fish and other species (Noyes et al. 2009). Increasing temperature is also a major driver of rising sea levels through thermal expansion.

Changes in timing, form, and quantity of precipitation:

- On average, precipitation in the United States has increased approximately five percent in the last 50 years (USGCRP 2009).
- Models suggest northern (wet) areas of the United States will become wetter, while southern (dry) areas of the country will become drier (USGCRP 2009).

As mean global temperature increases, the capacity of the atmosphere to hold water vapor increases, resulting in alterations in precipitation patterns. The combination of changes in temperature and precipitation impacts water quantity, water quality, and hydrology on a variety of scales across ecosystems (USGCRP 2009). These changes vary regionally. The Northeast and Midwest are experiencing higher precipitation and runoff in the winter and spring, while the arid West is seeing less precipitation in spring and summer (USGCRP 2009). In areas of high snowpack, runoff is beginning earlier in the spring, causing flows to be lower in the late summer. These changes in precipitation combined with increased temperatures are also expected to increase the instance and severity of drought, the conditions of which can lead to an increase in the frequency and intensity of fires. For example, during the extreme drought suffered by Texas in the summer of 2011, the state experienced unprecedented wildfires.

Changes in the frequency and magnitude of extreme events:

- Extreme weather events such as heat waves, flooding, and regional droughts have become more frequent and intense during the past 40 to 50 years (USGCRP 2009).
- Rain falling in the heaviest downpours has increased approximately 20 percent in the past century (USGCRP 2009).
- Hurricanes have increased in strength (USGCRP 2009).

According to the USGCRP (2009), over the past few decades, most of the United States has been experiencing more unusually hot days and nights, fewer unusually cold days and nights, and fewer frost days. Droughts are also becoming more severe in some regions. These types of extreme events can have major impacts on the distribution, abundance, and phenology of species, as well as on ecosystem structure and function. Extreme storm events also may result in intense and destructive riverine and coastal flooding. Over the next century, current research suggests a decrease in the total number of extratropical storm events but an increase in number of intense events (Lambert and Fyfe 2006, Bengtsson et al. 2009).

Changes in atmospheric and ocean circulation

- Warming of the atmosphere and ocean change the location and intensity of winds which affect surface ocean circulation (Colling 2001)..

- Changes in ocean circulation patterns will change larval dispersal patterns (Cowen and Sponaugle 2009) and the geographic distributions of marine species (Block et al. 2011).

Changes in atmospheric and ocean circulation can affect both the marine environment as well as continental weather. By studying ocean sediment cores, scientists can learn about paleoclimatic conditions, which will provide insights about how dynamic and sensitive ocean circulation can be under different climatic conditions.

2.2 Existing Stressors on Fish, Wildlife, and Plants

Fish, wildlife, plants, and ecosystem processes are threatened by a number of existing stressors. Many of these stressors will be exacerbated by climate change, while some may reduce a species' ability to adapt to changing conditions. While the magnitude of climate change is expected to vary regionally, the overall vulnerability of some ecosystems may be primarily driven by the severity of these non-climate stressors. Resource managers must consider climate impacts in the context of multiple natural and human-induced changes that are already significantly affecting species, habitats, and ecosystem functions and services, including habitat loss, fragmentation and degradation, invasive species, over-use, and disease.

Non-Climate Stressors

In the context of climate adaptation, non-climate stressors refer to those current or future pressures impacting species and natural systems that do not stem from climate change, such as habitat loss and fragmentation, invasive species, pollution and contamination, changes in natural disturbance, disease, pathogens, and parasites, and over-exploitation.

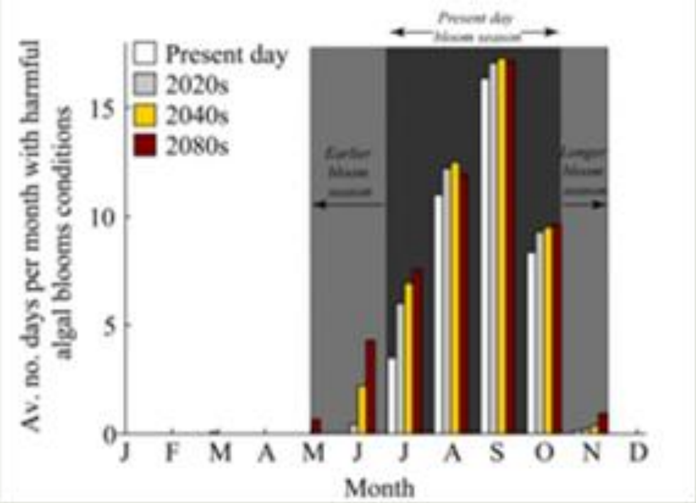
Habitat fragmentation, loss, and degradation have been pervasive problems for natural systems and are expected to continue. For example, grasslands, shrublands, and forests are being converted to agricultural uses. Desert systems are stressed by overgrazing and off-highway vehicles. Tundra and marine ecosystems are being affected by energy and mineral exploration and extraction, and coastal ecosystems are experiencing extensive development. Adding changes in climate to habitat fragmentation will put species with narrow geographic ranges and specific habitat requirements at even greater risk than they would otherwise be. Range reductions and population declines from synergistic impacts of climate and non-climate stressors may be severe enough to threaten some species with extinction over all or significant portions of their ranges. For example, the Rio Grande cutthroat trout, a candidate for listing under the Endangered Species Act (ESA), is primarily threatened by habitat loss, fragmentation, and impacts from non-native fish (FWS 2008). However, the habitat of the Rio Grande cutthroat is likely to further decrease in response to warmer water temperatures, while wildfire and drought impacts are likely to increase in response to climate change, further exacerbating the non-climate stressors on the species (FWS 2011).

HARMFUL ALGAL BLOOMS

In the past three decades, harmful algal blooms (HABs) have become more frequent, more intense, and more widespread in freshwater, estuarine, and marine systems (Sellner et al. 2003). These blooms are taking a serious ecological and economic toll. Algal blooms may become harmful in multiple ways. For example, when the algae die and sink, bacteria consume them, using up oxygen in the deep water. This is a problem especially during calm periods, when water circulation and reoxygenation from the atmosphere are reduced. Increases in the nutrients that fuel these blooms have resulted in an increasing number of massive fish kills. Another type of harmful bloom happens when the dominant species of algae such as those of Cyanobacteria (commonly known as blue-green algae) produce potent nerve and liver toxins that can kill fish, seabirds, sea turtles, and marine mammals. These toxins also sicken people and result in lost income from fishing and tourism. The toxic HABs do not even provide a useful food source for the invertebrate grazers that are the base of most aquatic food webs.

The cause of the increasing number of blooms? One of them is climate change. Warmer temperatures are boosting the growth of harmful algae (Jöhnk et al. 2008). More floods and other extreme precipitation events are increasing the runoff of phosphorus and other nutrients from farms and other landscapes, fueling the algae’s growth. The problem is only expected to get worse. By the end of the 21st century, HABs in Puget Sound may begin up to two months earlier in the year and persist for one month later compared to today—increasing the chances that paralytic toxins will accumulate in Puget Sound shellfish (Moore et al. 2009). In addition, the ranges of many harmful algal species may expand, with serious consequences. For example, a painful foodborne illness known as ciguatera, caused by eating fish that have dined on a toxin-producing microalga, is already becoming much more common in many tropical areas. Global warming will increase the range of the microalga—and the threat of poisoning.

It is possible, however, to successfully combat some HAB problems. One key strategy is reducing the flow of nutrients into waterbodies. Proven steps include adding buffer strips beside streams or restoring wetlands to absorb nutrient pollution before the nutrients can reach streams, rivers, lakes, and oceans. In addition, better detection and warning systems can reduce the danger to people.



Projected changes to the harmful algal bloom season in Puget Sound in a future warmer climate. (NOAA/S. Moore)

Globalization and the increasing movement of people and goods around the world have enabled pests, pathogens, and other species to travel quickly over long distances and effectively occupy new areas. Historic invaders such as chestnut blight, Dutch elm disease, kudzu and cheatgrass changed forever the character of our natural, rural, and urban landscapes. Climate change has already enabled range expansion of some invasive species such as hemlock woolly adelgid and will likely create welcoming conditions for new invaders. The buffelgrass invasion has forever changed the southwestern desert ecosystems by crowding out native plants and fueling frequent and devastating fires in areas where fires were once rare (Betancourt et al. 2010). Species such as zebra and quagga mussels, Asian carp, and kudzu already cause ecological and economic harm, such as competition for habitat, decreases in biodiversity, and predation of native species. In Guam, the brown tree snake (an invasive species introduced from the South Pacific after World War II) has caused the extirpation of most of the native forest vertebrate species, thousands of power outages, and widespread loss of domestic birds and pets (Fritts and Leasman-Tanner 2001). These invasions of new species are also getting a boost from land-use changes, the alteration of nutrient cycles, and climate change (Vitousek et al. 1996, Mooney and Hobbs 2000). Climate change can shift the range of invasive species, serve as the trigger by which non-native species do become invasive, and introduce and spread invasive species through severe weather events such as storms and floods. Species that have already colonized new areas in the United States may become more pervasive with changing conditions. For example, some invasive species like kudzu or cheatgrass may benefit when CO_2 concentrations increase or historical fire regimes are disturbed (Dukes and Mooney 1999). In addition, poison ivy, another invasive species (though native), may not only increase with the increase in CO_2, but is also likely to increase its production of urushiol, the oil in poison ivy that causes a rash for many people (Ziska et al. 2007).

Invasive Species

Invasive species are defined in Executive Order 13112 as alien species whose introduction does or is likely to cause economic or environmental harm or harm to human health. These are typically non-indigenous or non-native species that adversely affect the habitats and ecosystems they invade. These effects can be economic, environmental, and/or ecological. In addition, some native species can become invasive in certain ecological contexts, while many non-native species do not negatively affect natural systems. Today, climate change may be redefining traditional concepts of native and non-native, as species move into new areas in response to changing conditions.

Over-use of America’s fish, wildlife, and plants has also had major impacts. Some species have been lost from certain areas, while others have gone completely extinct. For example, overfishing of commercial and recreational fish stocks in some regions has harmed the resources and the communities and economies that depend on them. However, overfishing of specific stocks is not the only problem associated with fishing. Fishing methods can damage habitats and bycatch can cause significant impacts to non-target species (NOAA 2011).

Many pathogens of terrestrial and marine taxa are sensitive to temperature, rainfall, and humidity making them sensitive to climate change. The effect of climate change may result in increasing pathogen development and survival rates, disease transmission, and host susceptibility. Although most host-parasite systems are predicted to experience more frequent or severe disease impacts under climate change, a subset of pathogens might decline with warming, releasing hosts from a source of population regulation. The most detectable effects of climate change on disease relate to geographic range expansion of pathogens such as Rift Valley fever, dengue, and Eastern oyster disease. Factors other than climate change—such as changes in land-use, vegetation, pollution, or increase in drug-resistant strains—may also contribute to these range expansions. To improve our ability to predict epidemics in wild populations, it will be necessary to separate the independent and interactive effects of multiple climate drivers on disease impacts (Harvell et al. 2002).

Resource managers have long worked hard to reduce the impact of these stressors in their management strategies. But as climate change will likely exacerbate these existing human-induced pressures on natural systems, one of the most successful strategies for increasing the resilience of fish, wildlife, and plants to a changing climate may be reducing the impact of these non-climate stressors (see Goal 7). For instance, warmer water temperatures have already caused many fish stocks off the Northeast coast to shift northward and/or to deeper depths over a 40 year period (Nye et al. 2009). As populations move to new locations, fishing effort reductions may be necessary to ensure sustainable populations. Increasing our understanding of how climate change combines with multiple stressors to affect species, ecosystems, and ecological processes in complex and synergistic ways is needed to help inform and improve adaptation planning.

2.3 Climate Change Impacts on Fish Wildlife, and Plants

A changing climate can affect growth rates, alter patterns of food availability, and change rates and patterns of decomposition and nutrient cycling. Changes can be driven by one or multiple climate related factors acting in concert or synergistically and can alter the distribution, abundance, phenology, and behavior of species, and the diversity, structure, and function of ecosystems. One forecast that seems certain is that the more rapidly the climate changes, the higher the probability of substantial disruption and unexpected events within natural systems (Root and Schneider 1993). The possibility of major surprises, in turn, increases the need for adaptive management strategies—where actions and approaches are flexible enough to be adjusted in the face of changing conditions.

Species and populations likely to have greater sensitivities to climate change include those with highly specialized habitat requirements, species already near temperature limits or having other narrow environmental tolerances, currently isolated, rare, or declining populations with poor dispersal abilities, and groups especially sensitive to pathogens (Foden et al. 2008). Species with these traits will be even more vulnerable if they have a small population, a low reproductive rate, long generation times, low genetic diversity, or are threatened by other factors. For example, the southwestern willow flycatcher may be considered especially vulnerable as it is currently threatened, especially sensitive to heat, primarily dependent on a habitat type projected to decline, and reliant on climate-driven environmental cues that are likely to be altered under future climate change (Glick et al. 2011a). For these reasons, maintaining rare or already threatened or endangered species will present significant challenges in a changing climate, because many of these species have limited dispersal abilities and opportunities (CCSP 2008b).

In addition, migratory species are likely to be strongly affected by climate change, as animal migration is closely connected to climatic factors, and migratory species use multiple habitats, sites, and resources during their migrations. In extreme cases, species have abandoned migration altogether, while in other cases species are now migrating to new areas where they were previously only occasional vagrants (Foden et al. 2008). However, an ability to move and utilize multiple habitats and resources may make some migratory species relatively less vulnerable to negative impacts of climate change. Similarly, many generalist species such as white-tailed deer or feral hogs are likely to continue to thrive in a changing climate (Johnston and Schmitz 2003, Campbell and Long 2009).

Climate impacts will vary regionally and by ecosystem across the United States (see Figures 1 and 2). Understanding the regional variation of impacts and how species and ecosystems will respond is critical to developing successful adaptation strategies. Examples of current and projected climate change impacts on ecosystems are summarized in Table 1, and discussed in greater detail in the following sections.

The following sections are intended to summarize current knowledge on impacts of climate change on fish, wildlife, and plants within each of the major types of ecosystems within U.S. jurisdictions. Within each ecosystem type, a number of individual climate factors are listed and their direct effects on biota are discussed. However, many of the observed impacts are the result of climate factors acting in combination, as well as the combination of impacts across the ecosystem. While the individual effects are serious in themselves, it is the potential interactions of them through ecosystem processes that will likely lead to the greatest risk, both in potential magnitude of effects and in our uncertainty regarding the direction and magnitude of changes. For example, in marine systems, changes in community composition and food web structure resulting from the shifts in ecological niches for individual species are likely to be the largest influence of climate change (Harley et al. 2006). Single-factor studies will likely under-predict the magnitude of effects (Fabry et al. 2008, Perry et al. 2010).

RANGE SHIFTS IN A CHANGING CLIMATE

All across the country, species are already on the move in response to climate change. For example, Edith's checkerspot butterfly has shifted northward an average of almost 60 miles, with population extinctions seen along the southern range (Parmesan 2006). Species such as the red fox are increasingly able to move into previously inhospitable northern regions, which may lead to new competition and pressures on the Arctic fox (Killengreen et al. 2007). In Yosemite National Park, half of 28 species of small mammals (e.g., pinyon mouse, California vole, alpine chipmunk, and others) monitored showed substantial (500 meters on average) upward changes in elevation, consistent with an increase in minimum temperatures (Moritz et al. 2008).

Species are shifting in marine environments as well. In the Northeast United States, two-thirds of 36 examined fish stocks shifted northward and/or to deeper depths over a 40-year time period in response to consistently warm waters (Nye et al. 2009). Similarly, in the Bering Sea, fish have moved northward as sea ice cover is reduced (Mueter and Litzow 2008). In the California Current ecosystem, shifts in spatial distribution were more pronounced in species that were commercially exploited, and these species may be more vulnerable to climate variability (Hsieh et al. 2008).

These types of range shifts are already widespread—indeed, in one analysis up to 80 percent of species analyzed were found to have moved consistent with climate change predictions (Parmesan and Yohe 2003). However, movements may not always be straightforward: recent evidence suggests that some alpine plant species in the Sierra Nevada may actually be shifting their distributions “downslope” in response to changes in water availability rather than changes in temperature (Crimmins et al. 2011).

Range shifts are not always negative: habitat loss in one area may be offset by an increase elsewhere such that if a species is able to disperse, it may face little long-term risk. However, it is clear that shifting distributions can lead to a number of new challenges for natural resource managers such as the arrival of new pests, the disruption of ecological communities and interspecies relationships, and the loss of particularly valued species from some areas. In addition, barriers to movement (such as development, altered ecosystems, or physical barriers like dams, fences, or roads) can keep species from reaching newly appropriate habitat. Goal 1 of the *Strategy* describes the importance of providing linkages and corridors to facilitate connectivity while working to monitor and manage the movement of invasive species, pests, and pathogens.

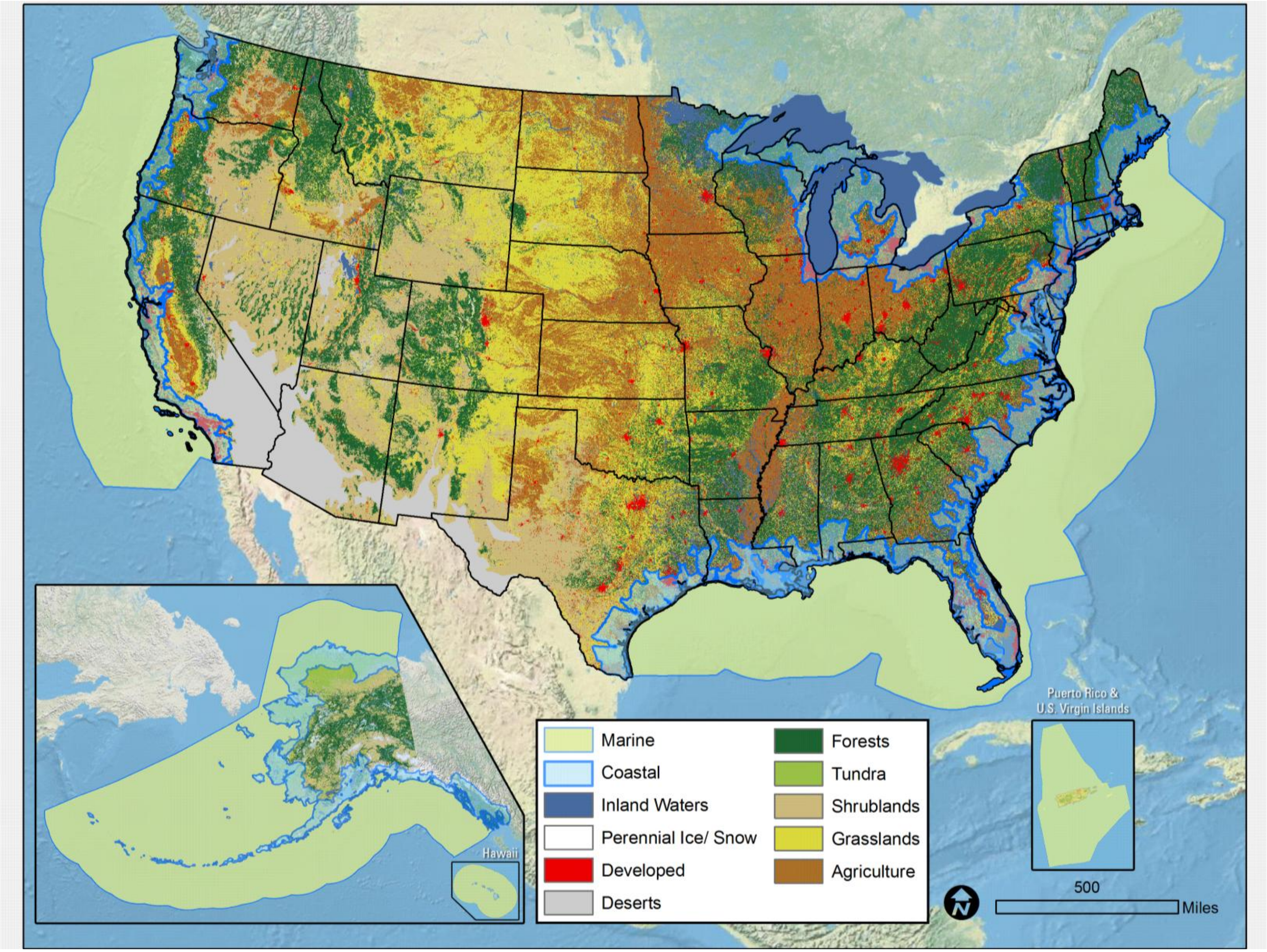


Figure 1: *The distribution of the eight major ecosystems (forests, grasslands, shrublands, deserts, tundra, inland waters, coastal, and marine systems) described in the Strategy, agriculture, and developed areas. Data source: Multi-Resolution Land Characterization (MRLC) Consortium National Land Cover Database (NLCD) 2006 (continental U.S, Hawaii), MRLC Consortium NLCD 2001 (Alaska), analysis by USGS EROS data center; NOAA's Coastal Geospatial Data Project and U.S. Maritime Zones, analysis by NOAA; USGS 1;250,000 hydrologic units of the United States.*

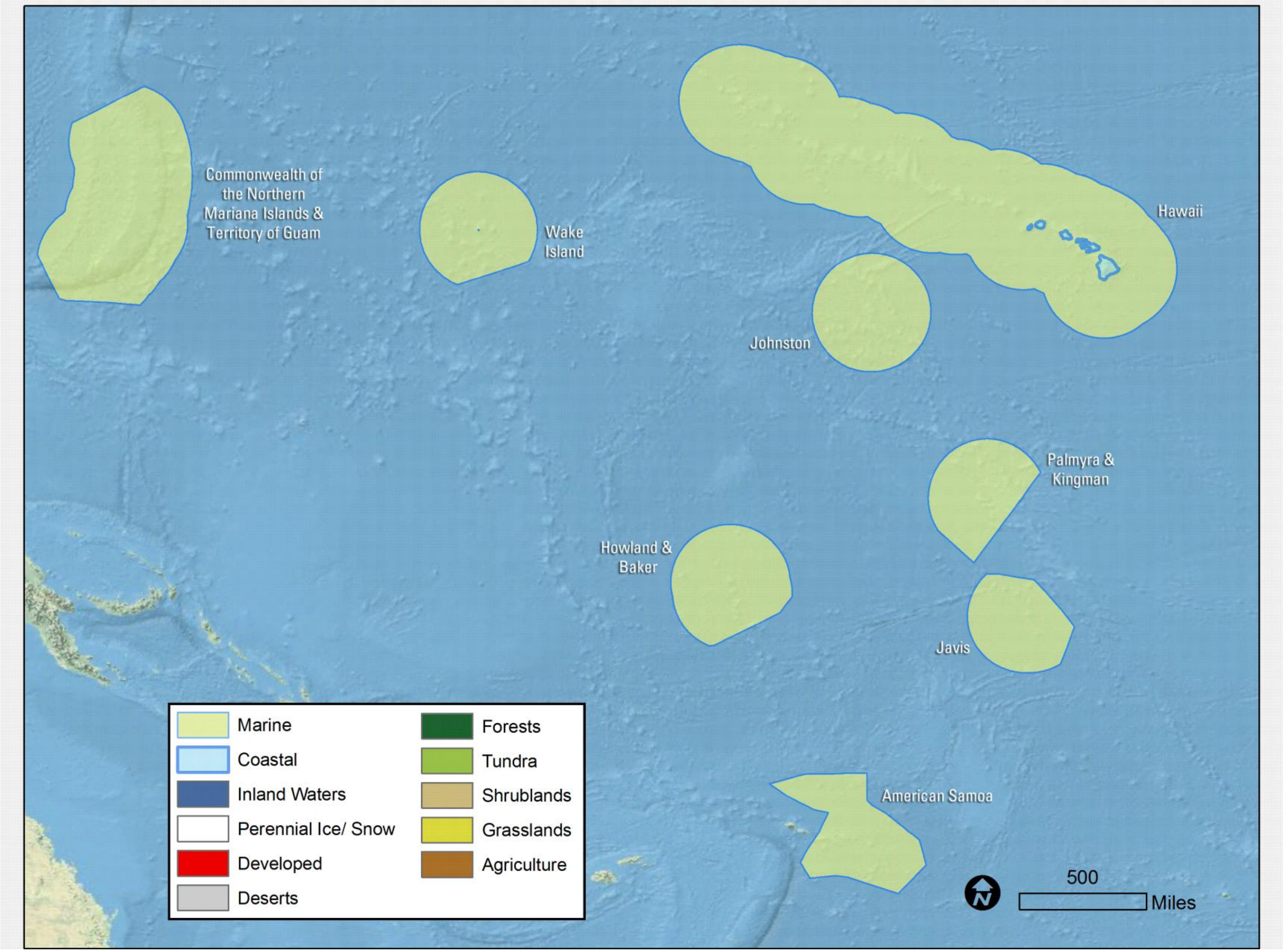


Figure 2: *The distribution of the eight major ecosystems (forests, grasslands, shrublands, deserts, tundra, inland waters, coastal, and marine systems) described in the Strategy, agriculture, and developed areas for the U.S. territories in the Pacific. See Figure 1 for data sources.*

Table 1: Examples of Observed and Projected Ecological Changes Associated With Increasing Levels of GHGs on U.S. Ecosystems and Species*

Major Changes Associated With Increasing Levels of GHGs	**Examples of Observed or Predicted Ecological Changes (by Major Ecosystem Type)****							
	Forests	**Shrublands**	**Grasslands**	**Deserts**	**Tundra**	**Inland Waters**	**Coastal**	**Marine**
Increased temperatures: U.S. average temperatures have increased more than 2 °F in the last 50 years, and are projected to increase further. Global ocean temperatures rose 0.2 °F between 1961 and 2003.	• Increase in forest pest damage • Changing fire patterns • Longer growing season may increase productivity • Higher evapotranspiration /drought stress	• Increased fire frequency may favor grasses over shrubs • Increased evapo-transpiration/ intensified water stress • Spread of non-native species	• Spread of non-native plants and pests • Changing fire patterns	• Elevated water stress • Mortality in heat-sensitive species • Possible desert expansion • Spread of non-native species	• Higher water stress • Changing plant communities • Longer growing season • Invasion by new species • Increased fire • More freeze-thaw-freeze events	• Expansion of warm-water species • Depleted O_2 levels • Stress on cold-water species • Increased disease/parasite susceptibility • More algal blooms	• Growth of salt marshes/ forested wetlands • Distribution shifts • Phenology changes (e.g., phytoplankton blooms) • Altered ocean currents and larval transport into/out of estuaries	• Coral mortality • Distribution shifts • Spread of disease and invasives • Altered ocean currents and larval dispersal patterns • New productivity patterns • Increased stratification • Lower dissolved O_2
Melting sea ice/ snowpack/snow melt: Arctic sea ice extent has fallen at a rate of 3 to 4 percent per decade over the last 30 years, and further loss is predicted. In terrestrial habitats, reduced snowpack, earlier snow melt, and widespread glacier melt and permafrost thawing are predicted.	• Longer frost-free periods • Increase in freeze/thaw events can lead to icing/ covering of winter forage • Decreased survival of some insulation-dependent pests	• Reduced snowpack leads to hydrological changes (timing and quantity)	• Reduced snowpack leads to hydrological changes (timing and quantity)	• Reduced snowpack leads to hydrological changes (timing and quantity)	• Thawing permafrost/soil • Hydrological changes • Terrain instability • Vegetation shifts • Longer snow-free season • Contaminant releases	• Snowpack loss changes the temperature, amount, duration, distribution and timing of runoff • Effects on coldwater and other species • Loss of lake ice cover	• Loss of anchor ice and shoreline protection from storms/waves • Loss of ice habitat • Changes in ocean carbon cycle • Salinity shifts	• Loss of sea ice habitats and dependent species • Changes in distribution and level of ocean • Changes in ocean carbon cycle • Salinity shifts
Rising sea levels: Sea level rose by roughly 8 inches over the past century, and in the last 15 years has risen twice as fast as the rate observed over the past 100 years. Sea level will continue to rise more in the future.	*NA*	*NA*	*NA*	*NA*	• Salt water intrusion • Loss of coastal habitat to erosion	• Inundation of freshwater areas • Groundwater contamination • Higher tidal/storm surges	• Inundation of coastal marshes/low islands • Higher tidal/ storm surges • Geomorphology changes • Loss of nesting habitat • Beach erosion	• Loss of coral habitats • Negative impacts on many early life stages • Loss of sea turtle nesting sites
Changes in circulation patterns: Warming of the atmosphere and ocean can change spatial and temporal patterns of water movement and stratification at variety of scales.	*NA*	*NA*	*NA*	*NA*	*NA*	• Altered productivity and distribution of fish and other species with changes in lake circulation patterns	• Altered productivity, survival and/or distribution of fish and other estuarine dependent species	• Altered productivity, survival and/or distribution of fish and other species (particularly early life history stages)

Table 1 (cont.): Examples of Observed and Projected Ecological Changes Associated With Increasing Levels of GHGs on U.S. Ecosystems and Species*

Major Changes Associated With Increasing Levels of GHGs	Examples of Observed or Predicted Ecological Changes (by Major Ecosystem Type)**							
	Forests	Shrublands	Grasslands	Deserts	Tundra	Inland Waters	Coastal	Marine
Changing precipitation patterns: Precipitation has increased approximately 5 percent in the last 50 years. Predictions suggest historically wet areas will become wetter, while historically dry areas will become drier.	• Longer fire season • Increased frequency/severity of wildfires • Both wetter and drier conditions projected	• Dry areas getting drier • Changing fire regimes	• Invasion of non-native grasses and pests • Species range shifting • Increased fire • Loss of prairie potholes/ wetlands	• Loss of riparian habitat and movement corridors	• More icing/rain-on-snow events affect animal movements and access to forage • Changes in subnivean temperature • Increased fire	• Decreased lake levels • Changes in salinity, flow	• Changes in salinity, nutrient, and sediment flows • Changing estuarine conditions may lead to hypoxia/anoxia • New productivity patterns	• Changes in salinity, nutrient and sediment flows • New productivity patterns
Drying conditions/drought: Extreme weather events, such as heat waves and regional droughts, have become more frequent and intense during the past 40 to 50 years.	• Decreased forest productivity and increased tree mortality • Increased fire	• Loss of prairie pothole wetlands • Loss of nesting habitat • Increased fire	• Loss of prairie pothole wetlands • Loss of nesting habitat • Invasion of non-native grasses • Increased fire	• Increased water stress • Increased susceptibility to plant diseases	• Moisture stressed vegetation • Loss of wetlands • Fish passage issues	• Loss of wetlands and intermittent streams • Lower summer base flows	• Changes in salinity, nutrient and sediment flows • Shifting freshwater input to estuaries • New productivity patterns	• Changes in salinity, nutrient and sediment flow • New productivity patterns
More extreme rain/weather events: Rain falling in the heaviest downpours has increased approximately 20 percent in the past century. Hurricanes have increased in strength. These trends are predicted to continue.	• Increased forest disturbance • More young forest stands	• More variable soil water content	• Changing pest and disease epidemiology	• Higher losses of water through run-off	• More landslides/ slumps	• Increased flooding • Widening floodplains • Altered habitat • Spread of invasive species/ contaminants	• Higher waves and storm surges • Loss of barrier islands • Beach erosion • New nutrient and sediment flows • Salinity shifts; • Increased physical disturbance	• Higher waves and storm surges • Changes in nutrient and sediment flows • Impacts to early life stages • Increased physical disturbance

Table 1 (cont.): Examples of Observed and Projected Ecological Changes Associated With Increasing Levels of GHGs on U.S. Ecosystems and Species*

Major Changes Associated With Increasing Levels of GHGs	Examples of Observed or Predicted Ecological Changes (by Major Ecosystem Type)**							
	Forests	**Shrublands**	**Grasslands**	**Deserts**	**Tundra**	**Inland Waters**	**Coastal**	**Marine**
Increase in atmospheric CO_2: The concentration of CO_2 in the atmosphere has increased by roughly 35 percent since the start of the industrial revolution.	• Increase forest productivity/growth in some areas • Insect pests may be affected • Changes in species composition	• Spread of exotic species such as cheatgrass • Impacts on insect pests • Changes in species composition	• Declines in forage quality from increased C:N ratios • Insect pests may be affected • Changes in species composition	• Increased productivity of some plants • Changes in communities • Increased fire risk	• Increased productivity of some plant species • Changes in plant community composition	• Increased growth of algae and other plants, • Changes in species composition and dominance	• Increased terrestrial, emergent, and submerged plant productivity	• Increased plant productivity
Ocean acidification: The pH of seawater has decreased significantly since 1750, and is projected to drop much more by the end of the century as CO_2 concentrations continue to increase.	*NA*	*NA*	*NA*	*NA*	*NA*	*NA*	• Declines in shellfish and other species • Impacts on early life stages	• Harm to species (e.g., corals, shellfish) • Impacts on early life stages • Phenology changes

**This table is intended to provide examples of how climate change is currently affecting or is projected to affect U.S. ecosystems and the species they support, including documented impacts, modeled projections, and the best professional judgment of future impacts from* Strategy *contributors. It is not intended to be comprehensive, or to provide any ranking or prioritization. Climate change impacts to ecosystems are discussed in more detail in sections 2.3.1-2.3.8, and in online ecosystem specific background papers (see Appendix A).*

***References: See IPCC AR4 2007, USGCRP 2009.*

2.3.1 Forest Ecosystems

Photo: FWS

Approximately 750 million acres of the United States is forest, both public and private (Heinz Center 2008), including deciduous, evergreen, or mixed forests. This includes embedded natural features such as streams, wetlands, meadows, and other small openings, as well as alpine landscapes where they occur above the treeline (see Figure 1). Changing climate can affect forest growth, mortality, reproduction, and eventually, forest productivity and ecosystem carbon storage (McNulty and Aber 2001, Butnor et al. 2003, Thomas et al. 2004).

Atmospheric CO_2

National and regional scale forest process models suggest that in some areas, elevated atmospheric CO_2 concentrations may increase forest productivity by five to 30 percent (Finzi et al. 2007). Wetter future conditions in some areas may also enhance the uptake of carbon by ecosystems. However, other regions may experience greater than 20 percent reduction in productivity due to increasing temperatures and aridity. In some areas of the United States, higher atmospheric CO_2 may lead to greater forest water-use efficiency, while in other areas, higher evapotranspiration may result in decreased water flow (McNulty and Aber 2001). Species in today's highly fragmented landscape already face unprecedented obstacles to expansion and migration (Thomas et al. 2004), which may magnify the climate change threat to forests.

Temperature Increases and Water Availability

In general, boreal forest and taiga ecosystems are expected to move northward or upward at the expense of Arctic and alpine tundra, and forests in the northwestern and southeastern United States might initially expand, although uncertainties remain (Iverson et al. 2008). Within temperate and boreal forests, increases in summer temperatures typically result in faster development and reproductive success of insects as well as changes in timing of development. As a result, these insects may interact with plant and wildlife species in different and sometimes problematic ways (Asante et al. 1991, Porter et al. 1991). Conversely, decreases in snow depth typically decrease overwinter survival of insects that live in the forest litter and rely on insulation by snow (Ayers and Lombardero 2000). Drier

Carbon Sequestration

According to the U.S. Forest Service, terrestrial carbon sequestration is the process by which atmospheric CO_2 is taken up by trees, grasses, and other plants through photosynthesis and stored as carbon in biomass (trunks, branches, foliage, and roots) and soils (U.S. Forest Service 2009). Reducing CO_2 emissions from deforestation and forest degradation (known internationally as REDD/REDD+) and restoring forested land cover in areas where it has been lost could play a major role in efforts to constrain the further increase of CO_2 in the atmosphere. Although the destruction and conversion of tropical rainforests accounts for the majority of the buildup in GHGs from global land-use changes (IPCC AR4 2007), forests in North America are responsible for taking 140 to 400 million tons of carbon from the atmosphere and storing it in organic material per year. Because land-use changes and human population growth are expected to continue, the management of boreal and other North American forests for carbon sequestration is an important component in adapting and responding to climate change (Birdsey et al. 2007).

In the continental United States, land-use management can be utilized as a means of contributing to GHG sequestration efforts. For example, the National Wildlife Refuge System has conducted a number of projects restoring forested land cover throughout the system, and there is potential for many more such projects. In addition, no-till agriculture may reduce the emissions of CO_2 from the breakdown of organic matter in soils, and broader utilization of this cropping technique in the American agricultural sector could make a substantial contribution to limiting emissions of CO_2 (Paustian et al. 2000). Also, opportunities to protect U.S. tropical forests in Hawaii, Puerto Rico, and elsewhere as well as habitats such as coastal marshes may provide dual benefits of carbon sequestration and habitat protection.

conditions in the southern United States and elsewhere could lead to increased fire severity and result in decreases in ecosystem carbon stocks (Aber 2001, Westerling et al. 2006, Bond-Lamberty et al. 2007). Similarly, prolonged drought may lead to decreases in primary production and forest stand water use (Van Mantgem et al. 2009). Drought can also alter decomposition rates of forest floor organic materials, impacting fire regimes and nutrient cycles (Hanson and Weltzin 2000). Changes in temperature, precipitation, soil moisture, and relative humidity can also affect the dispersal and colonization success of other forest pathogens (Brasier 1996, Lonsdale and Gibbs 1996, Chakraborty 1997, Houston 1998).

BARK BEETLE OUTBREAKS IN WARMER WINTERS

From British Columbia to New Mexico, forests are being devastated at unprecedented levels by an epidemic—a tiny insect called the mountain pine beetle. The beetles lay their eggs under the bark of trees, and in the process, infect the trees with fungus. When the eggs hatch, the combination of fungal infection and feeding by the beetle larvae kill the trees.

Bark beetles and pine trees have co-existed for eons, causing regular outbreaks of forest death but nothing like those now being seen. So why has the beetle suddenly become so destructive? In the past, sub-zero winter temperatures kept beetle populations in check by directly killing the insects. Cold temperatures also kept the beetle from extending its range farther north and to higher elevations (Amman 1974).

The warming over the last few decades, however, has enabled more beetles to survive the winter and to move to higher elevations and northward to regions like British Columbia. They have rapidly colonized areas that were previously climatically unsuitable (Carroll et al. 2003). Because these new areas had not previously experienced beetle outbreaks, they contained mature stands of trees, which are particularly susceptible. In addition, warmer summer temperatures have sped up the life cycle of the beetle, enabling it to complete more generations per year (Carroll et al. 2003). All these changes have resulted in unprecedented forest death. The current outbreak in British Columbia, for instance, is 10 times larger in area and severity than all previous recorded outbreaks (Kurz et al. 2008).

This massive loss of trees poses major challenges to forest and ecosystem managers. But there are steps that can be taken to reduce the negative impacts and prevent spreading. According to the U.S. Forest Service, the governments of British Columbia and Alberta, in an attempt to avoid further eastward expansion and potential invasion of the boreal jack pine forests, implemented an aggressive control program to suppress beetle populations east of the Rocky Mountains through felling and burning infested trees. Since its inception in 2004, the program has managed to keep beetle populations from expanding (RMRS 2009).

Disturbances and Extreme Events

Disturbances such as wildfires, wind storms, and pest outbreaks are important to forests. Climate change is anticipated to alter disturbance frequency, intensity, duration, and timing, and may cause extreme changes in forest structure and processes (Dale et al. 2000, Running 2008). For example, predictive models suggest that the seasonal fire severity rating will increase by 10 to 50 percent over most of North America, which has the potential to overshadow the direct influences of climate on species distribution and migration (Flannigan et al. 2000). Certain forest systems, such as ponderosa pine forests, may be less resilient to fire disturbance than others because of infilling from young trees, which grew during periods of low fire frequency, increasing the severity of fires (Climate Impacts Group 2004). While projections of hurricane response to climate change are still uncertain, models agree on a dramatic increase in cyclone activity in the western North Pacific (Emanuel et al. 2008), and the intensity of Atlantic hurricanes is likely to increase as well (USGCRP 2009). If hurricane frequency and intensity increase, then a larger percentage of forests could be set back to earlier successional stages (Lugo 2000).

2.3.2 Shrubland Ecosystems

Shrublands of various types and sizes occur throughout the United States and total approximately 480 million acres (Heinz Center 2008) (see Figure 1). Shrublands are landscapes dominated by woody shrub species, often mixed with grasses and forbs (non-woody flowering plants). They provide habitat for numerous native plant and animal species. Sagebrush habitats alone support more than 400 plant species and 250 wildlife species (Idaho National Laboratory 2011), including 100 birds and 70 mammals (Baker et al. 1976, McAdoo et al. 2003). Climate change will increase the risk to shrubland species because many already live near their physiological limits for water and temperature stress.

Photo: NPS

Atmospheric CO_2

Increased CO_2 can lead to changes in species distribution and community composition in the shrublands. For example, the spread of cheatgrass has likely been favored by rising CO_2 concentrations, which has been shown to benefit species that utilize the type of photosynthesis (C3) (D'Antonio and Vitousek 1992, Larrucea and Brussard 2008) used by this species. In contrast, warmer and drier conditions may favor plants that utilize a different photosynthetic system (C4).

Temperature Increases

Since 1980, western U.S. winter temperatures have been consistently higher than the previous long-term average temperature, and average winter snow packs have declined (McCabe and Wolock 2009). Higher temperatures associated with climate change are likely to intensify water stress through increased potential evapotranspiration (Hughes 2003). The increase in temperature also further benefits invasive cheatgrass, which thrives in hot, open, fire-prone environments and crowds out native shrubland species, and may alter fire regimes. These types of changes in community composition may impact shurbland species like the greater sage grouse (Aldridge et al. 2008).

Water Availability

As a result of the warmer temperatures, the onset of snow runoff in the Great Basin is currently 10 to15 days earlier than 50 years ago, with significant impacts on the downstream use of the water (Ryan et al. 2008), though periods of higher than average precipitation have helped to offset the declining snow packs (McCabe and Wolock 2009). This can reduce the forage available for grazing wildlife, as well as the livestock carrying capacity on working lands. Climate changes in shrubland areas can be complex: in areas where both a reduction in total annual rainfall and increased intensity of individual precipitation events are projected, wet areas are likely to become wetter while dry areas may become drier. More intense rainfall events without increased total precipitation can lead to lower and more variable soil water content, and thus, reduce above-ground net primary production. However, some regions such as the Great Basin region are projected to become both warmer and possibly wetter over the next few decades (Larrucea and Brussard 2008).

2.3.3 Grassland Ecosystems

Photo: NPS

Grasslands, including agricultural and grazing lands, cover about 285 million acres of the United States, and occur mostly between the upper Midwest to the Rocky Mountains and from Canada to the central Gulf Coast (CEC 1997, Heinz Center 2008). Vegetation is very diverse, and includes many grass species mixed with a wide variety of wildflowers and other forbs. Grassland types include tallgrass, shortgrass, and mixed-grass systems, as well as embedded features such as the shallow, ephemeral wetlands known as prairie potholes and playas that dot the Great Plains and the Eastern grasslands that are openings in the prevailing forest matrix (see Figure 1). Grassland function is tied directly to temperature, precipitation and soil moisture, and therefore, climate change is likely to lead to shifts in the structure, function, and composition of this system. Grasslands also store significant amounts of carbon, primarily in the soil (IPCC WGII 2007).

Atmospheric CO_2

Increased CO_2 levels may affect the grassland system in multiple ways. For example, forage quality may decline due to increases in the carbon (C) to nitrogen ratios of plant material, resulting in lower crude protein content (Milchunas et al. 2005). In addition, plants that utilize C3-type photosynthesis (e.g., cheatgrass) stand to benefit from increased atmospheric CO_2 (D'Antonio and Vitousek 1992, Larrucea and Brussard 2008), while C4 species are more efficient at using water under hot, dry conditions and may respond favorably to increased water stress and lower soil moisture conditions. One CO_2 enrichment experiment on shortgrass prairie showed a 20-fold increase in cover of a C3 shrub over C4 grass cover (Morgan et al. 2007), while other reports show an advantage for C4 over C3 grasses in a CO_2-enriched, warmer environment (Morgan et al. 2011). The future distribution of these species will no doubt be influenced by the interaction of CO_2, available moisture, and temperature, which may produce grassland communities with altered species composition of plants and animals.

Temperature Increases and Water Availability

In recent decades, average temperatures have increased throughout the northern Great Plains, with cold days occurring less often and hot days more often (DeGaetano and Allen 2002). Precipitation has increased overall (Lettenmaier et al. 2008). Future changes projected for the Great Plains include increasing average annual temperatures from approximately 1.5 to 6 ºF by mid-century to 2.5 to 13 ºF by the end of the century. More frequent extreme events such as heat waves, droughts, and heavy rains; and wetter conditions north of the Texas Panhandle are also projected (USGCRP 2009). However, the projected increases in precipitation are unlikely to be sufficient to offset overall decreases in soil moisture and water availability due to increased temperature and water utilization by plants as well as aquifer depletion (USGCRP 2009).

Climate change is expected to stress the sensitive prairie pothole habitat with increasing temperatures and changing rainfall patterns, which will alter rates of evaporation, recharge, and runoff in these pond systems (Matthews 2008). Recent modeling projects that the prairie pothole region of the Great Plains will become a much less resilient ecosystem, with western areas (mostly in Canada) likely becoming drier and eastern areas (mostly in the United States) having fewer functional wetlands. These changes are likely to reduce nesting habitat and limit this "duck factory" system's ability to continue to support historic levels of waterfowl and other native wetland-dependent species (Johnson et. al 2010). In addition to the significant ecological consequences, this could mean fewer ducks for waterfowl hunters across the United States.

Temperature changes are also likely to combine with other existing stressors to further increase the vulnerability of grasslands to pests, invasive species, and loss of native species. For example, populations of some non-native pests better adapted to a warmer climate are projected to increase, while native insects may be able to reproduce more quickly (Dukes and Mooney 1999).

LESSER PRAIRIE-CHICKEN IN A CHANGING CLIMATE

The lesser prairie-chicken, which resides mainly in the grasslands of the southern Great Plains region, is a species in trouble. The conversion of native rangelands to cropland, decline in habitat quality due to herbicide use, petroleum and mineral extraction activities, and excessive grazing of rangelands by livestock have all contributed to a significant decline in population leading to its Candidate status under the federal ESA (NRCS 1999).

Photo: AFWA

Climate change is expected to make the bird's plight worse. Climate change models project that temperatures in the lesser prairie-chicken's range will climb by about 5 °F and that precipitation will decrease by more than one inch per year by 2060 (USGCRP 2009). Such changes would likely harm the lesser prairie-chicken's chances of survival.

The good news is that simple management steps can make a big difference. Under existing U.S. Department of Agriculture conservation programs, farmers and ranchers are paid to take land out of production to create wildlife habitat. In fact, a landscape-scale geospatial analysis has shown that restoring native prairie grasses and sagebrush on 10 percent of land enrolled in the Conservation Reserve Program, if properly targeted, could offset the projected population decline of lesser prairie-chicken from climate change (McLachlan et al. 2011).

2.3.4 Desert Ecosystems

Deserts are characterized by temperate climates having low annual rainfall, high evaporation, and large seasonal and diurnal temperature contrasts. The hot desert systems of the United States include the Mohave, Sonoran, and Chihuahuan Deserts (note that the so-called "cold deserts" including much of the Great Basin, are covered in this *Strategy* under Shrublands, see Figure 1). This definition includes embedded features such as "sky islands" and mosaics of grasses and shrubs. Desert systems harbor a high proportion of endemic plants, reptiles, and fish (Marshall et al. 2000). Desert ecosystems are particularly susceptible to climate change and climate variability because slight changes in temperature, precipitation regimes, or the frequency and magnitude of extreme events can substantially alter the distribution and composition of natural communities and services that arid lands provide (Archer and Predick 2008, Barrows et al. 2010).

Temperature Increases

Photo: AFWA

Like most of the rest of the United States, the arid west and southwest have been warming over the last century. Climate models project that these areas will continue to warm a further 3.6 to 9.0 °F by 2040 to 2069 in the summer months (AZ CCAG 2006), while parts of southern Utah and Arizona have already seen greater than average increases in temperature (e.g., 3 to 5 °F; USGCRP 2009). Most models project drying, increased aridity, and continued warming in the deserts, as well as increased severity and duration of droughts (USGCRP 2009). Higher temperatures and decreased soil moisture will likely reduce the stability of soil aggregates, making the surface more erodible (Archer and Predick 2008). Other trends include widespread warming in winter and spring, decreased frequency of freezing temperatures, a longer freeze-free season, and increased minimum winter temperatures (Weiss and Overpeck 2005).

Water Availability

The southwest has experienced the smallest increase in precipitation in the last 100 years of any region in the coterminous United States (CCSP 2008b). Precipitation is projected to increase slightly in the eastern Chihuahuan Desert but decrease westward through the Sonoran and Mojave Deserts (Archer and Predick 2008). Overall water inputs are expected to decline due to the combined effects of reduced total precipitation, elevated water stress in plants at higher temperatures, and greater run-off losses associated with increased frequencies of high intensity convectional storms (Archer and Predict 2008). Declining rainfall may eliminate wetlands, especially in marginally wet habitats such as vernal pools and in near-deserts. Varied rainfall and higher temperatures will also likely exacerbate existing stressors coming from recreation, residential, and commercial development and improper livestock grazing (Marshall et al. 2000).

Although precipitation-fed systems are most at risk, groundwater-fed systems in which aquifer recharge is largely driven by snowmelt may also be heavily affected (Burkett and Kusler 2000, Winter 2000). Reductions in water levels and increases in water temperatures will potentially lead to reduced water quality and decreased dissolved oxygen concentrations (Poff et al. 2002). Decreased water availability and expanded development will also impact desert riverine and riparian ecosystem function and disrupt movement corridors through the desert, which provide important habitat for arid land vertebrates and migratory birds (Archer and Predick 2008).

Many desert plants and animals already live near their physiological limits for water and temperature stress. For example, diurnal reptiles may be particularly sensitive due to their sedentary behavior and occurrence in very hot and dry areas (Barrows 2011). When compounded by persistent drought, climate change creates conditions that favor drought-tolerant species, leading to new species compositions of natural communities (CCSP 2009b). For example, Saguaro density and growth has declined with drought and reduced perennial shrub cover, and the range and abundance of this charismatic species will likely decline as well. Similarly, the abundance and range of nonnative grasses will most likely increase in future climates, including the spread of cheatgrass and buffelgrass (Enquist and Gori 2008). These and other non-native species have significantly altered fire regimes, increasing the frequency, intensity, and extent of fires in the American Southwest (D'Antonio and Vitousek 1992, Brooks and Pyke 2002, Heinz Center 2008).

CACTUS VULNERABILITY

Photo: FWS

Cacti may be an iconic symbol of the arid American desert, but this symbol faces an increasingly uncertain future. Adapted to hot, dry environments such as those found in the southwestern deserts of the United States, most cacti species have very specific habitat requirements that also make them highly vulnerable to climate change and susceptible to small changes in their environment. Another key vulnerability is potential disruption of associated species interactions under climate change. For example, many cacti depend on other species for pollination, to provide habit, or to protect them from herbivores. Changes in climate may result in mismatches in time or space between the cacti and other species upon which they depend.

While helping these species adapt will be challenging, the first key management step is figuring out which species are the most vulnerable and which might be able to survive or even thrive in a climate-changed world. One such assessment is already underway. NatureServe is seeking to develop Climate Vulnerability Indices for over a hundred cactus species found in the Sonoran, Mojave, and Chihuahuan deserts. This process includes assessing a species' exposure and sensitivity to climate change through several factors, which are combined into a categorical vulnerability score. For example, in the Chihuahuan Desert, most cactus species assessed were either moderately (43 percent), highly (21 percent) or extremely (four percent) vulnerable to climate change (Hernández et al. 2010).

These types of vulnerability indices highlight the need for continued research on how climate change is likely to impact particular species and can help to establish priorities for adaptation activities. They are also tools to better inform management plans and conservation activities. In addition, vulnerability assessments may also help us identify those instances when viable adaptation measures simply may not be available.

Disturbances and Extreme Events

An increased frequency of extreme weather events such as heat waves, droughts, and floods is projected (Archer and Predick 2008, IPCC 2011). For example, climate change is projected to increase the frequency and intensity of storm events in the Sonoran Desert (Davey et al. 2007). This will result in longer dry periods interrupted by high-intensity rainstorms, and has the paradoxical effect of increasing both droughts and floods. Erosive water forces will increase during high-intensity runoff events, and wind erosion will increase during intervening dry periods (Archer and Predick 2008).

2.3.5 Arctic Tundra Ecosystems

Arctic tundra is the ecological zone of the polar regions of the Earth, occurring mainly north and west of the Arctic Circle and north of the boreal forest zone. Alpine tundra is the ecological zone occurring above treeline even in the non-polar regions of the Earth (see Case Study on Alpine Tundra on p. 37). This section focuses on the much more extensive Arctic tundra. Arctic tundra is characterized by an absence of trees, and occurs where tree growth is limited by low temperatures and short growing seasons. In the United States, Arctic tundra ecosystems represent 135 million acres on the North Slope and west coast of

Photo: FWS

Alaska (Gallant et al. 1995, Heinz Center 2008) (see Figure 1). In most areas, soils are underlain by permanently frozen ground, known as permafrost, with a shallow thawed layer of soil that supports plant growth in the summer. Alaska's tundra contains one of the largest blocks of sedge wetlands in the circumpolar Arctic (one quarter of global distribution) and provides breeding grounds for millions of birds (more than 100 species). Climate-driven changes in the tundra ecosystem are already being observed, and include early onset and increased length of growing season, melting of ground ice and frozen soils, increased encroachment of shrubs into tundra, and rapid erosion of shorelines in coastal areas (Hinzman et al. 2005, Richter-Menge and Overland 2010).

Atmospheric CO_2

Fire is predicted to increase in the Arctic tundra if the climate continues to warm (Krawchuck et al. 2009). This has the potential to release carbon that has taken decades to store, in a matter of hours, increasing the amount of CO_2 in the atmosphere (Hansen and Hoffman 2011, Mack et al. 2011). In addition, the thawing of frozen organic material stored in tundra soils will release huge amounts of GHGs such as CO_2 and methane into the atmosphere, contributing to climate change (Schaefer et al. 2011) and exacerbating climate change in a way that none of the global climate change models have taken into account.

Temperature Increases

Climate is changing worldwide, but the Arctic has already warmed at a rate almost twice the global average (ACIA 2004). Spring snow melt has been occurring earlier as temperatures increase, leading to an earlier "green-up" of plants. A longer snow-free season also leads to local landscape warming that contributes to further climate change (Hinzman et al. 2005). Increased frequency of freeze-thaw-freeze events are another by-product of warming winter temperatures in the Arctic and sub-Arctic. Historically, fires have been rare on Alaskan tundra, but fire frequency will likely increase as the climate warms. A positive feedback relationship can result, as soils tend toward warmer and drier conditions after fire, promoting shrub growth and a more fire-prone landscape (Racine et al. 2004).

Analysis of satellite images has shown an increase in greenness in arctic Alaska over the last three decades indicating increased plant cover (Hinzman et al. 2005). Other studies have documented recent advancement of trees and tall shrubs onto tundra, which is expected to continue (Lloyd et al. 2003, Tape et al. 2006). Similarly, Arctic specialist animals may face increased competition as less cold-tolerant species expand their ranges northward (Martin et al. 2009). For example, the arctic fox may suffer if competitors such as red foxes continue to increase in abundance.

CLIMATE CHANGE IN ALPINE TUNDRA SYSTEMS

In 2007, researchers found a significant decline in the alpine tundra (or Köppen) ecosystem in the mountainous western United States (Diaz and Eischeid 2007). Average temperatures in the western United States have risen considerably in the last 20 years, greatly affecting alpine tundra systems. The warmest month in many of these areas has seen an average temperature rise from as low as 47.3 °F to over 50 °F (Diaz and Eischeid 2007). This phenomenon has resulted in a loss of 73 percent of area classified as alpine tundra in the last 20 years. Many of the remaining areas still classified as alpine tundra systems are experiencing average warmest month temperatures creeping towards the critical threshold of 50 °F, making it likely that with continued warming, these areas will no longer sustain alpine tundra systems in the long term (Diaz and Eischeid 2007).

In alpine systems, snow is of particular importance as it influences plant phenology, growth, and species composition (Wipf et al. 2009). Climate change also affects alpine areas as the snow -to-rain ratio decreases while the timing of snowmelt advances. While warming temperatures may allow for a longer growing season, the decrease in snow depth and earlier snowmelt will ultimately have a negative effect on many alpine plants, because the advanced snowmelt creates a higher number of frost days as well as lower soil temperatures due to lower snow cover (Wipf et al. 2009). Not every plant species has the same reaction to climate warming, but research suggests that greater temperatures and advanced snowmelt could harm alpine systems and the species that depend on them.

Water Availability

While precipitation is generally expected to increase in the future, models project a generally drier summer environment due to higher air temperatures, increased evaporation, and increased water use by plants (SNAP 2008). Changes in overall water balance strongly affect this habitat, where water remains frozen most of the year. Fish will be affected by higher water temperatures and by the changes in precipitation, soil moisture, soil and water chemistry, and drainage related to permafrost degradation (Martin et al. 2009). Similarly, changes in water flow, water chemistry, turbidity, and temperature could cause physiological stress to species that cannot adapt to the new conditions. Some Arctic fish species migrate between marine and freshwaters, while others remain in freshwater throughout their life history, and involve movements from limited overwintering habitat to spawning and feeding habitat. These fish species will suffer if stream changes prevent fish passage (Martin et al. 2009).

ALASKA CLIMATE CHANGE WORKING GROUP

Indigenous communities possess local environmental knowledge and relationships with particular resources and homeland areas, built up through hundreds and even thousands of years of place-based history and tradition, which may make them highly sensitive to and aware of environmental change. Climate change, with its promise of unprecedented landscape-level environmental change, is a threat not only to particular resources or features, but also to the traditions, the culture, and ultimately, the very health of the community itself. Indigenous communities lend unique and important perspectives and knowledge about landscapes and climates to the overall effort to respond to climate change, and recognize that they must work together to nurture native environmental knowledge, enhance indigenous capacity to use modern scientific methods, and create indigenous climate-change leadership.

Due to climate warming impacts such as coastal erosion, increased storm effects, sea ice retreat, and permafrost melt, the village of Newtok, home to the Qaluyaarmiut people for at least 2,000 years, has begun relocation plans. The Qaluyaarmiut are avid fishermen and depend on the natural environment for subsistence. With an average erosion rate of 68 feet per year from 1953 to 2003 and the combination of all the climate warming impacts it is enduring, Newtok is no longer a sustainable long-term home for the Qaluyaarmiut people (Feifel and Gregg 2010).

Members of the American Indian Alaska Native Climate Change Working Group represent a broad alliance of indigenous communities, tribal colleges, scientists, and activists, who recognize the significance of situations like Newtok, working together to empower indigenous climate-change adaptation. They argue that indigenous educational institutions are critical vehicles for nurturing indigenous environmental knowledge and scientific capacity, and can be organizers and leaders of regional indigenous responses to climate change (Upham 2011). Indigenous working groups provide neutral ground in a relaxed setting that promotes broad participation, and often lead to consideration of a broader spectrum of resources and issues than externally driven approaches.

Thawing Permafrost

Increasing seasonal melting of ground ice and frozen soils (permafrost) is already measurably altering habitats and water distribution on the landscape, allowing new hydrologic patterns to form (Jorgenson et al. 2006). Because of warming in western Alaska, permafrost has become absent or thin and discontinuous, and more changes are expected such as lake drying (Yoshikawa and Hinzman 2003). Large mammals such as caribou and muskoxen suffer when access to forage is hampered by deep snow pack or a hard snow crust, caused by winter thawing or rain-on-snow events which are expected to increase in a warmer climate (Martin et al. 2009). Changes in the quantity and quality of forage may also have profound effects on mammal populations, while wildlife pests and diseases are projected to increase their northern range limits (Martin et al. 2009). Warmer summers, a longer open water season, and delayed freeze-up would likely improve reproductive success for some bird species, though warmer summers could also cause drying of the wetland habitats and aquatic food sources that many birds rely upon. While birds time their breeding primarily to the solar calendar, increasing water temperature may cause aquatic insects to hatch earlier, resulting in a mismatch in timing.

Sea Level Rise

Particularly in western Alaska, large areas of low-lying coastal plain bird habitat are predicted to disappear within this century, due to sea level rise and storm surges. This degradation may only be partially offset by increased sedimentation rates and tectonic rebound in some areas.

Additionally, the vast shallow wetlands of coastal plain tundra are sensitive to changes that could lead to drying. Any intrusion of saline water into formerly fresh systems results in rapid and dramatic change in vegetation (Martin et al. 2009).

Sea Ice Change

Summer sea ice has receded dramatically near northern and western Alaska in recent decades. The lack of near-shore ice in summer has made the shoreline more vulnerable to storm-induced erosion, reducing the value of these areas as wildlife habitat (Hinzman et al. 2005). In some areas, erosion rates have doubled since the middle of the last century (Mars and Houseknecht 2007). Decreasing sea ice is causing more polar bears to den and forage on land rather than on the sea ice. As a result, they can experience negative encounters with grizzly bears and humans.

2.3.6 Inland Water Ecosystems

Inland waters range from ephemeral pools and intermittent streams to large regional and national features such as the Great Lakes, Mississippi River, Ogallala aquifer, and Everglades. For the purposes of the *Strategy*, inland waters end at the high tide line and include natural features such as wetlands, rivers, and lakes, as well as artificial and human-altered waterbodies such as ponds, reservoirs, canals, and ditches (Cole 1994, see Figure 1). These waters and associated riparian areas provide habitats to support a broad range of aquatic and terrestrial wildlife and vegetation, and provide ecological connectivity. Increasing global air temperatures and changing precipitation patterns are raising water temperatures and changing stream flows, affecting such ecosystem processes as productivity and decomposition and disrupting food web relationships.

Temperature Increases

Photo: FWS

A recent analysis showed that many rivers and streams in the United States have warmed over the past 50 to 100 years (Kaushal et al. 2010), and will continue to warm up to 0.5 °F per decade, based on GHG emissions scenarios (IPCC AR4 2007). Water temperature affects the physiology, behavior, distribution, and survival of freshwater organisms, and even slight changes can have an impact (Elliott 1994). Water temperature increases will allow the geographic area suitable for warm-water aquatic species to expand (Eaton et al. 1995, Eaton and Sheller 1996, Pilgrim et al. 1998, Poff et al. 2002, Rieman et al. 2007, Rahel and Olden 2008, Williams et al. 2009). The number of streams with temperatures suitable for warm-water fish and other freshwater organisms is projected to increase by 31 percent across the United States (Mohseni et al. 2003). This would likely mean a concomitant decline of cold water fisheries habitat.

These temperature increases will harm some inland water species. For example, one long-term study showed that a 1.2 °F increase in stream temperature caused coho salmon fry to emerge from the gravel six weeks earlier and move to the ocean two weeks earlier. This causes lower survival rates due to a mismatch in timing with peak prey abundance in the ocean (Holtby et al. 1990). Higher temperatures and more severe droughts also dry up streambeds and wetlands, harming species such as waterfowl (Johnson et al. 2005). Temperature increases could lead to changes in predation. For instance, it is projected that there would be a four to six percent increase in per capita consumption of salmonids by smallmouth bass and walleye for every 1.8 °F increase of annual river temperatures near the Bonneville Dam on the Columbia River (Rahel and Olden 2008). Warming temperatures also increase the susceptibility of organisms to disease, and may allow diseases to spread for longer periods and reproduce more quickly. For example, low flows and warmer waters contributed to a massive fish kill from a parasite infestation among spawning Chinook salmon in the Klamath River in September 2002 (CADFG 2008).

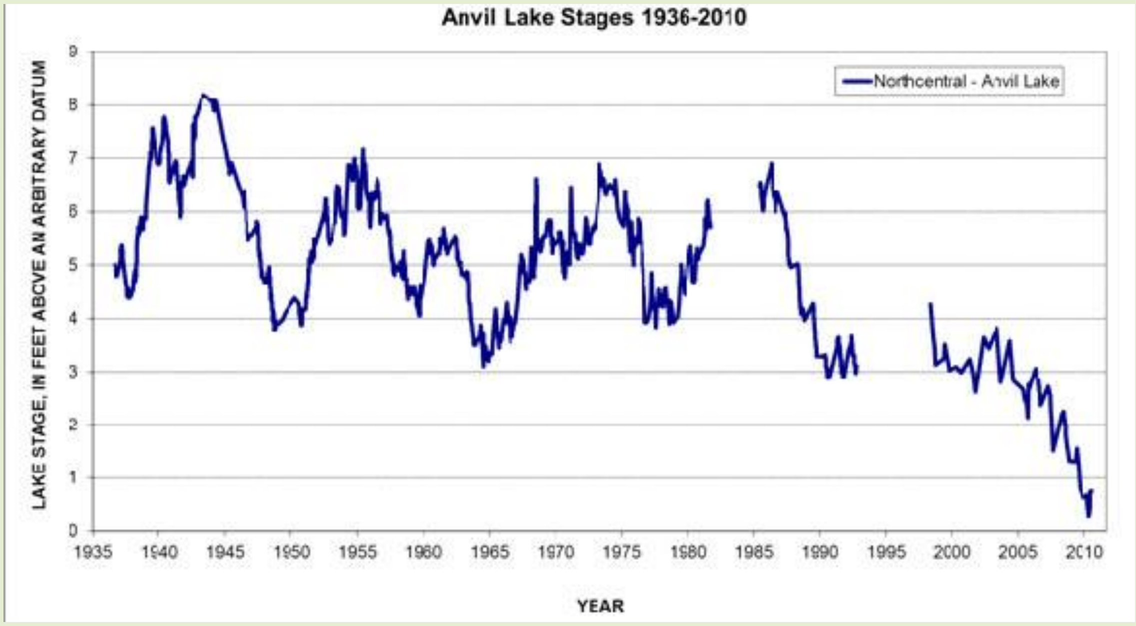
WATER LOSSES UNDER CLIMATE CHANGE

Between 2000 and 2010, the worst drought ever recorded since Euro-American settlement hit the Colorado River Basin. Water levels in Lake Mead dropped to record lows. The drought not only threatened the supply of water to cities like Las Vegas, it also harmed the ecosystems and riparian areas that support countless fish, plants, and animals and endangered species, like the humpback chub and the southwestern willow flycatcher.

Climate models project that the decade-long drought that gripped the region may become the normal climate instead of the rare exception, perhaps as soon as the end of the 21st century (Barnett and Pierce 2009, Rajagopalan et al. 2009). The threat is being taken seriously by the Bureau of Reclamation, which has developed a plan that brings all stakeholders together in an attempt to balance human needs for water while providing sufficient flows and habitat for sustainable fish, wildlife, and plant populations.

Similar challenges must be faced around the nation. Long-term records at Anvil Lake, a groundwater-fed lake in northern Wisconsin, highlight the importance of water levels to fish, wildlife, and plant species. Over centuries, the lake's water level has risen and fallen. However, Anvil Lake's water level became progressively lower during each succeeding dry period, especially during the most recent dry period (WICCI 2011). In the future, any water loss through evapotranspiration associated with warmer temperatures would be expected to exacerbate any drought effect in similar aquatic systems.

These examples hold an important lesson for adaptation strategies. To help plants, wildlife, and ecosystems adapt to a changing climate, it is not enough to focus just on the natural world. Ensuring that ecosystems have enough water in regions expected to experience more droughts will require working with farmers, municipalities, energy industries, among others, to reduce the overall demand for the increasingly scarce water.



Water levels for Anvil Lake in North central Wisconsin, 1936-2010 (WICCI 2011; USGS lake stage data)

Water Availability

Precipitation changes in the United States are projected to vary regionally. Higher precipitation and runoff in the winter and spring are expected in the Northeast and Midwest, and decreasing precipitation and runoff are expected in the arid West in spring and summer (USGCRP 2009). In areas of high snowpack, runoff is beginning earlier in the spring and stream flows are lower in the late summer. This affects flow-dependent species and estuarine systems and reduces habitat area and connectivity while increasing water temperature and pollution levels. In contrast, higher flows and frequent storms can create wider floodplains, alter habitat, increase connectivity, displace riparian and bottom-dwelling species, or further distribute invasive species (Le Quesne et al. 2010). Changing flood and freshwater runoff patterns can impact critical life events such as the spawning and migration of salmon. Increased evaporation of seasonal wetlands and intermittent streams can also destabilize permanent waterbodies and cause a loss of habitat or a shift in species composition (Le Quesne et al. 2010).

Lake Stratification

Ice cover on freshwater systems is sensitive to climate changes (Magnuson 2002). Higher air and water temperatures shorten lake ice cover seasons, increase evapotranspiration and thermal stratification, and increase winter productivity of lake systems. In shallow lakes these changes will increase winter oxygen levels and favor predator fish such as northern pike over a diverse community of fish species adapted to depleted oxygen levels (WICCI 2011). In contrast, deeper, less productive lakes in the northern United States could face lower oxygen levels in bottom waters during the summer as prolonged warm weather lengthens thermal stratification periods, isolating bottom waters from oxygen exchange. Depleted oxygen throughout the entire zone of bottom waters would harm coldwater fish such as lake trout and cisco.

Lake Level Change

Great Lakes water levels are expected to decrease significantly due to climate-driven changes in precipitation and evapotranspiration (USGCRP 2009, Angel and Kunkel 2010). Lower water levels will lead to desiccation of coastal habitats that do not (or cannot) migrate with retreating shoreline, likely stressing fish species that rely on wetlands as nursery habitat. Shorebirds may also experience a loss of nesting habitat as beaches may become overrun by opportunistic invasive species such as *Phragmites.* At the same time, new wetlands may be formed as a result of accretion in other areas. A decrease in the extent and duration of lake ice will also affect lake species and habitats. For example, lake ice enhances the overwinter survival of fish eggs and protects shoreline habitat from erosion during winter storms (ASCE 1999). Longer periods without lake ice cause greater evaporation and can increase lake-effect snows if air temperature is favorable for snow (Lofgren et al. 2002).

Disturbance and Extreme Events

As the climate warms, altered precipitation patterns may manifest as heavy storms that punctuate extended periods of hot, dry weather, yielding floods. Heavy storms will also cause increased run-off with associated erosion, sedimentation, and pollution. Increased tidal/storm surges will also affect freshwater ecosystems, especially with increases in hurricane and typhoon intensities (IPCC WGII 2007). Tidal and storm surges can cause oxygen depletion, changes in salinity, mud suffocation, and turbulence (Tabb and Jones 1962).

2.3.7 Coastal Ecosystems

Photo: NOAA

The Pacific, Atlantic, Arctic, Gulf of Mexico, and Great Lakes coastal systems, as defined for the *Strategy*, extend seaward to mean lower-low water and landward to all lands that drain directly into an estuary, ocean (including the entirety of off-shore islands), or Great Lake (see Figure 1). They include the waters and sub-tidal zones of estuaries, semi-enclosed bays, and lagoons, as well as emergent and wooded wetlands, open water and aquatic beds, and unconsolidated and rocky shorelines. In addition to increases in air and water temperature, coastal ecosystems will experience climate impacts that include: sea and lake level changes; increases in storm surge; alterations in precipitation patterns and subsequent delivery of freshwater, nutrients, pathogens, and sediment; changes in intensity of coastal storms; changes in water chemistry; and changes in sea ice.

Elevated CO_2 and Ocean Acidification

While not a climate change impact per se, ocean acidification is associated with increasing atmospheric CO_2 and will cause changes to many key biological processes in coastal and marine systems. For example, increased acidity in estuaries will affect shellfish species that use carbonate minerals to build their shells, as these minerals are more readily dissolved in lower pH environments (USGCRP 2009). Elevated CO_2 concentrations are also expected to increase photosynthesis and productivity for many plants, such as mangroves and emergent and submerged vegetation. These increased growth rates may be reduced in areas that experience additional stress due to coastal pollution, which can also exacerbate the effects of ocean acidification (Adam 2009).

Temperature Increases

Global ocean temperatures rose 0.2 °F between 1961 and 2003 (IPCC AR4 2007). Temperature changes affect species phenology, including key events such as the spring phytoplankton bloom, plant germination and turtle nesting. Changes in temperature also can cause species range shifts (Harley et al. 2006, Hoegh-Guldburg and Bruno 2010). While warmer temperatures could cause increased growth of coastal salt marshes and forested wetlands, they could also cause expansion of invasive species and disease pathogens. Extreme changes may also stress organisms to the point of mortality. In estuarine environments, increased water temperature will affect water column stratification and eutrophication; and could cause range shifts. In addition, warmer temperatures will exacerbate low summer oxygen levels (such as those in mid-Atlantic estuaries and the Gulf of Mexico) due to increased oxygen demand and decreased oxygen solubility (Najjar et al. 2000). In Alaska, rapid warming has led to severe shoreline erosion due to longer seasons without ice cover as well as to land subsidence due to permafrost melt and sea level rise. These changes have made the coast far more vulnerable to wind and wave damage (Larsen and Goldsmith 2007). For high islands, such as those in Hawaii, warmer temperatures will increase stress on forest species, including birds, plants, and insects, which need cool, moist conditions to survive.

Sea Level Rise

As water warms, it expands, and the ocean surface rises. Additional sea level rise is caused by the melting of inland glaciers and continental ice sheets, including those in Greenland and Antarctica. Sea level is projected to increase 16 to 79 inches by 2090 (IPCC AR4 2007, Rahmstorf 2010); however, sea level change is highly variable regionally.

Changes in Sea Ice

Changes in the extent, thickness, condition, and duration of sea ice are direct impacts of changes in global temperature. Warming triggers loss of sea ice, creating open water conditions. These conditions in turn allow higher wave energy to reach the shoreline (particularly during storms), accelerating the rate of coastal erosion (USGCRP 2009). Retreat of sea ice will result in loss of important habitat for species that depend on the ice, such as polar bears and walrus. Similarly, the timing of the spring phytoplankton bloom is directly tied to the location of the sea ice edge over the Bering Sea shelf (Stabeno et al. 2001). In addition, warmer temperatures could change food web dynamics by allowing for the migration of different predator and prey species in the Arctic (Forbes et al. 2011). Changing ice conditions are threatening lifestyles and subsistence economics of indigenous peoples as well, such as by making trips to hunting grounds more hazardous (Forbes et al. 2011). Warmer temperatures could also extend the growing season, increasing primary production in the summer.

Sea Level Rise and Coastal Inundation

Sea level rise is a key driver of coastal geomorphologic change. The immediate effects of sea level rise are the submergence and increased inundation of coastal land and increased salinity in estuaries and coastal rivers. Additional physical effects include increased erosion, changes in geomorphology, and saltwater intrusion in groundwater and into tidal freshwater marsh systems. Sea level rise will also exacerbate flooding events ranging from spring tides to tropical or extratropical storms, and will cause inland penetration of storm surge into areas not accustomed to inundation. These areas will likely experience flooding more often. While sea-level changes have occurred repeatedly in the geologic past, the accelerated pace of sea level rise in the 20th and 21st centuries raises questions about how coastal ecosystems will respond (USGCRP 2009).

To preserve the current acreage of tidal wetlands, either wetlands need to keep pace with sea-level rise or migrate inland to adjacent lands that are undeveloped, which is dependent on the availability and slope of an upland corridor, the pace of the rise, erosion rates, and the potential for wetland accretion (CCSP 2009a). Other important factors that affect wetland response to sea-level rise depend on the rate of sea level rise, tides, salinity, elevation, sediment dynamics, and the habitats and species present. In populated coastal areas, wetland migration is often constrained by land development and shoreline stabilization measures. These conditions can result in the crowding of foraging and bank-nesting birds and the loss of crucial coastal habitat for certain species such as the diamondback terrapin, which requires both marsh and beach habitats (Shellenbarger Jones et al. 2009). Marsh islands are already being lost in the Mid-Atlantic due to sea level-related flooding and erosion, which threatens island nesting bird species (Shellenbarger Jones et al. 2009). In addition, the degradation and loss of tidal marshes affect estuarine habitat, production of commercially important fish and shellfish species, and flood attenuation, key ecosystem services for coastal communities.

As noted in the previous section (Inland Water Ecosystems) Great Lakes levels are expected to decrease, having different shoreline and habitat effects from ocean coasts that will experience rising water levels.

ATLANTIC COAST PIPING PLOVER HABITAT CONSERVATION

Photo: Bill Byrne

Decisions regarding coastal management, such as stabilization, retreat, and beach nourishment will strongly influence the effects of sea level rise on the Atlantic Coast piping plover, a threatened beach-nesting bird protected under the ESA. Piping plovers breed from Maine to North Carolina, and favor wide, gently sloping ocean beaches with blowouts, washovers, ephemeral pools, and sparse vegetation.

Federal and state agencies, nongovernmental organizations, and academic institutions are collaborating to couple a model of piping plover habitat evolution with a model of piping plover nest density and distribution. The habitat evolution model relates changes in physical habitat, such as topography, shoreline position, and vegetation, to changes in sea level and storminess (Gutierrez et al. 2011). A Bayesian approach is particularly well-suited to understanding and responding to climate change because future conditions, including results of habitat management experiments, are uncertain. Empirical data will be used to update and improve model forecasts. Model predictions will be used to develop sea level rise-related piping plover habitat conservation recommendations that can be implemented by land managers and inform regulatory authorities. Case studies incorporating explicit measures to preserve resilience of piping plover habitat to sea level rise into management plans for specific locations will demonstrate potential applications. Collaborators anticipate that model results may be readily translated to inform habitat management for other sensitive beach-strand species, such as least terns, American oystercatchers, Wilson’s plovers, and seabeach amaranth (a federally threatened plant species).

Sea level rise may also result in the inland movement of seawater, shifting the tidal influence zone of streams and rivers upstream and permanently inundating downstream riparian/coastal portions with brackish water (Riggs and Ames 2003). In the United States, these impacts are already apparent in freshwater swamps along Louisiana and Florida (IPCC 1997, Bowman et al. 2010, Migeot and Imbert 2011). In Florida, mangroves have advanced 0.93 miles inland over the last 50 years (Rivera-Monroy et al. 2011), and another 10 to 50 percent of the freshwater sawgrass prairie will be transformed to salt marsh or mangroves by 2100 (Kimball 2007). Salinity increases in formerly fresh or brackish surface waters and saltwater intrusion of shallow coastal groundwater aquifers will also result from sea level rise (USGS 2010). This may threaten systems such as tidal freshwater forested wetlands that support a variety of wildlife species and critical drinking water sources, especially in island ecosystems (Huppert et al. 2009). Sea level rise also threatens small and low-lying islands with erosion or inundation (Baker et al. 2006, Church et al. 2006, USGCRP 2009), many of which support high concentrations of rare, threatened, and endemic species (Baker et al. 2006).

Water Availability

Changes in precipitation will primarily impact coastal systems through changes in quantity, timing, intensity, and quality of freshwater flow into estuarine systems. The quantity of freshwater will affect salinity gradients and nutrient inputs, while changes in peak flow timing could affect phenology and migration cues. Changes in the timing and amount of freshwater, nutrient, and sediment delivery will also impact estuarine productivity. For example, changes in flow regimes may affect the abundance and distribution of suspension feeders, such as mussels, clams, and oysters, which could in turn alter food web dynamics as well as water clarity (Wildish and Kristmanson 1997). Increases in flow, turbidity, and eutrophication could also impact submerged aquatic vegetation due to reduced light penetration (Najjar et al. 2000), as well as organisms that rely on this habitat for food and shelter. These impacts of precipitation changes in estuaries will likely be exacerbated by non-climate stressors such as freshwater demand and extraction, eutrophication, and hypoxia.

Disturbances and Extreme Events

Increased storm wind strength due to elevated sea surface temperatures could lead to increases in wave height and storm surge (Scavia et al. 2002) and would be magnified by a higher sea level. The primary impacts associated with more intense storm systems include increased flooding and erosion. More intense storms, coupled with common manmade ecosystem alterations such as shoreline stabilization measures that impede or eliminate long-shore transport could lead certain barrier islands (and their habitats) to fragment and disappear instead of migrating and rebuilding. Impacts to coastal and estuarine beaches would affect biota such as: microscopic invertebrates that are critical to the food web; horseshoe crabs that rely on beaches for egg deposition; and migratory shorebirds that feed on the eggs, such as the red knot (Shellenbarger Jones et al. 2009). Shifts in the seasonal distribution of major storm events could also affect plants, wildlife, and fish. For example, an increase in the number or intensity of storms during the spring and early summer could substantially affect breeding success of coastal birds such as the piping plover. More infrequent but intense precipitation events can also lead to scouring of sediment and vegetation during peak flows, redistribution of sediment, resuspension of contaminated sediments, as well as increased pollutants from events such as combined sewer overflows.

2.3.8 Marine Ecosystems

For the purposes of the *Strategy*, marine ecosystems extend from the coastline to 200 miles seaward or the nearest international boundary (see Figure 1). This area, generally referred to as the U.S. Exclusive Economic Zone, spans 3.4 million square nautical miles of ocean, encompassing 1.7 times the land area of the continental United States. The *pelagic* (open water) and *benthic* (bottom) habitats support species ranging from microscopic planktonic organisms that comprise the base of the marine food web through kelp and eelgrass beds to a wide range of invertebrates and vertebrates. Higher temperatures and CO_2 levels have significant impacts on marine species and ecosystems. Marine systems and taxa respond physically, chemically, and biologically to both increases in ocean temperatures and the absorption of atmospheric CO_2. This leads to changes in nutrient availability, biological productivity, reproductive success, the timing of biological processes, distributions, migrations, community structure, predator-prey relationships, and entire biomes.

Photo: NOAA

Temperature Increases

Between 1961 and 2003, it is estimated that 90 percent of the heat gained by the planet has been stored in the world's oceans resulting in a global ocean temperatures rise of 0.2 °F, with much greater changes observed in some locations such as the Atlantic basin (Levitus et al. 2005, IPCC WGI 2007). The physical consequences of such warming include sea level rise, increases in storm frequency and intensity, increased stratification of the water column, and changes in ocean circulation. Warming sea temperatures also boost the energy available to initiate and intensify hurricanes and typhoons, and storm intensity is expected to increase as sea surface temperatures rise (IPCC WGI 2007).

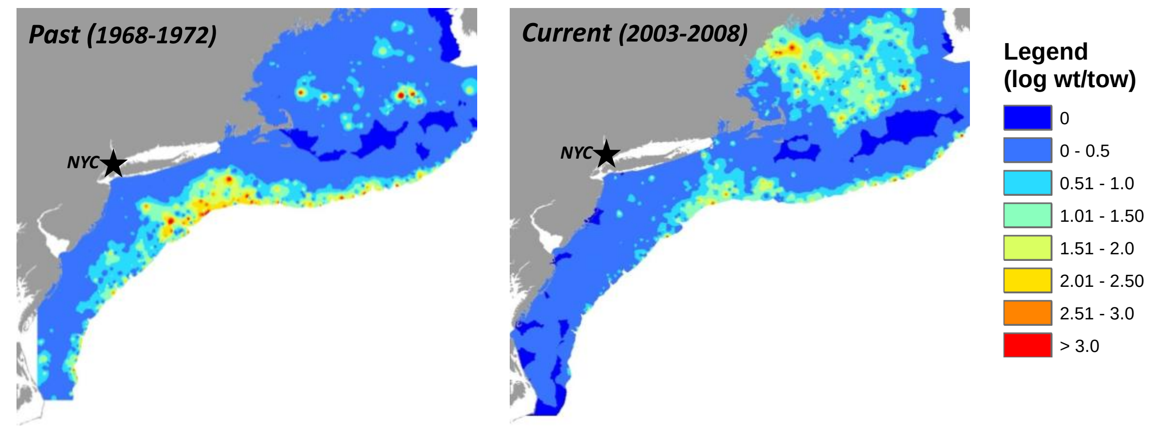
Altered patterns of wind and water circulation in the ocean environment will influence the vertical movement of ocean waters (i.e., upwelling and downwelling). This coupled with increased stratification of the water column resulting from changes in salinity and water temperature will change the availability of essential nutrients and oxygen to marine organisms throughout the water column.

Increasing ocean temperatures and the other associated changes in ocean conditions have a variety of impacts on fish, wildlife, and plants at multiple levels. These impacts range from changes in metabolic rates and energy budgets of individuals to changes in ecological processes such as productivity, species interactions, and even toxicity of compounds found in marine systems (Schiedek et al. 2007). Increasing air temperatures can also affect the growth and survivorship of early life history stages of some marine species whose larvae or juveniles use estuaries and other near-shore habitats as nursery areas (Hare and Able 2007). For example, increasing winter temperatures along coastal areas could increase the juvenile survivorship of these estuarine dependent species resulting in northward shifts in their distribution.

SHIFTING SPATIAL DISTRIBUTIONS OF U.S. FISH STOCKS

The United States is fortunate to have several multispecies fish monitoring programs in its large marine ecosystems where the abundance and location of important fish and macroinvertebrate species are consistently documented each year. Without these long time series of data, shifts in spatial distribution of U.S. fish stocks would never have been detected. Several studies using these data have found large distributional shifts in marine fish in the California Current Ecosystem (Hsieh et al. 2008), Bering Sea (Mueter and Litzow 2008), and the Northeast United States (Nye et al. 2009).

In the Northeast, two-thirds of 36 examined fish stocks shifted northward and/or to deeper depths over a 40-year time period in response to consistently warm waters (Nye et al. 2009). The figure below shows the past and present spatial distribution of a commercially important fish species, silver hake, as an example of shifts that have been observed in this area. Surf clams in this area also suffered higher mortality in recent warm years and are now found only at deeper depths (Weinberg 2005). Similarly, in the Bering Sea, fish have moved northward as sea ice cover is reduced and the amount of cold water from melting sea ice is reduced (Mueter and Litzow 2008). In both cases, fishers have to travel further and set their nets to deeper depths, increasing the costs associated with fishing. In both ecosystems, fish stocks are shifting closer to the borders of neighboring Canada and Russia, requiring coordinating monitoring and assessment of key stocks. In the California ecosystem, shifts in spatial distribution were more dramatic in species that were heavily fished (Hsieh et al. 2008). Combined, these studies stress the importance in preventing overfishing in healthy stocks to enhance recovery of those at low abundance such that these shifts in spatial distribution and the resilience of these species will not be exacerbated by climate change.



Silver hake distribution in the past as compared to its present distribution (Nye et al. 2011).

As discussed previously, species can respond to temperature changes by migrating poleward or toward deeper depths, reducing their climate niche within the existing range, evolving, or going extinct (Mueter and Litzow 2008, Cheung et al. 2009, Nye et al 2009, Overholtz et al. 2011). These individual responses lead to new combinations of species that will interact in unpredictable ways. In addition, changes in ocean circulation patterns will change larval dispersal patterns (Cowen and Sponaugle 2009) and the geographic distributions of marine species (Block et al. 2011). Between 2000 and 2100, warming in the North Pacific is projected to result in a 30 percent increase in the area of the subtropical biome, while areas of the equatorial upwelling and temperate biomes will decrease by 28 percent and 34 percent, respectively (Polovina et al. 2011).

Melting of sea ice and seabed permafrost is also a consequence of atmospheric and ocean warming, and will produce associated physical, chemical, and biological changes, including increased stratification in the water column. Species are particularly vulnerable in the Arctic, where shrinking ice cover reduces habitat and increases adult and juvenile mortality in some species. In Alaska, the melting of sea ice has forced walruses to congregate in large dense populations, which has led to many calves being crushed and a depletion of bottom food resources in the long term, due to the limited areas where they can rest between excursions for food (CEICC 2008). Variation in the spatial extent of sea ice and timing of the spring retreat has strong effects on the productivity of the Bering Sea ecosystem. For example, the timing of the spring phytoplankton bloom is directly tied to the location of the sea ice edge over the Bering Sea shelf (Stabeno et al. 2001). In 2008, the polar bear was listed as a threatened species under the ESA because of a projected decline in abundance. The main cause of this projected decline is malnutrition and reduced survival resulting from the projected loss of sea ice habitat required by polar bears and their prey (e.g., ring seals). In contrast, some species may benefit from climate change, such as the Atlantic croaker (see Case Study on Atlantic Croaker, p. 51, Hare et al. 2010) while some warmer water marine fishes may grow bigger or more rapidly (Nye et al. 2009).

Elevated CO_2 Levels and Ocean Acidification

Increased ocean acidification associated with increasing atmospheric CO_2 concentrations will directly and indirectly impact physiological and biological processes of a wide variety of marine organisms such as growth, development, and reproduction (Le Quesne and Pinnegar 2011). Even the most optimistic predictions of future atmospheric CO_2 concentrations (such as stabilization at 450 parts per million) could bring levels high enough to cause coral reefs to no longer be sustainable (Hoegh-Guldberg et al. 2007, Veron et al. 2009), bivalve reefs to slow or even stop developing, and large areas of polar waters to become corrosive to shells of some key marine species. There also are expected to be major effects on phytoplankton and zooplankton that form the base of the marine food chain. On the organismal level, a moderate increase in CO_2 facilitates photosynthetic carbon fixation of some phytoplankton groups. It also enhances the release of dissolved carbohydrates, most notably during the decline of nutrient-limited phytoplankton blooms. On the ecosystem level, these responses influence phytoplankton species composition and succession, favoring algal species which predominantly rely on CO_2 utilization (Riebesell 2004). These effects will then have cascading impacts on productivity and diversity throughout the ocean food web.

WEST COAST OYSTER PRODUCTION

In 2007 and 2008, two of the three major West Coast oyster hatcheries discovered that their Pacific oyster larvae were dying. It did not happen all the time, so researchers set out to understand why. Was something wrong in the water pumped from the sea into the hatcheries? By testing the water, researchers discovered a telltale pattern. The larvae died only when upwelling off the coast brought deep, cold water to the surface—and into the hatcheries (Feely et al. 2008). This cold water was low in calcium carbonate, the basic material in oyster shells. Without enough dissolved calcium carbonate (in a form known as aragonite), the oyster larvae struggled to survive.

The finding pointed to the ultimate culprit—the same rising CO_2 levels in the atmosphere that cause climate change. When CO_2 concentrations increase in the air, the ocean absorbs more CO_2. That increases the acidity of the water. Higher acidity (lower pH), in turn, means that the water cannot hold as much dissolved calcium carbonate. Compounding the issue is the fact that cold water, like that found on the bottom of the ocean, cannot dissolve as much calcium carbonate as warmer water can. Thus, the acidic cold water that is churned up during upwelling is especially harmful to the oyster larvae.

The hatcheries figured out ways around the problem. One of them measured concentrations of dissolved CO_2 in the seawater and pumped in water only when it was above a pH level of 7.75 (typically late in the day after plankton had lowered water CO_2 levels through photosynthesis). The other hatchery moved its intake from deep to shallow water.

But these steps do not solve the larger, far more significant problem—the increasing acidification of the oceans. Over the last six years, the difficulties faced by the hatcheries in rearing Pacific oyster larvae have been paralleled by poor supplies of naturally produced seed oysters in Willapa Bay, Washington—the most important oyster-producing bay on the West Coast. Acidification is already having a serious effect on the West Coast's $80 million per year oyster industry, which employs thousands of people in economically depressed coastal communities (PCSGA 2010). If the acidification of the oceans is the cause, then the problem will just get worse. Not just oysters will be at risk, but also the basic food webs in the oceans because so many species use calcium carbonate to build shells and skeletons.

Ocean Currents

Ongoing warming of the atmosphere and the ocean could cause major changes for key water masses and the processes they control. A change in the intensity and location of winds, such as the Westerlies moving northward in the Atlantic, will change surface ocean circulation. Currents such as the thermohaline circulation, which is driven by temperature and salinity gradients, can also be significantly affected by the warming climate. For instance, the circulation of deep ocean currents in the Atlantic and Pacific Oceans could slow. These large scale changes in circulation could have localized impacts such as increased ocean stratification and alterations to upwelling and coastal productivity, which in turn will change the availability of essential nutrients and oxygen to marine organisms throughout the water column. In addition, changes in ocean circulation patterns will change larval dispersal patterns and the geographic distributions of marine species (Block et al. 2011).

CORAL REEF BLEACHING

Photo: NOAA/Eakin

Coral reefs are one the most productive ecosystems on Earth. At the heart of the coral reef's success is a symbiotic relationship between coral and microscopic algae within the living coral. The coral provides the nutrients that the algae need to capture CO_2 through photosynthesis. The algae, in turn, provide coral with the carbon they need to build their skeletons—and thus, the reef itself.

A changing climate is threatening this symbiotic relationship and the whole coral reef ecosystem. When sea temperatures rise too much, the coral expel their alage, a process called bleaching (since the coral become whiter without their symbionts). In 2005, up to 90 percent of shallow-water corals in the British Virgin Islands bleached in response to increased water temperatures (Wilkinson and Souter 2008). Bleaching has profound effects on corals and the loss of the symbionts can ultimately cause the bleached coral to starve to death.

Bleaching isn't the only threat to coral. Rapid increases in the atmospheric CO_2 concentration, and thus, ocean acidification, may be the final insult to these ecosystems. The absorption of atmospheric CO_2 by the world's oceans contributes to chemical reactions which ultimately reduce the amount of carbonate making it unavailable to coral to build their skeletons (Hoegh-Guldberg et al. 2007).

An effort is underway to try to protect coral reefs by making them more resilient to climate change. The Nature Conservancy has started a Reef Resilience program, working in the Florida Keys in partnership with the State of Florida, NOAA, and Australia's Great Barrier Reef Marine Park Authority, to understand the non-climate factors that adversely affect coral reefs such as damage from charter and private vessels and improper erosion control. The hope is that by reducing these non-climate stressors, the coral will be better able to resist being bleached when sea temperatures increase. A related approach, being studied by scientists at the University of Miami, Australia Institute of Marine Science, and elsewhere, is actively inoculating corals with algal symbionts that are resistant to higher water temperatures.

2.4 Impacts to Ecosystem Services

As noted in Section 1.2.3, species and the ecosystems they form provide a wide range of important products and services to the nation, including food, clean water, protection from storms, recreation, and cultural heritage. These natural resources and ecological systems are a significant source of economic wealth. Climate change is likely to affect the spectrum of ecosystems services. In some cases or for some periods, these changes may be positive as with expanded growing zones for some agricultural crops in the Northern latitudes, or with the expansion of warm water fisheries. On balance, however, the scientific community has warned that an increase in global average temperature above 4 ^{0}F risks dangerous interference with the climate system and many adverse impacts on natural systems and the wealth they generate (IPCC AR4 2007). Recall that the current range of estimates for global average temperature increase by 2100 is 2.0 to 11.5 ^{0}F.

The products and services that natural resources provide support millions of jobs and billions of dollars in economic activity. As a result, the impacts from climate change on species and ecosystems are expected to have significant implications for America's communities and economies. In some cases, the implications could be positive and in other cases negative. The timing of any of these changes is uncertain. For example, changes in distribution and productivity of forests will have direct consequences for both global carbon sequestration and the forest products industry, and will also influence other uses of forested ecosystems such as recreation and non-timber products.

Agriculture is a fundamental component within the grassland system matrix, and is also sensitive to climate changes. The same stressors that affect grasslands affect agriculture, and can decrease crop yields (Ziska and George 2004). In the case of crop production, research suggests that crop plant responses to increasing CO_2 are varied, and therefore, it is difficult to determine winners and losers (Taub 2010). The benefits from increased CO_2 and a longer growing season may not be sufficient to offset losses from decreasing soil moisture and water availability due to rising temperatures and aquifer depletion. Decreasing agricultural yields per acre could also increase pressure for the conversion of more acres of native grasslands to agriculture (USGCRP 2009).

Some benefits provided by well-functioning inland water and coastal ecosystems will also change or be lost due to climate change impacts, especially when compounded with other stressors such as land-use change and population growth. For example, there may be fewer salmon for commercial and recreational harvest, as well as for traditional ceremonial and cultural practices of indigenous peoples. Coastal marshes and mangroves provide natural buffers against storms, absorbing floodwaters and providing erosion control with vegetation that stabilizes shorelines and absorbs wave energy. If those habitats are degraded and/or destroyed, then adjacent inland communities will have less protection from sea level rise, and may experience more direct storm energy and flooding (NC NERR 2007). Tidal marshes and associated submerged aquatic plant beds are important spawning, nursery, and shelter areas for fish and shellfish, including commercially important species like blue crab, nesting habitat for birds, and invertebrate food for shorebirds. At least 50 percent of commercially-valuable fish and shellfish depend upon estuaries and nearshore coastal waters in at least one life history stage (Lellis-Dibble et al. 2008);

others reported estuarine dependency for approximately 85 percent of commercially-valuable fish and shellfish (NRC 1997).

In marine systems, large scale changes to biogeochemical processes, ocean currents, and the increased acidification of ocean waters are expected to have profound impacts on marine ecosystem services, including fisheries. Shifts of fish stocks to higher latitudes and deeper depths may force fishers to travel farther and spend more time in search of fish, or to undertake the costly task of updating infrastructure to effectively harvest the changing mixture of fish stocks. Fishery agencies will also have to update regulatory measures to conform to these new stock boundaries. Melting sea ice is also changing transportation routes, oil and gas exploration and extraction, fishing, and tourism in the Arctic, which in turn could impact the fish, wildlife, and plants in this region through a variety of mechanisms, including increased noise associated with increases in shipping (AMSA 2009).

The effects that climate change will have on marine aquaculture are not fully understood, but it is likely that there will be both positive and negative effects. For example, warmer temperatures may increase growth of some species, but decrease that of others, emphasizing the need for vulnerability assessments and adaptation planning that can reduce negative impacts and promote positive effects where possible (De Silva and Soto 2009). Climate change will directly affect aquaculture's choice of species, location, technology, and production costs (Hall et al. 2011). Direct impacts may include rising ocean levels, more frequent extreme weather events, changes in rain patterns, and distribution of diseases and parasites. The more subtle effects are even harder to gauge; for example, the effects that climate change may have on ocean currents, inshore salinities, and water mixing patterns; which may in turn affect aquatic productivity; the effects on fishmeal supply and global trade, or on incidence of harmful algal blooms (FAO 2010)

POTENTIAL BENEFITS OF CLIMATE CHANGE: ATLANTIC CROAKER FISHERY

One species which may benefit from marine climate change and a conservative management regime is the Atlantic croaker, which inhabits the coastal Atlantic of the United States and supports a commercial and recreational fishery worth approximately $9M per year. Annual fish surveys along the East Coast have recorded croaker populations expanding northward since 1975. Recent research suggests that its range expansion is due to a combination of increasing sea surface temperature and a constant fishing pressure or catch level by anglers. Spawning occurs in the coastal waters during the late summer, fall, and winter. Between 30-60 days after spawning, larvae enter the estuaries of the Mid-Atlantic region to overwinter and grow to juveniles. Juvenile survival during the winter is determined by water temperature with cold water adversely affecting recruitment to the fishery. Using sea surface temperature forecasts from an ensemble of global climate models, researchers have projected increased recruitment of juveniles in estuaries leading to more adult fish (Hare et al. 2010). As sea surface temperature increases the range and if fishing pressure remains relatively low, the croaker fishery is expected to shift northward 100-400 km as new estuarine habitat becomes available.