Climate Change Impacts in the United States

CHAPTER 8 ECOSYSTEMS,
BIODIVERSITY, AND ECOSYSTEM SERVICES

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8 ECOSYSTEMS, BIODIVERSITY, AND ECOSYSTEM SERVICES

Key Messages

1. **Climate change impacts on ecosystems reduce their ability to improve water quality and regulate water flows.**

2. **Climate change, combined with other stressors, is overwhelming the capacity of ecosystems to buffer the impacts from extreme events like fires, floods, and storms.**

3. **Landscapes and seascapes are changing rapidly, and species, including many iconic species, may disappear from regions where they have been prevalent or become extinct, altering some regions so much that their mix of plant and animal life will become almost unrecognizable.**

4. **Timing of critical biological events, such as spring bud burst, emergence from overwintering, and the start of migrations, has shifted, leading to important impacts on species and habitats.**

5. **Whole system management is often more effective than focusing on one species at a time, and can help reduce the harm to wildlife, natural assets, and human well-being that climate disruption might cause.**

Climate change affects the living world, including people, through changes in ecosystems, biodiversity, and ecosystem services. Ecosystems entail all the living things in a particular area as well as the non-living things with which they interact, such as air, soil, water, and sunlight.[1] Biodiversity refers to the variety of life, including the number of species, life forms, genetic types, and habitats and biomes (which are characteristic groupings of plant and animal species found in a particular climate). Biodiversity and ecosystems produce a rich array of benefits that people depend on, including fisheries, drinking water, fertile soils for growing crops, climate regulation, inspiration, and aesthetic and cultural values.[2] These benefits are called "ecosystem services" – some of which, like food, are more easily quantified than others, such as climate regulation or cultural values. Changes in many such services are often not obvious to those who depend on them.

Ecosystem services contribute to jobs, economic growth, health, and human well-being. Although we interact with ecosystems and ecosystem services every day, their linkage to climate change can be elusive because they are influenced by so many additional entangled factors.[3] Ecosystem perturbations driven by climate change have direct human impacts, including reduced water supply and quality, the loss of iconic species and landscapes, distorted rhythms of nature, and the potential for extreme events to overwhelm the regulating services of ecosystems. Even with these well-documented ecosystem impacts, it is often difficult to quantify human vulnerability that results from shifts in ecosystem processes and services. For example, although it is more straightforward to predict how precipitation will change water flow, it is much harder to pinpoint which farms, cities, and habitats will be at risk of running out of water, and even more difficult to say how people will be affected by the loss of a favorite fishing spot or a wildflower that no longer blooms in the region. A better understanding of how a range of ecosystem responses affects people – from altered water flows to the loss of wildflowers – will help to inform the management of ecosystems in a way that promotes resilience to climate change.

Forests absorb carbon dioxide and provide many other ecosystem services, such as purifying water and providing recreational opportunities.

Key Message 1: Water

Climate change impacts on ecosystems reduce their ability to improve water quality and regulate water flows.

Climate-driven factors that control water availability and quality are moderated by ecosystems. Land-based ecosystems regulate the water cycle and are the source of sediment and other materials that make their way to aquatic ecosystems (streams, rivers, lakes, estuaries, oceans, groundwater). Aquatic ecosystems provide the critically important services of storing water, regulating water quality, supporting fisheries, providing recreation, and carrying water and materials downstream (Ch. 25: Coasts). Humans utilize, on average, the equivalent of more than 40% of renewable supplies of freshwater in more than 25% of all U.S. watersheds.[4] Freshwater withdrawals are even higher in the arid Southwest, where the equivalent of 76% of all renewable freshwater is appropriated by people.[5] In that region, climate change has likely decreased and altered the timing of streamflow due to reduced snowpack and lower precipitation in spring, although the precipitation trends are weak due to large year-to-year variability, as well as geographic variation in the patterns (Ch. 3: Water; Ch. 20: Southwest).[6] Depriving ecosystems of water reduces their ability to provide water to people as well as for aquatic plant and animal habitat (see Figure 8.1).

Habitat loss and local extinctions of fish and other aquatic species are projected from the combined effects of increased water withdrawal and climate change.[7] In the U.S., 47% of trout habitat in the interior West would be lost by 2080 under a scenario (A1B) that assumes similar emissions to the A2 scenario used in this report (Ch. 1: Overview, Ch. 2: Our Changing Climate) through 2050, and a slow decline thereafter.[8]

Across the entire U.S., precipitation amounts and intensity and associated river discharge are major drivers of water pollution in the form of excess nutrients, sediment, and dissolved organic carbon (DOC) (Ch. 3: Water).[9] At high concentrations, nutrients that are required for life (such as nitrogen and phosphorus) can become pollutants and can promote excessive phytoplankton growth – a process known as eutrophication. Currently, many U.S. lakes and rivers are polluted (have concentrations above government standards) by excessive nitrogen, phosphorus, or sediment. There are well-established links among fertilizer use, nutrient pollution, and river discharge, and many studies show that recent increases in rainfall in several regions of the United States have led to higher nitrogen amounts carried by rivers (Northeast,[10,11] California,[12] and Mississippi Basin[13,14]). Over the past 50 years, due to both climate and land-use change, the Mississippi Basin is yielding an additional 32 million acre-feet of water each year – equivalent to four Hudson Rivers – laden with materials washed from its farmlands.[15] This flows into the Gulf of Mexico, which is the site of the nation's largest hypoxic (low oxygen) "dead" zone.[4] The majority of U.S. estuaries are moderately to highly eutrophic.[16]

Links between discharge and sediment transport are well established,[17] and cost estimates for in-stream and off-stream damages from soil erosion range from $2.1 to $10 billion per year.[18,19] These estimates include costs associated with damages to, or losses of, recreation, water storage, navigation, commercial fishing, and property, but do not include costs of biological impacts.[18] Sediment transport, with accompanying nutrients, can play a positive role in the shoreline dynamics of coastlines and the life cycles of coastal and marine plants and animals. However, many commercially and recreationally important fish species such as salmon and trout that lay their eggs in the gravel at the edges of streams are especially sensitive to elevated sediment fluxes in rivers.[20] Sediment loading in lakes has been shown to have substantial detrimental effects on fish population sizes, community composition, and biodiversity.[21]

Dissolved organic carbon (DOC) fluxes to rivers and lakes are strongly driven by precipitation;[22] thus in many regions where precipitation is expected to increase, DOC loading will also increase. Dissolved organic carbon is the substance that gives many rivers and lakes a brown, tea-colored look. Precipitation-driven increases in DOC concentration not only increase the cost of water treatment for municipal use,[23] but also alter the ability of sunlight to act as nature's water treatment plant. For example, *Cryptosporidium*, a pathogen potentially lethal to the elderly, babies, and people with compromised immune systems, is present in 17% of drinking water supplies sampled

in the United States.[24] This pathogen is inactivated by doses of ultraviolet (UV) light equivalent to less than a day of sun exposure.[25] Similarly, UV exposures reduce fungal parasites that infect *Daphnia*, a keystone aquatic grazer and food source for fish.[26] Increasing DOC concentrations may thus reduce the ability of sunlight to regulate these UV-sensitive parasites.

Few studies have projected the impacts of climate change on nitrogen, phosphorus, sediment, or DOC transport from the land to rivers. However, given the tight link between river discharge and all of these potential pollutants, areas of the United States that are projected to see increases in precipitation, and increases in intense rainfalls, like the Northeast, Midwest, and mountainous West,[27] will also see increases in excess nutrients, DOC, and sediments transported to rivers. One of the few future projections available suggests that downstream and coastal impacts of increased nitrogen inputs could be profound for the Mississippi Basin. Under a scenario in which atmospheric CO_2 reaches double pre-industrial levels, a 20% increase in river discharge is expected to lead to higher nitrogen loads and a 50% increase in algae growth in the Gulf of Mexico, a 30% to 60% decrease in deep-water dissolved oxygen concentration, and an expansion of the dead zone.[28] A recent comprehensive assessment[10] shows that, while climate is an important driver, nitrogen carried by rivers to the oceans is most strongly driven by fertilizer inputs to the land. Therefore, in the highly productive agricultural systems of the Mississippi Basin, the ultimate impact of more precipitation on the expansion of the dead zone will depend on agricultural management practices in the Basin.[14,29]

Rising air temperatures can also lead to declines in water quality through a different set of processes. Some large lakes, including the Great Lakes, are warming rapidly.[30] Warmer surface waters can stimulate blooms of harmful algae in both lakes and coastal oceans,[9] which may include toxic cyanobacteria that are favored at higher temperatures.[31] Harmful algal blooms, which are caused by many factors, including climate change, exact a cost in freshwater degradation of approximately $2.2 billion annually in the United States alone.[32]

Water Supplies Projected to Decline

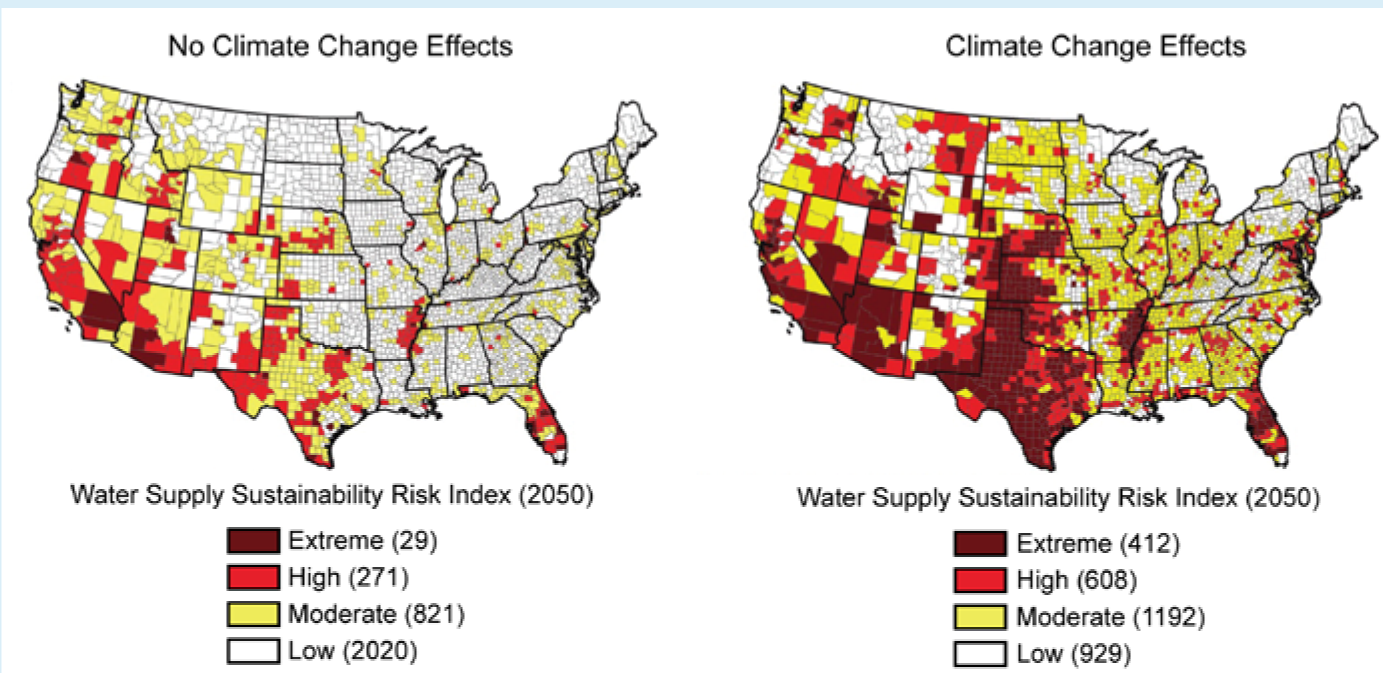

Figure 8.1. Climate change is projected to reduce the ability of ecosystems to supply water in some parts of the country. This is true in areas where precipitation is projected to decline, and even in some areas where precipitation is expected to increase. Compared to 10% of counties today, by 2050, 32% of counties will be at high or extreme risk of water shortages. Projections assume continued increases in greenhouse gas emissions through 2050 and a slow decline thereafter (A1B scenario). Numbers in parentheses indicate number of counties in each category. (Reprinted with permission from Roy et al., 2012.[27] Copyright 2012 American Chemical Society).

The Aftermath of Hurricanes

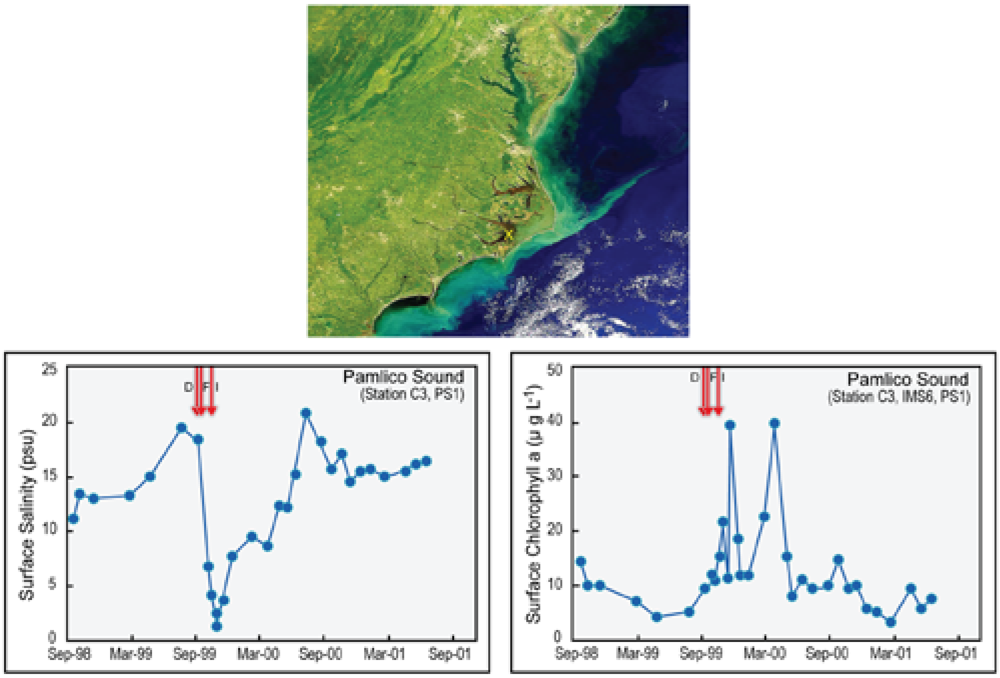

Figure 8.2. Hurricanes illustrate the links among precipitation, discharge and nutrient loading to coastal waters. Hurricanes bring intense rainfall to coastal regions, and ensuing runoff leads to blooms of algae. These blooms contribute to dead zone formation after they die and decompose. Photo above shows Pamlico Sound, North Carolina, after Hurricane Floyd. Note light green area off the coast, which is new algae growth. The graph on the left shows a steep drop in salinity of ocean water due to the large influx of freshwater from rain after a series of hurricanes. Red arrows indicate Hurricanes Dennis, Floyd, and Irene, which hit sequentially during the 1999 hurricane season. The graph on the right shows a steep rise in the amount of surface chlorophyll after these hurricanes, largely due to increased algae growth. (Figure source: (top) NASA SeaWiFS; (bottom) Paerl et al. 2003[33]).

Key Message 2: Extreme Events

Climate change, combined with other stressors, is overwhelming the capacity of ecosystems to buffer the impacts from extreme events like fires, floods, and storms.

Ecosystems play an important role in "buffering" the effects of extreme climate conditions (floods, wildfires, tornadoes, hurricanes) on the movement of materials and the flow of energy through the environment.[34] Climate change and human modifications often increase the vulnerability of ecosystems and landscapes to damage from extreme events while at the same time reducing their natural capacity to modulate the impacts of such events. Salt marshes, reefs, mangrove forests, and barrier islands provide an ecosystem service of defending coastal ecosystems and infrastructure against storm surges.[35] Losses of these natural features – from coastal development, erosion, and sea level rise – render coastal ecosystems and infrastructure more vulnerable to catastrophic damage during or after extreme events (Ch. 25: Coasts).[36] Floodplain wetlands, although greatly reduced from their historical extent, provide an ecosystem service of absorbing floodwaters and reducing the impact of high flows on river-margin lands. In the Northeast, even a small sea level rise (1.6 feet) would dramatically increase the numbers of people (47% increase) and property loss (73% increase) affected by storm surge in Long Island compared to present day storm surge impacts.[37] Extreme weather events that produce sudden increases in water flow and the materials it carries can decrease the natural capacity of ecosystems to process pollutants, both by reducing the amount of time water is in contact with reactive sites and by removing or harming the plants and microbes that remove the pollutants.[36]

Warming and, in some areas, decreased precipitation (along with past forest fire suppression practices) have increased the risk of fires exceeding historical size, resulting in unprecedented social and economic challenges. Large fires put people living in the wildland-urban interface at risk for health problems and property loss. In 2011 alone, more than 8 million acres burned in wildfires, causing 15 deaths and property losses greater than $1.9 billion.[38]

Key Message 3: Plants and Animals

Landscapes and seascapes are changing rapidly, and species, including many iconic species, may disappear from regions where they have been prevalent or become extinct, altering some regions so much that their mix of plant and animal life will become almost unrecognizable.

Vegetation model projections suggest that much of the United States will experience changes in the composition of species characteristic of specific areas. Studies applying different models for a range of future climates project biome changes for about 5% to 20% of the land area of the U.S. by 2100.[4,39] Many major changes, particularly in the western states and Alaska, will in part be driven by increases in fire frequency and severity. For example, the average time between fires in the Yellowstone National Park ecosystem is projected to decrease from 100 to 300 years to less than 30 years, potentially causing coniferous (pine, spruce, etc.) forests to be replaced by woodlands and grasslands.[40] Warming has also led to novel wildfire occurrence in ecosystems where it has been absent in recent history, such as arctic Alaska and the southwestern deserts where new fires are fueled by non-native annual grasses (Ch. 20: Southwest; Ch. 22: Alaska). Extreme weather conditions linked to sea ice decline in 2007 led to the ignition of the Anaktuvuk River Fire, which burned more than 380 square miles of arctic tundra that had not been disturbed by fire for more than 3,000 years.[41] This one fire (which burned deeply into organic peat soils) released enough carbon to the atmosphere to offset all of the carbon taken up by the entire arctic tundra biome over the past quarter-century.[42]

In addition to shifts in species assemblages, there will also be changes in species distributions. In recent decades, in both land and aquatic environments, plants and animals have moved to higher elevations at a median rate of 36 feet (0.011 kilometers) per decade, and to higher latitudes at a median rate of 10.5 miles (16.9 kilometers) per decade.[43] As the climate continues to change, models and long-term studies project even greater shifts in species ranges.[44] However, many species may not be able to keep pace with climate change for several reasons, for example because their seeds do not disperse widely or because they have limited mobility, thus leading, in some places, to local extinctions of both plants and animals. Both range shifts and local extinctions will, in many places, lead to large changes in the mix of plants and animals present in the local ecosystem, resulting in new communities that bear little resemblance to those of today.[4,8,45,46]

Some of the most obvious changes in the landscape are occurring at the boundaries between biomes. These include shifts in the latitude and elevation of the boreal (northern) forest/tundra boundary in Alaska;[47] elevation shifts of the boreal and subalpine forest/tundra boundary in the Sierra Nevada, California;[48] an elevation shift of the temperate broadleaf/conifer boundary in the Green Mountains, Vermont,[49] the shift of temperate the shrubland/conifer forest boundary in Bandelier National Monument, New Mexico,[50] and upslope shifts of the temperate mixed forest/conifer boundary in Southern California.[51] All of these are consistent with recent climatic trends and represent visible changes, like tundra switching to forest, or conifer forest switching to broadleaf forest or even to shrubland.

As temperatures rise and precipitation patterns change, many fish species (such as salmon, trout, whitefish, and char) will be lost from lower-elevation streams, including a projected loss of 47% of habitat for all trout species in the western U.S. by 2080.[8] Similarly, in the oceans, transitions from cold-water fish communities to warm-water communities have occurred in commercially important harvest areas,[52] with new industries developing in response to the arrival of new species.[53] Also, warm surface waters are driving some fish species to deeper waters.[54,55]

Warming is likely to increase the ranges of several invasive plant species in the United States,[56] increase the probability of establishment of invasive plant species in boreal forests in south-central Alaska, including the Kenai Peninsula,[57] and expand the range of the hemlock wooly adelgid, an insect that has killed many eastern hemlocks in recent years.[58] Invasive species costs to the U.S. economy are estimated at $120 billion per year,[59] including substantial impacts on ecosystem services. For instance, the yellow star-thistle, a wildland pest which is predicted to thrive with increased atmospheric CO_2,[60] currently costs California ranchers and farmers $17 million in forage and control efforts[61] and $75 million in water losses.[62] Iconic desert species such as saguaro cactus are damaged or killed by fires fueled by non-native grasses, leading to a large-scale transformation of desert shrubland into grassland in many of the familiar landscapes of the American West.[63] Bark beetles have infested extensive areas of the western United States and Canada, killing stands of temperate and boreal conifer forest across areas greater than any other outbreak in the last 125 years.[64] Climate change has been a major causal factor, with higher temperatures allowing more beetles to survive winter, complete two life cycles in a season rather than one, and to move to higher elevations and latitudes.[64,65] Bark beetle outbreaks in the Greater Yellowstone Ecosystem are occurring in habitats where outbreaks either did not previously occur or were limited in scale.[66]

It is important to realize that climate change is linked to far more dramatic changes than simply altering species' life cycles or shifting their ranges. Several species have exhibited population declines linked to climate change, with some declines so severe that species are threatened with extinction.[67] Perhaps the most striking impact of climate change is its effect on iconic species such as the polar bear, the ringed seal, and coral species (Ch. 22: Alaska; Ch. 24: Oceans). In 2008, the polar bear (*Ursus maritimus*) was listed as a threatened species, with the primary cause of its decline attributed to climate change.[68] In 2012, NOAA determined that four subspecies of the ringed seal (*Phoca hispida*) were threatened or endangered, with the primary threat being climate change.[69]

Key Message 4: Seasonal Patterns

Timing of critical biological events, such as spring bud burst, emergence from overwintering, and the start of migrations, has shifted, leading to important impacts on species and habitats.

The effect of climate change on phenology – the pattern of seasonal life cycle events in plants and animals, such as timing of leaf-out, blooming, hibernation, and migration – has been called a "globally coherent fingerprint of climate change impacts" on plants and animals.[70] Observed long-term trends towards shorter, milder winters and earlier spring thaws are altering the timing of critical spring events such as bud burst and emergence from overwintering. This can cause plants and animals to be so out of phase with their natural phenology that outbreaks of pests occur, or species cannot find food at the time they emerge.

Recent studies have documented an advance in the timing of springtime phenological events across species in response to increased temperatures.[71] Long-term observations of lilac flowering indicate that the onset of spring has advanced one day earlier per decade across the northern hemisphere in response to increased winter and spring temperatures[72] and by 1.5 days per decade earlier in the western United States.[73] Other multi-decadal studies for plant species have documented similar trends for early flowering.[74,75] In addition, plant-pollinator relationships may be disrupted by changes in nectar and pollen availability, as the timing of bloom shifts in response to temperature and precipitation.[76,77]

As spring is advancing and fall is being delayed in response to regional changes in climate,[78] the growing season is lengthening. A longer growing season will benefit some crops and natural species, but there may be a timing mismatch between the microbial activity that makes nutrients available in the soil and the readiness of plants to take up those nutrients for growth.[78,79] Where plant phenology is driven by day length, an advance in spring may exacerbate this mismatch, causing available nutrients to be leached out of the soil rather than absorbed and recycled by plants.[80] Longer growing seasons also exacerbate human allergies. For example, a longer fall allows for bigger ragweed plants that produce more pollen later into the fall (see also Ch. 9: Health).[81]

Changes in the timing of springtime bird migrations are well-recognized biological responses to warming, and have been documented in the western,[82] midwestern,[83] and eastern United States.[84,85] Some migratory birds now arrive too late for the peak of food resources at breeding grounds because temperatures at wintering grounds are changing more slowly than at spring breeding grounds.[86]

In a 34-year study of an Alaskan creek, young pink salmon (*Oncorhynchus gorbuscha*) migrated to the sea increasingly earlier over time.[87] In Alaska, warmer springs have caused earlier onset of plant emergence, and decreased spatial variation in growth and availability of forage to breeding caribou (*Rangifer tarandus*).

Key Message 5: Adaptation

Whole system management is often more effective than focusing on one species at a time, and can help reduce the harm to wildlife, natural assets, and human well-being that climate disruption might cause.

Adaptation in the context of biodiversity and natural resource management is fundamentally about managing change, which is an inherent property of natural ecosystems.[4,88,89] One strategy – adaptive management, which is a structured process of flexible decision-making under uncertainty that incorporates learning from management outcomes – has received renewed attention as a tool for helping resource managers make decisions relevant to whole systems in response to climate change.[89,90] Other strategies tinclude assessments of vulnerability and impacts,[91] and scenario planning,[92] that can be assembled into a general planning process that is flexible and iterative.

Guidance on adaptation planning for conservation has proliferated at the federal[92,93,94] and state levels,[95] and often emphasizes cooperation between scientists and managers.[94,96,97] Ecosystem-based adaptation[98,99] uses "biodiversity and ecosystem services as part of an overall adaptation strategy to help people adapt to the adverse effects of climate change."[99] An example is the explicit use of storm-buffering coastal wetlands or mangroves rather than built infrastructure like seawalls or levies to protect coastal regions (Ch. 25: Coasts).[100] An additional example is the use of wildlife corridors to connect fragmented wildlife habitat.[101]

Adaptation strategies to protect biodiversity include: 1) habitat manipulation, 2) conserving populations with higher genetic diversity or more flexible behaviors or morphologies, 3) re-planting with species or ecotypes that are better suited for future climates, 4) managed relocation (sometimes referred to as assisted migration) to help move species and populations from current locations to those areas expected to become more suitable in the future, and 5) offsite conservation such as seed banking, biobanking, and captive breeding.[92,94,96,97,102,103] Additional approaches focus on identifying and protecting features that are important for biodiversity and are less likely to be altered by climate change. The idea is to conserve the "stage" (the biophysical conditions that contribute to high levels of biodiversity) for whatever "actors" (species and populations) find those areas suitable in the future.[104]

One of the greatest challenges for adaptation in the face of climate change is the revision of management goals in fundamental ways. In particular, not only will climate change make it difficult to achieve existing conservation goals, it will demand that goals be critically examined and potentially altered in dramatic ways.[102,105] Climate changes can also severely diminish the effectiveness of current strategies and require fresh approaches. For example, whereas establishing networks of nature reserves has been a standard approach to protecting species, fixed networks of reserve do not lend themselves to adjustments for climate change.[105] Finally, migratory species and species with complex life histories cannot be simply addressed by defining preferred habitat and making vulnerability assessments. Often it could be specific life history stages that are the weak point in the species, and it is key to identify those weak links.[106]

While there is considerable uncertainty about how climate change will play out in particular locations, proactive measures can be taken to both plan for connectivity[96,107] and to identify places or habitats that may in the future become valuable habitat as a result of climate change and vegetation shifts.[108] It is important to note that when the Endangered Species Act (ESA) was passed in 1973, climate change was not a known threat or factor and was not considered in setting recovery goals or critical habitat designations.[109] However, agencies are actively working to include climate change considerations in their ESA implementation activities.

Adaptation Planning and Implementation Framework

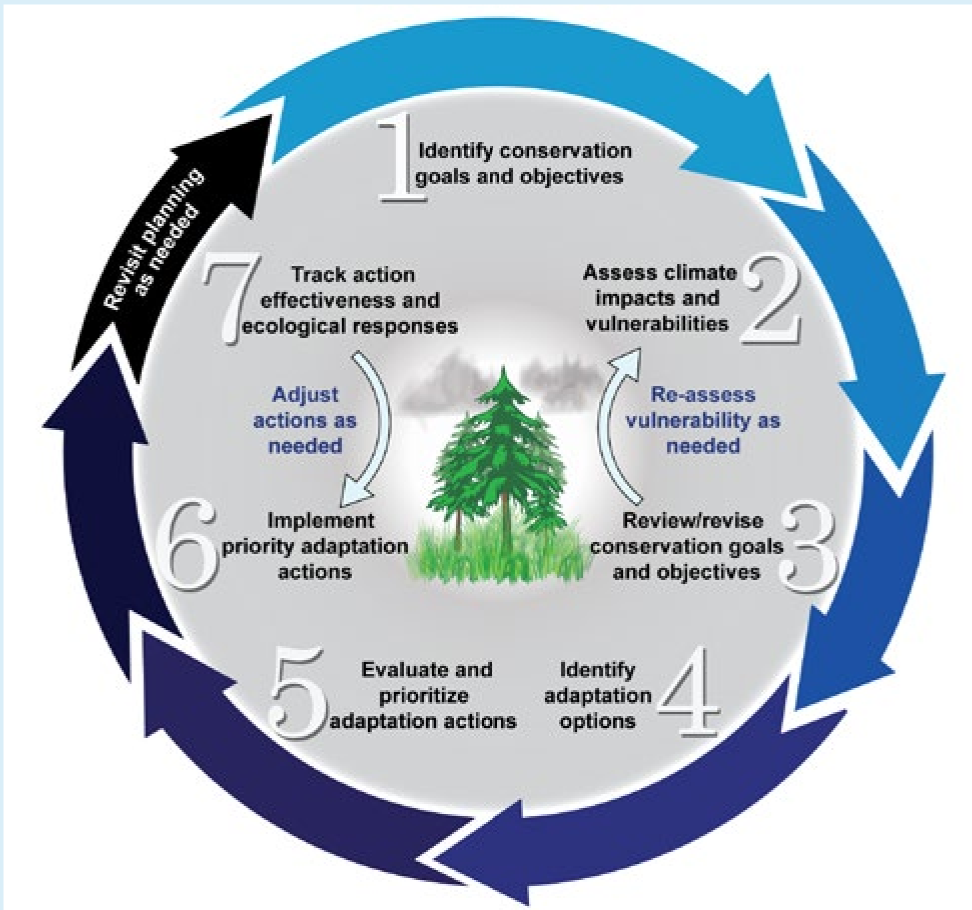

Figure 8.3. Iterative approaches to conservation planning require input and communication among many players to ensure flexibility in response to climate change. (Figure source: adapted from the National Wildlife Federation, 2013[142]).

Case study of the 2011 Las Conchas, New Mexico Fire

In the midst of severe drought in the summer of 2011, Arizona and New Mexico suffered the largest wildfires in their recorded history, affecting more than 694,000 acres. Some rare threatened and endangered species, like the Jemez salamander, were damaged by this unusually severe fire.[110] Fires are often part of the natural disturbance regime, but if drought, poor management, and high temperatures combine, a fire can be so severe and widespread that species are damaged that otherwise might even be considered to be fire tolerant (such as spotted owls). Following the fires, heavy rainstorms led to major flooding and erosion, including at least ten debris flows. Popular recreation areas were evacuated and floods damaged the newly renovated, multi-million dollar U.S. Park Service Visitor Center at Bandelier National Monument. Sediment and ash eroded by the floods were washed downstream into the Rio Grande, which supplies 50% of the drinking water for Albuquerque, the largest city in New Mexico. Water withdrawals by the city from the Rio Grande were stopped entirely for a week and reduced for several months due to the increased cost of treatment.

These fires provide an example of how forest ecosystems, biodiversity, and ecosystem services are affected by the impacts of climate change, other environmental stresses, and past management practices. Higher temperatures, reduced snowpack, and earlier onset of springtime are leading to increases in wildfire in the western United States,[111] while extreme droughts are becoming more frequent.[112] In addition, climate change is affecting naturally occurring bark beetles: warmer winter conditions allow these pests to breed more frequently and successfully.[113,114] The dead trees left behind by bark beetles may make crown fires more likely, at least until needles fall from killed trees.[114,115] Forest management practices also have made the forests more vulnerable to catastrophic fires. In New Mexico, even-aged, second-growth forests were hit hardest because they are much denser than naturally occurring forest and consequently consume more water from the soil and increase the availability of dry above-ground fuel.

Biological responses to climate change

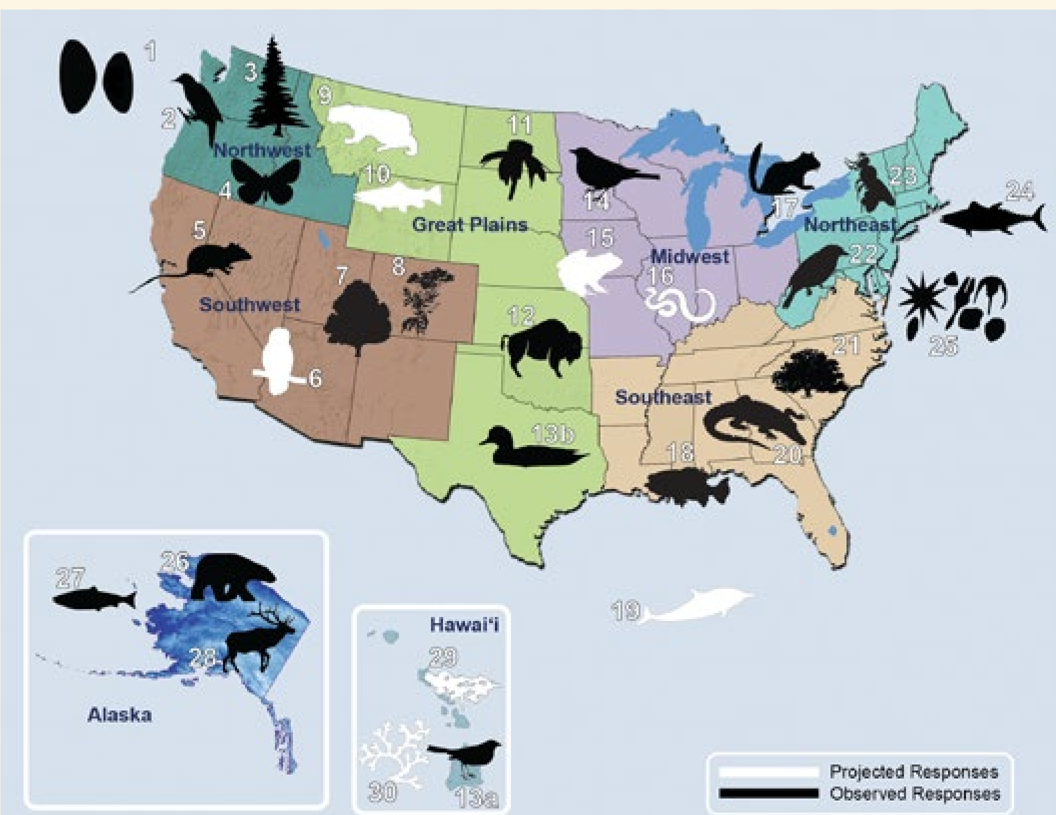

Figure 8.4. Map of selected observed and projected biological responses to climate change across the United States. Case studies listed below correspond to observed responses (black icons on map) and projected responses (white icons on map, bold italicized statements). In general, because future climatic changes are projected to exceed those experienced in the recent past, projected biological impacts tend to be of greater magnitude than recent observed changes. Because the observations and projections presented here are not paired (that is, they are not for the same species or systems), that general difference is not illustrated. (Figure source: Staudinger et al., 2012[4]).

Continued

Biological responses to climate change (continued)

1. Mussel and barnacle beds have declined or disappeared along parts of the Northwest coast due to higher temperatures and drier conditions that have compressed habitable intertidal space.[116]
2. Northern flickers arrived at breeding sites earlier in the Northwest in response to temperature changes along migration routes, and egg laying advanced by 1.15 days for every degree increase in temperature, demonstrating that this species has the capacity to adjust their phenology in response to climate change.[117]
3. Conifers in many western forests have experienced mortality rates of up to 87% from warming-induced changes in the prevalence of pests and pathogens and stress from drought.[118]
4. Butterflies that have adapted to specific oak species have not been able to colonize new tree species when climate change-induced tree migration changes local forest types, potentially hindering adaptation.[119]
5. In response to climate-related habitat change, many small mammal species have altered their elevation ranges, with lower-elevation species expanding their ranges and higher-elevation species contracting their ranges.[120]
6. ***Northern spotted owl populations in Arizona and New Mexico are projected to decline during the next century and are at high risk for extinction due to hotter, drier conditions, while the southern California population is not projected to be sensitive to future climatic changes.***[121]
7. Quaking aspen-dominated systems are experiencing declines in the western U.S. after stress due to climate-induced drought conditions during the last decade.[122]
8. Warmer and drier conditions during the early growing season in high-elevation habitats in Colorado are disrupting the timing of various flowering patterns, with potential impacts on many important plant-pollinator relationships.[77]
9. ***Population fragmentation of wolverines in the northern Cascades and Rocky Mountains is expected to increase as spring snow cover retreats over the coming century.***[123]
10. ***Cutthroat trout populations in the western U.S. are projected to decline by up to 58%, and total trout habitat in the same region is projected to decline by 47%, due to increasing temperatures, seasonal shifts in precipitation, and negative interactions with non-native species.***[8]
11. Comparisons of historical and recent first flowering dates for 178 plant species from North Dakota showed significant shifts occurred in over 40% of species examined, with the greatest changes observed during the two warmest years of the study.[75]
12. Variation in the timing and magnitude of precipitation due to climate change was found to decrease the nutritional quality of grasses, and consequently reduce weight gain of bison in the Konza Prairie in Kansas and the Tallgrass Prairie Preserve in Oklahoma.[124] Results provide insight into how climate change will affect grazer population dynamics in the future.
13. (a and b) Climatic fluctuations were found to influence mate selection and increase the probability of infidelity in birds that are normally socially monogamous, increasing the gene exchange and the likelihood of offspring survival.[125]
14. Migratory birds monitored in Minnesota over a 40-year period showed significantly earlier arrival dates, particularly in short-distance migrants, indicating that some species are capable of responding to increasing winter temperatures better than others.[126]
15. ***Up to 50% turnover in amphibian species is projected in the eastern U.S. by 2100, including the northern leopard frog, which is projected to experience poleward and elevational range shifts in response to climatic changes in the latter quarter of the century.***[127]
16. ***Studies of black ratsnake (Elaphe obsoleta) populations at different latitudes in Canada, Illinois, and Texas suggest that snake populations, particularly in the northern part of their range, could benefit from rising temperatures if there are no negative impacts on their habitat and prey.***[128]
17. Warming-induced hybridization was detected between southern and northern flying squirrels in the Great Lakes region of Ontario, Canada, and in Pennsylvania after a series of warm winters created more overlap in their habitat range, potentially acting to increase population persistence under climate change.[129]

Continued

Biological responses to climate change (continued)

18. Some warm-water fishes have moved northwards, and some tropical and subtropical fishes in the northern Gulf of Mexico have increased in temperate ocean habitat.[130] Similar shifts and invasions have been documented in Long Island Sound and Narragansett Bay in the Atlantic.[131]
19. ***Global marine mammal diversity is projected to decline at lower latitudes and increase at higher latitudes due to changes in temperatures and sea ice, with complete loss of optimal habitat for as many as 11 species by mid-century; seal populations living in tropical and temperate waters are particularly at risk to future declines.***[132]
20. Higher nighttime temperatures and cumulative seasonal rainfalls were correlated with changes in the arrival times of amphibians to wetland breeding sites in South Carolina over a 30-year time period (1978-2008).[133]
21. Seedling survival of nearly 20 resident and migrant tree species decreased during years of lower rainfall in the Southern Appalachians and the Piedmont areas, indicating that reductions in native species and limited replacement by invading species were likely under climate change.[134]
22. Widespread declines in body size of resident and migrant birds at a bird-banding station in western Pennsylvania were documented over a 40-year period; body sizes of breeding adults were negatively correlated with mean regional temperatures from the preceding year.[85]
23. Over the last 130 years (1880-2010), native bees have advanced their spring arrival in the northeastern U.S. by an average of 10 days, primarily due to increased warming. Plants have also showed a trend of earlier blooming, thus helping preserve the synchrony in timing between plants and pollinators.[135]
24. In the Northwest Atlantic, 24 out of 36 commercially exploited fish stocks showed significant range (latitudinal and depth) shifts between 1968 and 2007 in response to increased sea surface and bottom temperatures.[55]
25. Increases in maximum, and decreases in the annual variability of, sea surface temperatures in the North Atlantic Ocean have promoted growth of small phytoplankton and led to a reorganization in the species composition of primary (phytoplankton) and secondary (zooplankton) producers.[136]
26. Changes in female polar bear reproductive success (decreased litter mass and numbers of yearlings) along the north Alaska coast have been linked to changes in body size and/or body condition following years with lower availability of optimal sea ice habitat.[137]
27. Water temperature data and observations of migration behaviors over a 34-year time period showed that adult pink salmon migrated earlier into Alaskan creeks, and fry advanced the timing of migration out to sea. Shifts in migration timing may increase the potential for a mismatch in optimal environmental conditions for early life stages, and continued warming trends will likely increase pre-spawning mortality and egg mortality rates.[87]
28. Warmer springs in Alaska have caused earlier onset of plant emergence, and decreased spatial variation in growth and availability of forage to breeding caribou. This ultimately reduced calving success in caribou populations.[138]
29. ***Many Hawaiian mountain vegetation types were found to vary in their sensitivity to changes in moisture availability; consequently, climate change will likely influence elevation-related vegetation patterns in this region.***[139]
30. ***Sea level is predicted to rise by 1.6 to 3.3 feet in Hawaiian waters by 2100, consistent with global projections of 1 to 4 feet of sea level rise (see Ch. 2: Our Changing Climate, Key Message 10). This is projected to increase wave heights, the duration of turbidity, and the amount of re-suspended sediment in the water; consequently, this will create potentially stressful conditions for coral reef communities.***[140]


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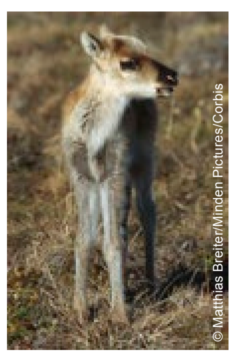
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SUPPLEMENTAL MATERIAL
TRACEABLE ACCOUNTS

Process for Developing Key Messages

The key messages and supporting chapter text summarize extensive evidence documented in the Ecosystems Technical Input Report, *Impacts of Climate Change on Biodiversity, Ecosystems, and Ecosystem Services: Technical Input to the 2013 National Climate Assessment*.[4] This foundational report evolved from a technical workshop held at the Gordon and Betty Moore Foundation in Palo Alto, CA, in January 2012 and attended by approximately 65 scientists. Technical inputs (127) on a wide range of topics related to ecosystems were also received and reviewed as part of the Federal Register Notice solicitation for public input.

Key message #1 Traceable Account

Climate change impacts on ecosystems reduce their ability to improve water quality and regulate water flows.

Description of evidence base

The author team digested the contents of more than 125 technical input reports on a wide array of topics to arrive at this key message. The foundational Technical Input Report[4] was the primary source used.

Studies have shown that increasing precipitation is already resulting in declining water quality in many regions of the country, particularly by increasing nitrogen loading.[10,11,12,13,14] This is because the increases in flow can pick up and carry greater loads of nutrients like nitrogen to rivers.[11,12,13,14]

One model for the Mississippi River Basin, based on a doubling of CO_2, projects that increasing discharge and nitrogen loading will lead to larger algal blooms in the Gulf of Mexico and a larger dead zone.[28] The Gulf of Mexico is the recipient system for the Mississippi Basin, receiving all of the nitrogen that is carried downriver but not removed by river processes, wetlands, or other ecosystems.

Several models project that declining streamflow, due to the combined effects of climate change and water withdrawals, will cause local extinctions of fish and other aquatic organisms,[7] particularly trout in the interior western U.S. (composite of 10 models, A1B scenario).[8] The trout study[8] is one of the few studies of impacts on fish that uses an emissions scenario and a combination of climate models. The researchers studied four different trout species. Although there were variations among species, their overall conclusion was robust across species for the composite model.

Water quality can also be negatively affected by increasing temperatures. There is widespread evidence that warmer lakes can promote the growth of harmful algal blooms, which produce toxins.[31]

New information and remaining uncertainties

Recent research has improved understanding of the relative importance of the effects of climate and human actions (for example, fertilization) on nitrogen losses from watersheds,[10,12] and how the interactions between climate and human actions (for example, water withdrawals) will affect fish populations in the west.[7,8] However, few studies have projected the impacts of future climate change on water quality. Given the tight link between river discharge and pollutants, only areas of the U.S. that are projected to see increases in precipitation will see increases in pollutant transport to rivers. It is also important to note that pollutant loading – for example, nitrogen fertilizer use – is often more important as a driver of water pollution than climate.[10,12]

Assessment of confidence based on evidence

Given the evidence base and uncertainties, there is **high** confidence that climate change impacts on ecosystems reduce their ability to improve water quality and regulate water flows.

It is well established that precipitation and associated river discharge are major drivers of water pollution in the form of excess nutrients, sediment, and dissolved organic carbon (DOC) transport into rivers. Increases in precipitation in many regions of the country are therefore contributing to declines in water quality in those areas. However, those areas of the country that will see reduced precipitation may experience water-quality improvement; thus, any lack of agreement on future water-quality impacts of climate change may be due to locational differences.

Confidence Level
Very High
Strong evidence (established theory, multiple sources, consistent results, well documented and accepted methods, etc.), high consensus
High
Moderate evidence (several sources, some consistency, methods vary and/or documentation limited, etc.), medium consensus
Medium
Suggestive evidence (a few sources, limited consistency, models incomplete, methods emerging, etc.), competing schools of thought
Low
Inconclusive evidence (limited sources, extrapolations, inconsistent findings, poor documentation and/or methods not tested, etc.), disagreement or lack of opinions among experts

Key message #2 Traceable Account

Climate change, combined with other stressors, is overwhelming the capacity of ecosystems to buffer the impacts from extreme events like fires, floods, and storms.

Description of evidence base

The author team digested the contents of more than 125 technical input reports on a wide array of topics to arrive at this key message. The foundational Technical Input Report[4] was the primary source used.

Fires: Climate change has increased the potential for extremely large fires with novel social, economic, and environmental impacts. In 2011, more than 8 million acres burned, with significant human mortality and property damage ($1.9 billion).[38] Warming and decreased precipitation have made fire-prone ecosystems more vulnerable to "mega-fires" – large fires that are unprecedented in their social, economic, and environmental impacts. Large fires put people living in the urban-wildland interface at risk for health problems and property loss.

Floods: Natural ecosystems such as salt marshes, reefs, mangrove forests, and barrier islands defend coastal ecosystems and infrastructure against flooding due to storm surges. The loss of these natural features due to coastal development, erosion, and sea level rise render coastal ecosystems and infrastructure more vulnerable to catastrophic damage during or after extreme events (see Ch. 25: Coasts).[36] Floodplain wetlands, which are also vulnerable to loss by inundation, absorb floodwaters and reduce the impact of high flows on river-margin lands. In the Northeast, a sea level rise of 1.6 feet (within the range of 1 to 4 feet projected for 2100; Ch. 2: Our Changing Climate, Key Message 9) will dramatically increase impacts of storm surge on people (47% increase) and property loss (73% increase) in Long Island.[37]

Storms: Natural ecosystems have a capacity to buffer extreme weather events that produce sudden increases in water flow and materials. These events reduce the amount of time water is in contact with sites that support the plants and microbes that remove pollutants (Chapter 25: Coasts).[36]

New information and remaining uncertainties

A new analytical framework was recently developed to generate insights into the interactions among the initial state of ecosystems, the type and magnitude of disturbance, and effects of disturbance.[34] Progress in understanding these relationships is critical for predicting how human activities and climate change, including extreme events like droughts, floods, and storms, will interact to affect ecosystems.

Uncertainties: The ability of ecosystems to buffer extreme events is extremely difficult to assess and quantify, as it requires understanding of complex ecosystem responses to very rare events. However, it is clear that the loss of this buffering ecosystem service is having important effects on coastal and fire-prone ecosystems across the United States.

Assessment of confidence based on evidence

Given the evidence base and uncertainties, there is **high** confidence that climate change, combined with other stressors, is overwhelming the capacity of ecosystems to buffer the impacts from extreme events like droughts, floods, and storms.

Ecosystem responses to climate change will vary regionally. For example, whether salt marshes and mangroves will be able to accrue sediment at rates sufficient to keep ahead of sea level rise and maintain their protective function will vary by region.

Climate has been the dominant factor controlling burned area during the 20th century, even during periods of fire suppression by forest management,[40,111] and the area burned annually has increased steadily over the last 20 years concurrent with warming and/or drying climate. Warming and decreased precipitation have also made fire-prone ecosystems more vulnerable to "mega-fires" – large fires that are unprecedented in their social, economic, and environmental impacts. Large fires put people living in the urban-wildland interface at risk for health problems and property loss. In 2011 alone, 8.3 million acres burned in wildfires, causing 15 deaths and property losses greater than $1.9 billion.[38]

Key message #3 Traceable Account

Landscapes and seascapes are changing rapidly, and species, including many iconic species, may disappear from regions where they have been prevalent or become extinct, altering some regions so much that their mix of plant and animal life will become almost unrecognizable.

Description of evidence base

The analysis for the Technical Input Report applied a range of future climate scenarios and projected biome changes across 5% to about 20% of the land area in the U.S. by 2100.[4] Other analyses support these projections.[39] Studies predict that wildfire will be a major driver of change in some areas, including Yellowstone National Park[40] and the Arctic.[41] These biome shifts will be associated with changes in species distributions.[43]

Evidence indicates that the most obvious changes will occur at the boundaries between ecosystems.[47,48,49,51] Plants and animals are already moving to higher elevations and latitudes in response to climate change,[43] with models projecting greater range shifts[8,46] and local extinctions in the future, leading to new plant and animal communities that may be unrecognizable in some regions.[4,45,46] One study on fish[8] used global climate models (GCMs) simulating conditions in the 2040s and 2080s under the A1B emissions scenario, with the choice of models reflecting predictions of high and low climate warming as well as an ensemble of ten models. Their models additionally accounted for biotic interactions. In a second study, a 30-year baseline (1971-2000) and output from two GCMs under the A2 scenario (continued increases in global emissions) were used to develop climate variables that effectively predict present and future species ranges.[46] Empirical data from the Sonoran Desert (n=39 plots) were used to evaluate species responses to past climate variability.

Iconic species: Wildfire is expected to damage and kill iconic desert species, including saguaro cactus.[63] Bark beetle outbreaks, which have been exacerbated by climate change, are damaging extensive areas of temperate and boreal conifer forests that are characteristic of the western United States.[64]

New information and remaining uncertainties

In addition to the Technical Input Report, more than 20 new studies of observed and predicted effects of climate change on biomes and species distribution were incorporated in the assessment.

While changes in ecosystem structure and biodiversity, including the distribution of iconic species, are occurring and are highly likely to continue, the impact of these changes on ecosystem services is unclear, that is, there is uncertainty about the impact that loss of familiar landscapes will have on people.

Assessment of confidence based on evidence

Based on the evidence base and uncertainties, confidence is **high** that familiar landscapes are changing so rapidly that iconic species may disappear from regions where they have been prevalent, altering some regions so much that their mix of plant and animal life will become almost unrecognizable. Many changes in species distribution have already occurred and will inevitably continue, resulting in the loss of familiar landscapes and the production of novel species assemblages.

Key message #4 Traceable Account

Timing of critical biological events, such as spring bud burst, emergence from overwintering, and the start of migrations, has shifted, leading to important impacts on species and habitats.

Description of evidence base

The key message and supporting text summarizes extensive evidence documented in the Ecosystems Technical Input, *Phenology as a bio-indicator of climate change impacts on people and ecosystems: Towards an integrated national assessment approach*.[71] An additional 127 input reports, on a wide range of topics related to ecosystems, were also received and reviewed as part of the Federal Register Notice solicitation for public input.

Many studies have documented an advance in springtime phenological events of species in response to climate warming. For example, long-term observations of lilac flowering indicate that the onset of spring has advanced one day earlier per decade across the northern hemisphere in response to increased winter and spring temperatures, and by 1.5 days per decade earlier in the western United States.[72,73] Other multi-decadal studies for plant species have documented similar trends for early flowering.[74,75] Evidence suggests that insect emergence from overwintering may become out of sync with pollen sources,[77] and that the beginning of bird and fish migrations are shifting.[82,83,84,85,86,87]

New information and remaining uncertainties

In addition to the Ecosystems Technical Input[71] many new studies have been conducted since the previous National Climate Assessment,[141] contributing to our understanding of the impacts of climate change on phenological events. Many studies, in many areas, have shown significant changes in phenology, including spring bud burst, emergence from overwintering, and migration shifts.

A key uncertainty is "phase effects" where organisms are so out of phase with their natural phenology that outbreaks of pests occur, species emerge and cannot find food, or pollination is disrupted. This will vary with specific species and is therefore very difficult to predict.[70]

Assessment of confidence based on evidence

Given the evidence base and uncertainties, there is very high confidence that the timing of critical events, such as spring bud burst, emergence from overwintering, and the start of migrations, has shifted, leading to important impacts on species and habitats.

Key message #5 Traceable Account

Whole system management is often more effective than focusing on one species at a time, and can help reduce the harm to wildlife, natural assets, and human well-being that climate disruption might cause.

Description of evidence base

Adaptation planning for conservation at federal[92,93,94] and state levels,[95] is focused on cooperation between scientists and managers.[34,94,96,97] Development of ecosystem-based whole system management[98] utilizes concepts about "biodiversity and ecosystem services to help people adapt to climate change."[99] An example is the use of coastal wetlands or mangroves rather than built infrastructure like seawalls or levees to protect coastal regions from storms (Chapter 25: Coasts).[100]

New information and remaining uncertainties

Adaptation strategies to protect biodiversity include: 1) habitat manipulations, 2) conserving populations with higher genetic diversity or more plastic behaviors or morphologies, 3) changing seed sources for re-planting to introduce species or ecotypes that are better suited for future climates, 4) managed relocation (sometimes referred to as assisted migration) to help move species and populations from current locations to those areas expected to become more suitable in the future, and 5) ex-situ conservation such as seed banking and captive breeding.[92,94,96,97,102] Alternative approaches focus on identifying and protecting features that are important for biodiversity and are projected to be less altered by climate change. The idea is to conserve the physical conditions that contribute to high levels of biodiversity so that species and populations can find suitable areas in the future.[104]

Assessment of confidence based on evidence

Given the evidence and remaining uncertainties, there is **very high** confidence that ecosystem-based management approaches are increasingly prevalent, and provide options for reducing the harm to biodiversity, ecosystems, and the services they provide to society. The effectiveness of these actions is much less certain, however.