8. Ecosystems, Biodiversity, and Ecosystem Services

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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. **Land- and sea-scapes are changing rapidly and species, including many iconic species, may disappear from regions where they have been prevalent, changing 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, will shift, leading to important impacts on species and habitats.**
5. **Ecosystem-based management approaches are increasingly prevalent, and provide options for reducing the harm to biodiversity, ecosystems, and the services they provide to society.**

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 (Chapin et al. 2011). 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 (Millenium Ecosystem Assessment 2005). These benefits are called "ecosystem services" – some of which, like food and fisheries, are more easily quantified than others, such as climate regulation or cultural values.

Ecosystem services translate into jobs, economic growth, health, and human well-being.

Although ecosystems and ecosystem services are what we interact with every day, their linkage to climate change can be elusive because they are influenced by so many additional entangled factors. 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 overcome 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 straightforward to predict how precipitation will change water flow, it is much harder to pinpoint which farms and cities 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 spring. A better understanding of how everything from altered water flows to the loss of wildflowers matters to people may be key to managing ecosystems in a way that promotes resilience to climate change.

Water

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

Ecosystems modify climate-driven factors that control water availability and quality. 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). Aquatic ecosystems provide the critically important services of storing water, regulating water quality, supporting fisheries, providing recreation, and carrying water and materials downstream. Humans utilize, on average, the equivalent of more than 40% of renewable supplies of freshwater in more than 25% of all watersheds (USGS 2012). Freshwater withdrawals are even higher in the arid Southwest, where the equivalent of 76% of all renewable freshwater is appropriated by people (Sabo et al. 2010). In that region, climate change has decreased streamflow due to lower spring precipitation and reduced snowpack (Barnett et al. 2008; Ch. 3 Water Resources). Depriving ecosystems of water reduces their ability to provide high quality water to people and habitat for aquatic plants and animals.

Local extinctions of fish and other aquatic species are projected from the combined effects of increased water withdrawal and climate change (Spooner et al. 2011). 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 through 2050 and a slow decline thereafter (Wenger et al. 2011).

Across the entire U.S., precipitation and associated river discharge are major drivers of water pollution in the form of excess nutrients, sediment, and dissolved organic carbon (DOC). At high concentrations, nutrients that are required for life (such as nitrogen and phosphorus) can become pollutants and can promote excessive algae 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 is a well-established link between nitrogen pollution and river discharge, and many studies show that recent increases in rainfall in several regions of the U.S. have led to higher amounts of nitrogen carried by rivers (Northeast: (Howarth et al. 2012; Howarth et al. 2006), California: (Sobota et al. 2009), Mississippi Basin: (Justic et al. 2005; McIsaac et al. 2002)). 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. This flows into the Gulf of Mexico, which is the site of the nation's largest hypoxic (low oxygen) "dead" zone (USGS 2012). The majority of U.S. estuaries are moderately to highly eutrophic (Bricker et al. 2007).

Links between discharge and sediment transport are well established (Inman and Jenkins 1999), and cost estimates for in-stream and off-stream damages from soil erosion range from $2.1 to $10 billion per year (Clark 1985; Pimentel et al. 1995). These estimates include costs associated with damages to, or losses of, recreation, water storage, navigation, commercial fishing, and property damage, but do not include costs of biological impacts (Clark 1985). 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 (Greig et al. 2005; Julien and Bergeron 2006; Newcombe and Jensen 1996; Scheurer et al. 2009; Scrivener and Brownlee 1989; Suttle et al. 2004). Sediment loading in lakes has been shown to have substantial detrimental effects on fish population sizes, community composition, and biodiversity (Donohue and Molinos 2009).

Dissolved organic carbon fluxes to rivers and lakes are strongly driven by precipitation (Pace and Cole 2002; Raymond and Saiers 2010; Zhang et al. 2010)*;* 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 (Haaland et al. 2010), 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 U.S. (Rose et al. 1991). This pathogen is inactivated by doses of ultraviolet (UV) light equivalent to less than a day of sun exposure (Connelly et al. 2007; King et al. 2008). Similarly, UV exposures reduce fungal parasites that infect *Daphnia*, a keystone aquatic grazer and food source for fish (Overholt et al. 2012). Increasing DOC concentrations may thus reduce the ability of sunlight to regulate these UV-sensitive parasites.

Few studies have projected the impacts of future climate change on nitrogen, phosphorus, sediment, or DOC transport from the land to rivers. Given the tight link between river discharge and all of these potential pollutants, areas of the U.S. that are projected to see increases in precipitation, like the Northeast, Midwest, and mountainous West (Roy et al. 2012), 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 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 (Justic et al. 1996). A recent comprehensive assessment (Howarth et al. 2012) 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 (David et al. 2010; McIsaac et al. 2002; Raymond et al. 2012).

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 at rates faster than the world's oceans (Verburg and Hecky 2009) and the regions surrounding them (Schneider and Hook 2010). Warmer surface waters can stimulate blooms of harmful algae in both lakes and coastal oceans, which may include toxic cyanobacteria that are favored at higher temperatures (Paerl and Huisman 2008). Harmful algal blooms, which are caused by many factors, including climate change, exact a cost in freshwater degradation of approximately $2.2 billion annually (Dodds et al. 2009).

Water Supplies Projected to Decline

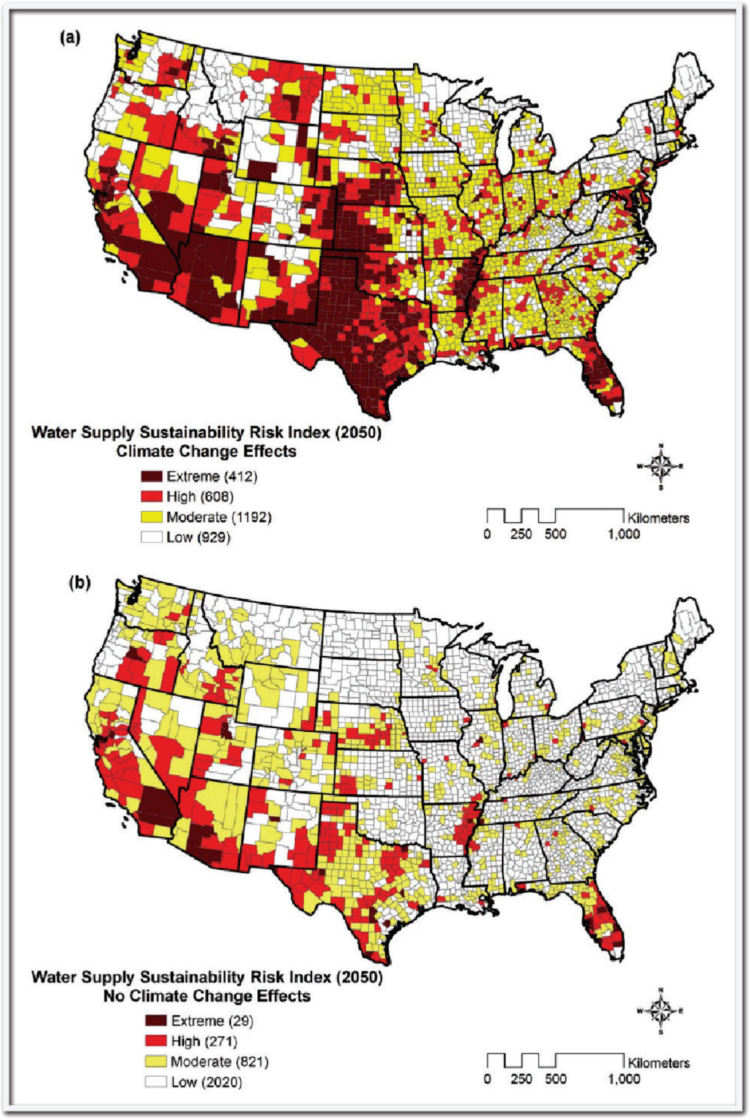

Figure 8.1: Water Supplies Projected to Decline

Caption: Climate change is projected to reduce water availability in some parts of the country. Compared to 10% of counties today, by 2050, 32% of counties will be at risk of water shortages. Projections assume continued increases in emissions through 2050 and a slow decline thereafter (A1B scenario). (Source: Roy et al., 2012)

The Aftermath of Hurricanes

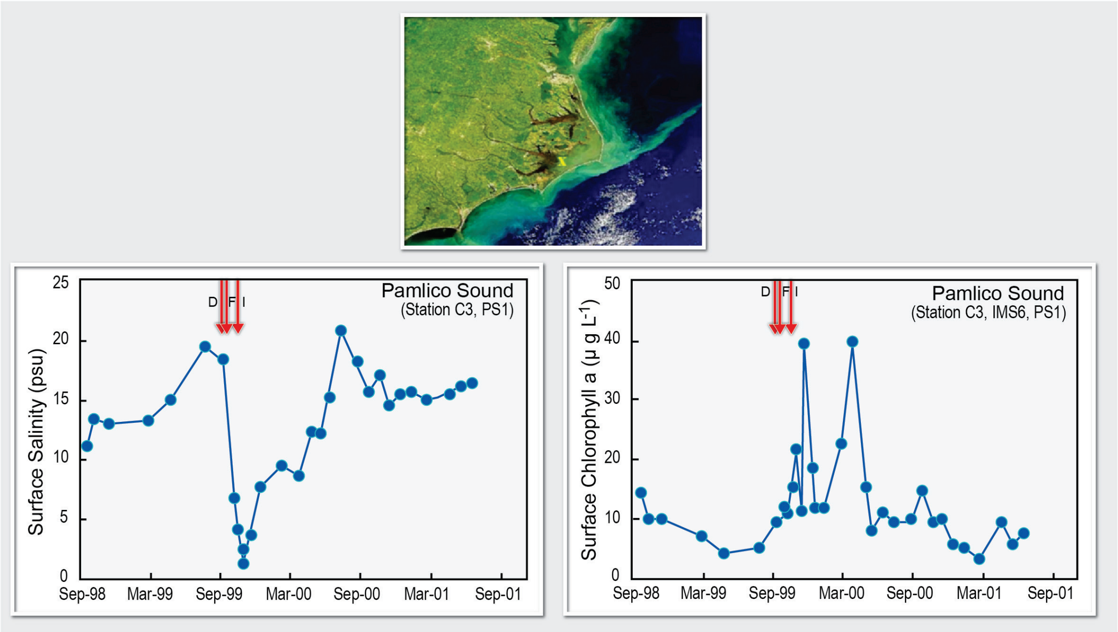

Figure 8.2: The Aftermath of Hurricanes

Caption: Hurricanes bring intense rainfall, which reduces the salinity of offshore water and leads to blooms of algae. 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: Paerl et al., 2003. Image source NASA SeaWiFS)

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, tornados, hurricanes) on the movements of materials and flow of energy (Peters et al. 2011). Climate change and human modifications of ecosystems and landscapes often increase their vulnerability 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 defend coastal ecosystems and infrastructure against storm surges. Their losses – 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 Coastal Zone; FitzGerald et al. 2008; McGranahan et al. 2007). Floodplain wetlands, although greatly reduced from their historical extent, absorb floodwaters and reduce the impact of high flows on river-margin lands. Where they are lost to inundation, the consequences would be profound. 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) impacted by storm surge in Long Island compared to present day storm surge impacts (Shepard et al. 2012). 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 (FitzGerald et al. 2008; McGranahan et al. 2007).

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 million (Hedde 2012).

Plants and Animals

Land- and sea-scapes are changing rapidly and species, including many iconic species, may disappear from regions where they have been prevalent, changing some regions so much that their mix of plant and animal life will become almost unrecognizable.

Vegetation model projections suggest that much of the U.S. will experience changes in the composition of species characteristic of an area. 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 (Alo and Wang 2008; Bergengren et al. 2011; Gonzalez et al. 2010; Sitch et al. 2008; USGS 2012). 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 resulting in a shift from coniferous (pine, spruce, etc.) forests to woodlands and grasslands (Westerling et al. 2011). 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. 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 over 3,000 years (Hu et al. 2010). 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 (Mack et al. 2011).

In addition to shifts in species assemblages, there will also be changes in species distributions (Chen et al. 2011). In recent decades in 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. As climates continue to change, models and long-term studies project even greater shifts in species ranges. However, many species may not be able to keep pace with climate change, either 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 composition of plants and animals, resulting in new communities that bear little resemblance to those of today (Cheung et al. 2009; Lawler et al. 2009; Stralberg et al. 2009; USGS 2012; Wenger et al. 2011).

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 forest/tundra boundary in Alaska (Beck et al. 2011; Dial et al. 2007; Lloyd and Fastie 2003; Suarez et al. 1999; Wilmking et al. 2004); elevational shifts of boreal and subalpine forest/tundra boundary in the Sierra Nevada, California (Millar et al. 2004); an elevational shift of temperate broadleaf/conifer boundary in the Green Mountains, Vermont (Beckage et al. 2008), the shift of temperate shrubland/conifer forest boundary in Bandelier National Monument, New Mexico (Allen and Breshears 1998), and upslope shifts of temperate mixed forest/conifer boundary in Southern California (Kelly and Goulden 2008). 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 48% of habitat for all trout species in the western U.S. by 2080 (Wenger et al. 2011). Similarly, in the oceans, transitions from cold-water fish communities to warm-water communities have occurred in commercially important harvest areas (Lucey and Nye 2010; Wood et al. 2008), with new industries developing in response to the arrival of new species (McCay et al. 2011; Pinnegar et al. 2010). Also, warm surface waters are driving some fish species to deeper waters (Caputi et al. 2010; Dulvy et al. 2008; Nye et al. 2009; Perry et al. 2005).

Warming is likely to increase the ranges of several invasive plant species in the U.S. (Bradley et al. 2010), increase the probability of establishment of invasive plant species in boreal forests in south-central and Kenai, Alaska (Wolken et al. 2011), and expand the range of the hemlock wooly adelgid, an insect that has killed many eastern hemlocks in recent years (Albani et al. 2010; Dukes et al. 2009; Orwig et al. 2012; Paradis et al. 2008). Invasive species costs to the U.S. economy are estimated at $120 billion per year (Pimentel et al. 2005), including substantial impacts on ecosystem services. For instance, the wildland pest yellow star-thistle, which is predicted to thrive with increased atmospheric CO_2 (Dukes et al. 2011), currently costs California ranchers and farmers $17 million in forage and control efforts (Eagle et al. 2007) and $75 million in water losses (Gerlach 2004). Iconic desert species such as saguaro cactus and Joshua trees (Saunders et al. 2009) 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. Bark beetles have infested extensive areas of the western U.S. and Canada, killing stands of temperate and boreal conifer forest across areas greater than any other outbreak in the last 125 years (Raffa et al. 2008). 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 (Bentz et al. 2010; Berg et al. 2006; Raffa et al. 2008). Bark beetle outbreaks in the Greater Yellowstone Ecosystem are outside the historic range of variability (Logan et al. 2010).

Seasonal Patterns

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

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 (Parmesan 2007; Parmesan and Yohe 2003; Root et al. 2003). 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 (Network U.N.P. 2012). 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 (Schwartz et al. 2006) and by 1.5 days per decade earlier in the western U.S. (Ault et al. 2011). Other multi-decadal studies for plant species have documented similar trends for early flowering (Cayan et al. 2001; Dunnell and Travers 2011; McEwan et al. 2011; Zhao and Schwartz 2003). In addition, plant-pollinator relationships may be disrupted by changes in the availability of nectar and pollen, as the timing of bloom shifts in response to temperature and precipitation (Aldridge et al. 2011; Forrest and Thomson 2011).

As spring is advancing and fall is being delayed in response to regional changes in climate (Beaubien and Hamann 2011; Huntington 2009; Jeong et al. 2011), 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 (Beaubien and Hamann 2011; Huntington 2009; Jeong et al. 2011; Muller and Bormann 1976). 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 (Groffman et al. 2012). Longer growing seasons exacerbate human allergies. For example, a longer fall allows for bigger ragweed plants that produce more pollen later into the fall. (Rogers et al. 2006; Staudt et al. 2010).

Changes in the timing of springtime bird migrations are well-recognized biological responses to warming, and have been documented in the western (MacMynowski et al. 2007), Midwestern (MacMynowski and Root 2007), and eastern United States (Miller-Rushing et al. 2008; Van Buskirk et al. 2008). For example, 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 (Jones and Cresswell 2010). In a 34-year study of an

Alaskan creek, young pink salmon (*Oncorhynchus gorbuscha*) migrated to the sea increasingly early over time (Taylor 2008). 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*).

Adaptation

Ecosystem-based management approaches are increasingly prevalent, and provide options for reducing the harm to biodiversity, ecosystems, and the services they provide to society.

Adaptation in the context of biodiversity and natural resource management is fundamentally about managing change, which is an inherent property of natural ecosystems (Staudinger et al. 2012; West et al. 2009; Link et al. 2010). 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 in response to climate change. Other strategies include assessments of vulnerability and impacts (Glick et al. 2011; Rowland et al. 2011), and scenario planning (Weeks et al. 2011), that can be assembled into a general planning process that is flexible, forward-thinking, and iterative.

Guidance on adaptation planning for conservation has proliferated at the federal (CEQ 2011a; EPA 2009; NOAA 2010; Peterson et al. 2011; Weeks et al. 2011) and state levels (AFWA 2009), and often emphasizes cooperation between scientists and managers (Cross et al. 2012; Halofsky et al. 2011; Peterson et al. 2011). Ecosystem-based adaptation (CBD 2010; Colls et al. 2009; The World Bank 2010; Vignola et al. 2009) uses “biodiversity and ecosystem services as part of an overall adaptation strategy to help people adapt to the adverse effects of climate change” (CBD 2010). 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 (Kershner 2010; Shaffer et al. 2009; Ch. 25 Coastal Zone). An additional example is the use of wildlife corridors (Chetkiewicz et al. 2006).

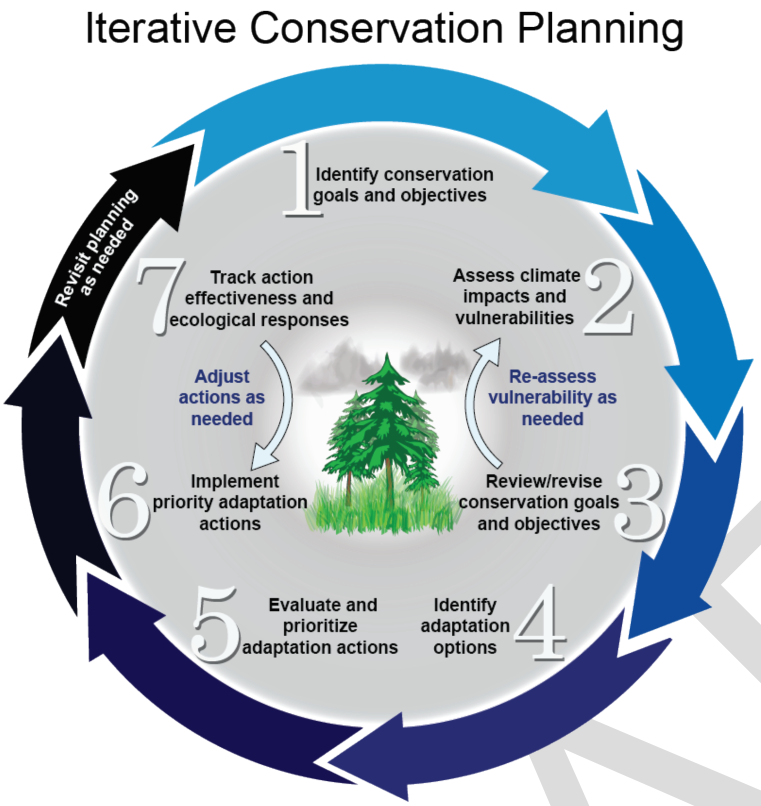

Figure 8.3: Iterative Conservation Planning

Caption: Iterative approaches to conservation planning require input and communication among many players to ensure flexibility in response to climate change (Figure source: Created for this report by Nancy B. Grimm of Arizona State University and by NOAA NCDC)

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) 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, biobanking, and captive breeding (Cross et al. 2012; Halofsky et al. 2011; Peterson et al. 2011; Poiani et al. 2011; Weeks et al. 2011). Alternative 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 physical conditions that contribute to high levels of biodiversity) for whatever "actors" (for example, species and populations) find those areas suitable in the future (Anderson and Ferree 2010; Beier and Brost 2010; Groves et al. 2012; Hunter et al. 1988).

Box 1. 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 recorded wildfires in their history, affecting more than 694,000 acres. Some rare threatened and endangered species, like Mexican spotted owls and the Jemez salamander, were devastated by the fire (NPS 2011). Following the fire, 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. Sediment and ash eroded by the floods were washed downstream into the Rio Grande, which supplies 50% of 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 U.S. (Westerling et al. 2006), while extreme droughts are becoming more frequent (Williams et al. 2011). In addition, climate change is affecting naturally occurring bark beetles: warmer winter conditions allow these pests to breed more frequently and successfully (Jonsson et al. 2009; Schoennagel 2011) . The dead trees left behind by bark beetles make crown fires more likely (Hoffman et al. 2010; Schoennagel 2011). 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.

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Box 2

Biological Responses to Climate Change

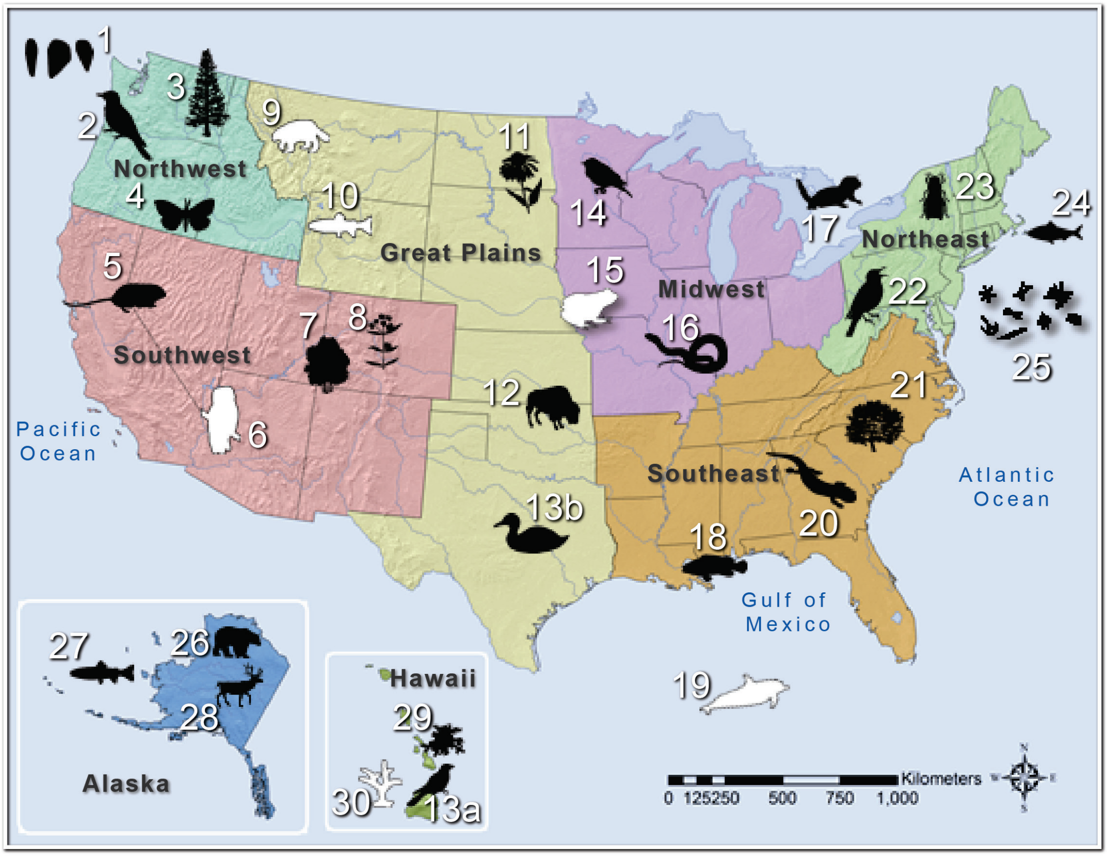

Figure 8.4: Biological Responses to Climate Change

Caption: Map of 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, italicized statements). (Figure source: Adapted from Staudinger et al., 2012)

1. Mussel and barnacle beds have declined or disappeared along parts of Northwest coast (Harley 2011).
2. Northern flickers arrived at breeding sites earlier in Northwest in response to temperature changes along migration routes (Wiebe and Gerstmar 2010).
3. Conifer forests in many western forests have died from warming-induced changes in the prevalence of pests and pathogens (van Mantgem et al. 2009).
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 (Pelini et al. 2010).

5. In response to climate-related habitat change, many small mammal species have altered their elevational ranges, with lower-elevation species expanding their ranges and higher-elevation species contracting their ranges (Moritz et al. 2008).
6. *Owl populations in Arizona and New Mexico are projected to decline during the next century and are at high risk for extinction due to future climatic changes, while the southern California population is not projected to be sensitive to future climatic changes* (Peery et al. 2012).
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 (Anderegg et al. 2012).
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 (Forrest and Thomson 2011).
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* (McKelvey et al. 2011).
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 48%, due to increasing temperatures, seasonal shifts in precipitation, and negative interactions with non-native species* (Wenger et al. 2011).
11. First flowering dates in 178 plant species from North Dakota have shifted significantly in more than 40% of all species examined (Dunnell and Travers 2011).
12. Variation in the timing and magnitude of precipitation was found to impact weight gain of bison in the Konza Prairie in Kansas and the Tallgrass Prairie Preserve in Oklahoma (Craine et al. 2008).
13. Increased environmental variation has been shown to influence mate selection and increase the probability of infidelity in birds that are normally socially monogamous to increase the gene exchange and the likelihood of offspring survival (Botero and Rubenstein 2012).
14. Migratory birds monitored in Minnesota over a 40-year period showed significantly earlier arrival dates, particularly in short-distance migrants, due to increasing winter temperatures (Swanson and Palmer 2009).
15. *The northern leopard frog is projected to experience poleward and elevational range shifts in response to climatic changes in the latter quarter of the century* (Lawler et al. 2010).
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 (Sperry et al. 2010).

17. Warming-induced hybridization was detected between southern and northern flying squirrels in the Great Lakes region of Ontario Canada, and Pennsylvania after a series of warm winters created more overlap in their habitat range (Garroway et al. 2009).
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 (Fodrie et al. 2009); Similar shifts and invasions have been documented in Long Island Sound and Narragansett Bay in the Northeast Atlantic (Wood et al. 2009).
19. *Global marine mammal diversity is projected to decline by as many as 11 species by mid-century, particularly in coastal habitats, due to climatic change* (Kaschner et al. 2011).
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) (Todd et al. 2011).
21. Seedling survival for nearly 20 species of trees decreased during years of lower rainfall in the Southern Appalachians and the Piedmont areas (Ibáñez et al. 2008).
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 (Van Buskirk et al. 2009).
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 (Bartomeus et al. 2011).
24. In the Northwest Atlantic, 24 out of 36 commercially exploited fish stocks showed significant range (latitudinal and depth) shifts between 1968–2007 in response to increased sea surface and bottom temperatures (Nye et al. 2009).
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 (Beaugrand et al. 2010).
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 (Rode et al. 2010).
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 (Taylor 2008).

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 (Post et al. 2008).

29. Many Hawai‘ian mountain vegetation types were found to vary in their sensitivity to changes in moisture availability; consequently, climate change will likely influence elevational patterns in vegetation in this region (Crausbay and Hotchkiss 2010).

30. *A 1.6 to 3.3 foot local sea level rise in Hawai‘ian waters, consistent with global projections of 1 to 4 feet of sea level rise (see Ch. 2: Our Changing Climate, Key Message 9) 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* (Cardinale et al. 2012; Hooper et al. 2012; Storlazzi et al. 2011)

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Traceable Accounts

Chapter 8: Ecosystems, Biodiversity, and Ecosystem Services

Key Message Process: The key messages and supporting chapter text summarize extensive evidence documented in the Ecosystems Technical Input, *Impacts of Climate Change on Biodiversity, Ecosystems, and Ecosystem Services: Technical Input to the 2013 National Climate Assessment,* Michelle D. Staudinger, Nancy B. Grimm, Amanda Staudt, Shawn L. Carter, F. Stuart Chapin III, Peter Kareiva, Mary Ruckelshaus, Bruce A. Stein. (2012). 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 #1/5	**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 over 125 technical input reports on a wide array of topics to arrive at this key message. The foundational USGS report 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 (Howarth et al. 2012; Howarth et al. 2006; Justic et al. 2005; McIsaac et al. 2002; Sobota et al. 2009). This is because the increases in flow can pick up and carry greater loads of nutrients like nitrogen to rivers. 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 (Justic et al. 1996). 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 wetlands, river processes, 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 (Spooner et al. 2011; Xenopoulos et al. 2005), particularly trout in the interior West (composite of 10 models, A1B scenario) (Wenger et al. 2011). This 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 and 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 (Paerl and Huisman 2008).
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 (Howarth et al. 2012; Sobota et al. 2009), and how the interactions between climate and human actions (for example, water withdrawals) will affect fish populations in the west (Spooner et al. 2011, Wenger et al. 2011). 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 (Howarth et al. 2012; Sobota et al. 2009).

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 many 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 is likely due to locational differences.

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

Chapter 8: Ecosystems, Biodiversity, and Ecosystem Services

Key Message Process: See key message #1.

Key message #2/5	**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	**Fires:** 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 million (Hedde 2012) . **Floods:** Salt marshes, reefs, mangrove forests, and barrier islands defend coastal ecosystems and infrastructure against storm surges, and their losses from coastal development, erosion, and sea-level rise render coastal ecosystems and infrastructure more vulnerable to catastrophic damage during or after extreme events (see Chap 25: Coastal Zone, Development and Ecosystems) (FitzGerald et al. 2008; McGranahan et al. 2007). Floodplain wetlands, although greatly reduced from their historical extent, absorb floodwaters and reduce the impact of high flows on river-margin lands. Where they are lost to inundation, the consequences would be profound. In the Northeast, even a small sea-level rise (1.6 ft, which is expected by 2080) will dramatically increase impacts of storm surge on people (47% increase) and property loss (73% increase) in Long Island (Shepard et al. 2012). **Storms:** 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 (FitzGerald et al. 2008; McGranahan et al. 2007; Ch. 25 Coastal Zone).
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 (Peters et al. 2011). 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 effect ecosystems, and how ecosystems will respond. Uncertainties: The ability of ecosystems to buffer extreme events is extremely difficult to assess and quantify, as it requires understanding of complex ecosystem response 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 U.S.
Assessment of confidence based on evidence	Give 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. Salt marshes, reefs, mangrove forests, and barrier islands defend coastal ecosystems and infrastructure against storm surges, but their losses from coastal development, erosion, and sea level rise render coastal ecosystems and infrastructure more vulnerable to catastrophic damage during or after extreme events (FitzGerald et al.

	2008; McGranahan et al. 2007). 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 (Blum and Roberts 2009; Craft et al. 2009; Gedan et al. 2011; Stralberg et al. 2011). Climate has been the dominant factor controlling burned area during the 20th century, even during periods of fire suppression by forest management (Littell et al. 2009; Miller et al. 2011; Westerling et al. 2006; Westerling et al. 2011), and the area burned annually has increased steadily over the last 20 years concurrent with warming and/or drying climate (Morton 2012). 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 million (Hedde 2012).

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

Chapter 8: Ecosystems, Biodiversity, and Ecosystem Services

Key Message Process: See key message #1.

Key message #3/5	**Land- and sea-scapes are changing rapidly and species, including many iconic species, may disappear from regions where they have been prevalent, changing 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 (USGS 2012b). Other analyses support these projections (Alo and Wang 2008; Bergengren et al. 2011; Gonzalez et al. 2010; Sitch et al. 2008). Studies predict that wildfire will be a major driver of change in some areas, including Yellowstone Nation Park (Westerling et al. 2011) and the Arctic (Hu et al. 2010). These biomes shifts will be associated with changes in species distributions (Chen et al. 2011). Evidence indicates that the most obvious changes will occur at the boundaries between ecosystems (Allen and Breshears 1998; Beck et al. 2011; Beckage et al. 2008; Dial et al. 2007; Kelly and Goulden 2008; Lloyd and Fastie 2003; Millar et al. 2004; Suarez et al. 1999; Wilmking et al. 2004). Plants and animals are already moving to higher elevations and latitudes in response to climate change (Chen et al. 2011), with models projecting greater range shifts (Munson et al. 2012; Stralberg et al. 2009; Wenger et al. 2011) and local extinctions in the future, leading to new plant and animal communities that may be unrecognizable in some regions (Cheung et al. 2009; Lawler et al. 2009; Stralberg et al. 2009; USGS 2012b). For fish, Wenger et al. (2011) used general circulation 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. Stralberg et al. (2009) used a 30-year baseline (1971-2000) and output from two GCMs under the A2 scenario to develop biologically meaningful climate variables for present and future predictions of species ranges. Munson et al. used empirical data from the Sonoran Desert (n=39 plots) to evaluate species responses to past climate variability. **Iconic species:** Wildfire is expected to damage and kill iconic desert species, including saguaro cactus and Joshua trees (Saunders et al. 2009), while bark beetle outbreaks, which have been exacerbated by climate change, are damaging extensive areas of temperate and boreal conifer forests that are characteristic of western U.S. (Raffa et al. 2008).
New information and remaining uncertainties	In addition to the technical input report, over 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, changing 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.

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

Chapter 8: Ecosystems, Biodiversity, and Ecosystem Services

Key Message Process: See key message #1.

Key message #4/5	**Timing of critical biological events, such as spring bud burst, emergence from overwintering, and the start of migrations, will shift, 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. A Technical Input to the 2013 National Climate Assessment Report., (2012), USA-NPN National Coordinating Office: Tucson, AZ.). 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 U.S. (Ault et al. 2011; Schwartz et al. 2006). Other multi-decadal studies for plant species have documented similar trends for early flowering (Cayan et al. 2001; Dunnell and Travers 2011; McEwan et al. 2011; Zhao and Schwartz 2003). Evidence suggests that insect emergence from overwintering may become out of sync with pollen sources (Forrest and Thomson 2011), and that the beginning of bird and fish migrations are shifting (Jones and Cresswell 2010; MacMynowski and Root 2007; MacMynowski et al. 2007; Miller-Rushing et al. 2008; Taylor 2008; Van Buskirk et al. 2009).
New information and remaining uncertainties	In addition to the Ecosystems Technical Input (Phenology as a bio-indicator of climate change impacts on people and ecosystems: towards an integrated national assessment approach. A Technical Input to the 2013 National Climate Assessment Report., (2012), USA-NPN National Coordinating Office: Tucson, AZ.), many new studies have been conducted since the previous assessment, contributing to our understanding of the impacts of climate change on phonological events. 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.
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, will shift leading to important impacts on species and habitats. Many studies, in many areas have shown significant changes in phenology, including spring bud burst, emergence from overwintering, and migration shifts.

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

Chapter 8: Ecosystems, Biodiversity, and Ecosystem Services

Key Message Process: See key message #1.

Key message #5/5	**Ecosystem-based management approaches are increasingly prevalent, and provide options for reducing the harm to biodiversity, ecosystems, and the services they provide to society.**
Description of evidence base	Guidance on adaptation planning for conservation has proliferated at the federal (CEQ 2011a; EPA 2009; NOAA 2010; Peterson et al. 2011; Weeks et al. 2011) and state levels (AFWA 2009), and often emphasizes cooperation between scientists and managers (Cross et al. 2012; Halofsky et al. 2011; Peters et al. 2011; Peterson et al. 2011). Ecosystem-based adaptation (CBD 2009, Colls et al. 2009, Vignola et al. 2009, World Bank 2010) uses "biodiversity and ecosystem services as part of an overall adaptation strategy to help people adapt to the adverse effects of climate change" (CBD 2010). 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 (Kershner 2010; Shaffer et al. 2009; Ch. 25 Coastal Zone);(See also Ch. 25: Coastal Zone).
New information and remaining uncertainties	Adaptation strategies to protect biodiversity include 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) 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 (Cross et al. 2012; Halofsky et al. 2011; Peterson et al. 2011; Poiani et al. 2011; Weeks et al. 2011). Alternative 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 physical conditions that contribute to high levels of biodiversity) for whatever "actors" (for example, species and populations) find those areas suitable in the future (Anderson and Ferree 2010; Beier and Brost 2010; Groves et al. 2012; Hunter et al. 1988).
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.

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

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