Ecosystems, Ecosystem Services, and Biodiversity

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Impacts, Risks, and Adaptation in the United States: Fourth National Climate Assessment, Volume II

7 Ecosystems, Ecosystem Services, and Biodiversity

Kodiak National Wildlife Refuge, Alaska

Key Message 1

Impacts on Species and Populations

Climate change continues to impact species and populations in significant and observable ways. Terrestrial, freshwater, and marine organisms are responding to climate change by altering individual characteristics, the timing of biological events, and their geographic ranges. Local and global extinctions may occur when climate change outpaces the capacity of species to adapt.

Key Message 2

Impacts on Ecosystems

Climate change is altering ecosystem productivity, exacerbating the spread of invasive species, and changing how species interact with each other and with their environment. These changes are reconfiguring ecosystems in unprecedented ways.

Key Message 3

Ecosystem Services at Risk

The resources and services that people depend on for their livelihoods, sustenance, protection, and well-being are jeopardized by the impacts of climate change on ecosystems. Fundamental changes in agricultural and fisheries production, the supply of clean water, protection from extreme events, and culturally valuable resources are occurring.

Key Message 4

Challenges for Natural Resource Management

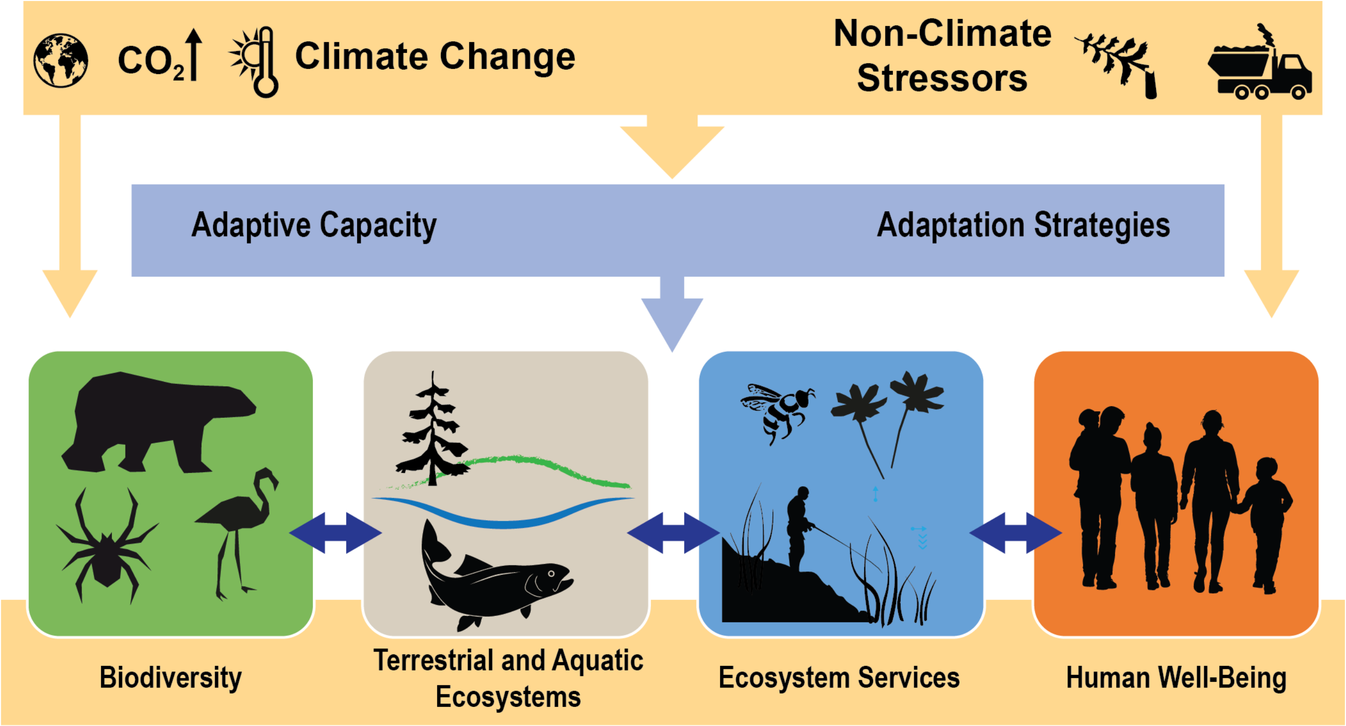
Traditional natural resource management strategies are increasingly challenged by the impacts of climate change. Adaptation strategies that are flexible, consider interacting impacts of climate and other stressors, and are coordinated across landscape scales are progressing from theory to application. Significant challenges remain to comprehensively incorporate climate adaptation planning into mainstream natural resource management, as well as to evaluate the effectiveness of implemented actions.

Executive Summary

Biodiversity—the variety of life on Earth—provides vital services that support and improve human health and well-being. Ecosystems, which are composed of living things that interact with the physical environment, provide numerous essential benefits to people. These benefits, termed ecosystem services, encompass four primary functions: provisioning materials, such as food and fiber; regulating critical parts of the environment, such as water quality and erosion control; providing cultural services, such as recreational opportunities and aesthetic value; and providing supporting services, such as nutrient cycling.[1] Climate change poses many threats and potential disruptions to ecosystems and biodiversity, as well as to the ecosystem services on which people depend.

Building on the findings of the Third National Climate Assessment (NCA3),[2] this chapter provides additional evidence that climate change is significantly impacting ecosystems and biodiversity in the United States. Mounting evidence also demonstrates that climate change is increasingly compromising the ecosystem services that sustain human communities, economies, and well-being. Both human and natural systems respond to change, but their ability to respond and thrive under new conditions is determined by their adaptive capacity, which may be inadequate to keep pace with rapid change. Our understanding of climate change impacts and the responses of biodiversity and ecosystems has improved since NCA3. The expected consequences of climate change will vary by region, species, and ecosystem type. Management responses are evolving as new tools and approaches are developed and implemented; however, they may not be able to overcome the negative impacts of climate change. Although efforts have been made since NCA3 to incorporate climate adaptation strategies into natural resource management, significant work remains to comprehensively implement climate-informed planning. This chapter presents additional evidence for climate change impacts to biodiversity, ecosystems, and ecosystem services, reflecting increased confidence in the findings reported in NCA3. The chapter also illustrates the complex and interrelated nature of climate change impacts to biodiversity, ecosystems, and the services they provide.

Climate Change, Ecosystems, and Ecosystem Services



Climate and non-climate stressors interact synergistically on biological diversity, ecosystems, and the services they provide for human well-being. The impact of these stressors can be reduced through the ability of organisms to adapt to changes in their environment, as well as through adaptive management of the resources upon which humans depend. Biodiversity, ecosystems, ecosystem services, and human well-being are interconnected: biodiversity underpins ecosystems, which in turn provide ecosystem services; these services contribute to human well-being. Ecosystem structure and function can also influence the biodiversity in a given area. The use of ecosystem services by humans, and therefore the well-being humans derive from these services, can have feedback effects on ecosystem services, ecosystems, and biodiversity. *From Figure 7.1 (Sources: NOAA, USGS, and DOI).*

State of the Sector

All life on Earth, including humans, depends on the services that ecosystems provide, including food and materials, protection from extreme events, improved quality of water and air, and a wide range of cultural and aesthetic values. Such services are lost or compromised when the ecosystems that provide them cease to function effectively. Healthy ecosystems have two primary components: the species that live within them, and the interactions among species and between species and their environment. Biodiversity and ecosystem services are intrinsically linked: biodiversity contributes to the processes that underpin ecosystem services; biodiversity can serve as an ecosystem service in and of itself (for example, genetic resources for drug development); and biodiversity constitutes an ecosystem good that is directly valued by humans (for example, appreciation for variety in its own right).[3] Significant environmental change, such as climate change, poses risks to species, ecosystems, and the services that humans rely on. Consequently, identifying measures to minimize, cope with, or respond to the negative impacts of climate change is necessary to reduce biodiversity loss and to sustain ecosystem services.[4]

This chapter focuses on the impacts of climate change at multiple scales: the populations and species of living things that form ecosystems; the properties and processes that support ecosystems; and the ecosystem services that underpin human communities, economies, and well-being. The key messages from NCA3 (Table 7.1) have been strengthened over the last four years by new research and monitoring networks. This chapter builds on the NCA3 findings and specifically emphasizes how climate impacts interact with non-climate stressors to affect ecosystem services. Furthermore, it describes new advances in climate adaptation efforts, as well as the challenges natural resource managers face when seeking to sustain ecosystems or to mitigate climate change (Figure 7.1).

Key Messages from Third National Climate Assessment
Climate change impacts on ecosystems reduce their ability to improve water quality and regulate water flows.
Climate change, combined with other stressors, is overwhelming the capacity of ecosystems to buffer the impacts from extreme events like fires, floods, and storms.
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.
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.
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.

Table 7.1: Key Messages from the Third National Climate Assessment Ecosystems, Biodiversity, and Ecosystem Services Chapter[2]

Climate Change, Ecosystems, and Ecosystem Services

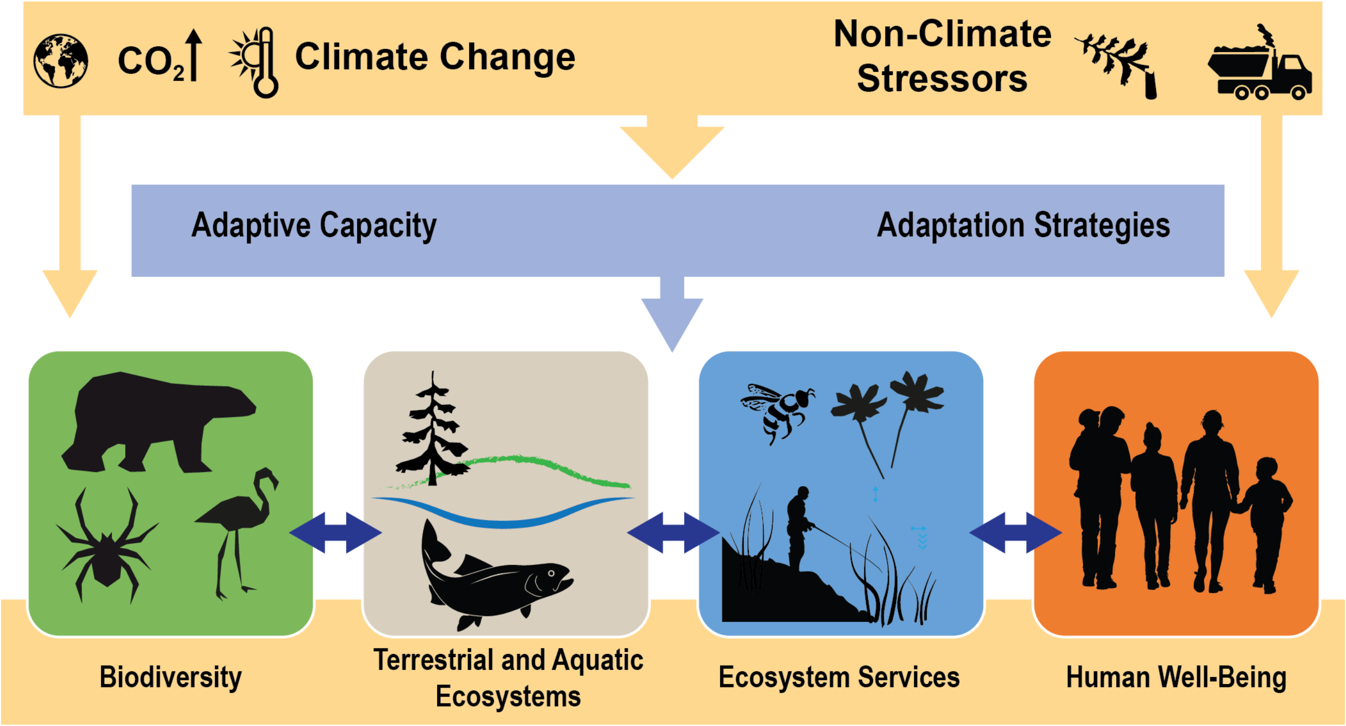


Figure 7.1: Climate and non-climate stressors interact synergistically on biological diversity, ecosystems, and the services they provide for human well-being. The impact of these stressors can be reduced through the ability of organisms to adapt to changes in their environment, as well as through adaptive management of the resources upon which humans depend. Biodiversity, ecosystems, ecosystem services, and human well-being are interconnected: biodiversity underpins ecosystems, which in turn provide ecosystem services; these services contribute to human well-being. Ecosystem structure and function can also influence the biodiversity in a given area. The use of ecosystem services by humans, and therefore the well-being humans derive from these services, can have feedback effects on ecosystem services, ecosystems, and biodiversity. Sources: NOAA; USGS; DOI.

Species and Populations

There is increasing evidence that climate change is impacting biodiversity, and species and populations are responding in a variety of ways. Individuals may acclimate to new conditions by altering behavioral, physical, or physiological characteristics, or populations may evolve new or altered characteristics that are better suited to their current environment. Additionally, populations may track environmental conditions by moving to new locations. The impacts of climate change on biodiversity have been observed across a range of scales, including at the level of individuals (such as changes in genetics, behavior, physical characteristics, and physiology), populations (such as changes in the timing of life cycle events), and species (such as changes in geographic range).[5]

Changes in individual characteristics: At an individual level, organisms can adapt to climate change through shifts in behavior, physiology, or physical characteristics.[5,6,7,8] These changes have been observed across a range of species in terrestrial, freshwater, and marine systems.[5,6,7,8] Some individuals have the ability to immediately alter characteristics in response to new environmental conditions. Behavioral changes, such as changes in foraging, habitat use, or predator avoidance, can provide an early indication of climate change impacts because they are often observable before other impacts are apparent.[6]

However, some immediate responses to environmental conditions are not transmitted to the next generation. Ultimately, at least some evolutionary response is generally required to accommodate long-term, directional change.[9] Although relatively fast evolutionary changes have been documented in the wild,[10,11,12] rapid environmental changes can exceed the ability of species to track them.[13] Thus, evidence to date suggests that evolution will not fully counteract negative effects of climate change for most species. Importantly, many human-caused stressors, such as habitat loss or fragmentation (Figure 7.2) (see also Ch. 5: Land Changes, "State of the Sector" and KM 2), reduce the abundance as well as the genetic diversity of populations. This in turn compromises the ability of species and populations to cope with additional disturbances.[14]

Changes in phenology: The timing of important biological events is known as phenology and is a key indicator of the effects of climate change on ecological communities.[16,17,18,19] Many plants and animals use the seasonal cycle of environmental events (such as seasonal temperature transitions, melting ice, and seasonal precipitation patterns) as cues for blooming, reproduction, migration, or hibernation. Across much of the United States, spring is starting earlier in the year relative to 20th-century averages, although in some regions spring onset has been delayed (Figure 7.3) (see also Ch. 1: Overview, Figure 1.2j).[20,21,22] In marine and freshwater systems, the transition from winter to spring temperatures[23] and the melting of ice[24] are occurring earlier in the spring, with significant impacts on the broader ecosystem. Phytoplankton can respond rapidly to such changes, resulting in significant shifts in the timing of phytoplankton blooms and causing cascading food web effects (Ch. 9: Oceans, KM 2).[19,24]

Genetic Diversity and Climate Exposure

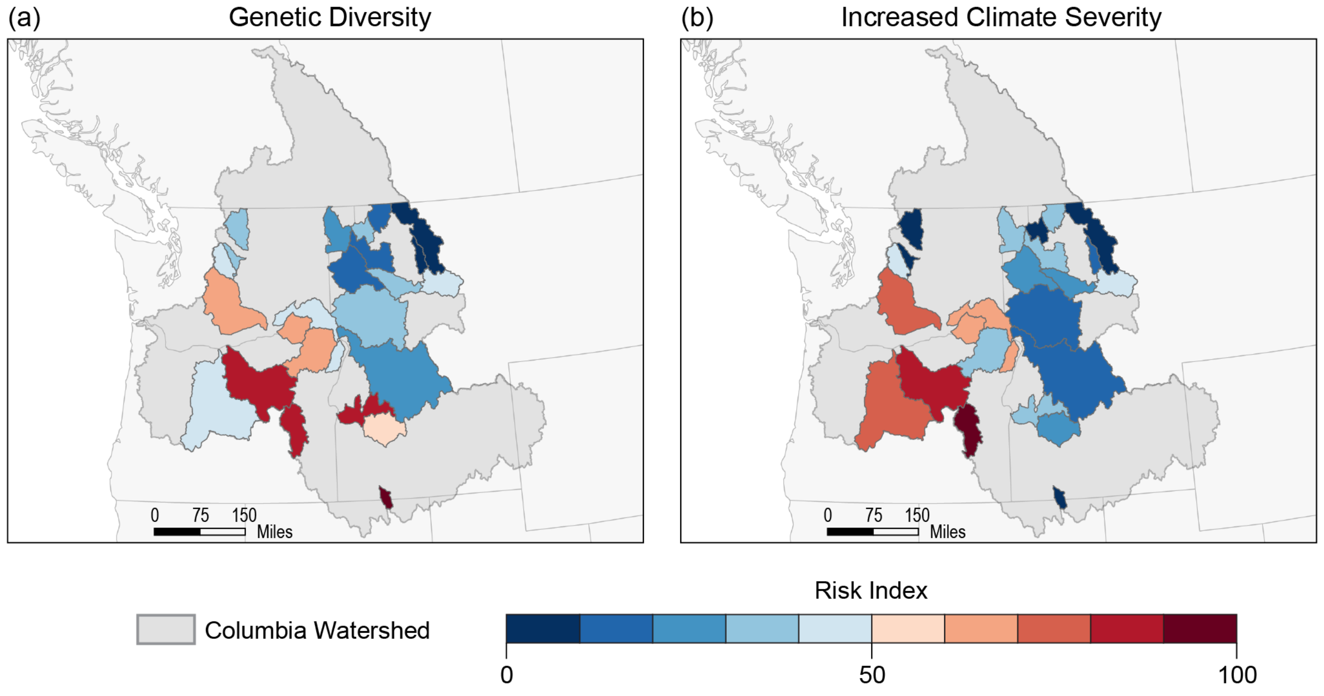


Figure 7.2: Genetic diversity is the fundamental basis of adaptive capacity. Throughout the Pacific Northwest, (a) bull trout genetic diversity is lowest in the same areas where (b) climate exposure is highest; in this case, climate exposure is a combination of maximum temperature and winter flood risk. Sub-regions within the broader Columbia River Basin (shaded gray) represent different watersheds used in the vulnerability analysis. Values are ranked by threat, such that the low genetic diversity and high climate exposure are both considered "high" threats (indicated as red in the color gradient). Source: adapted from Kovach et al. 2015.[15]

Trends in First Leaf and First Bloom Dates

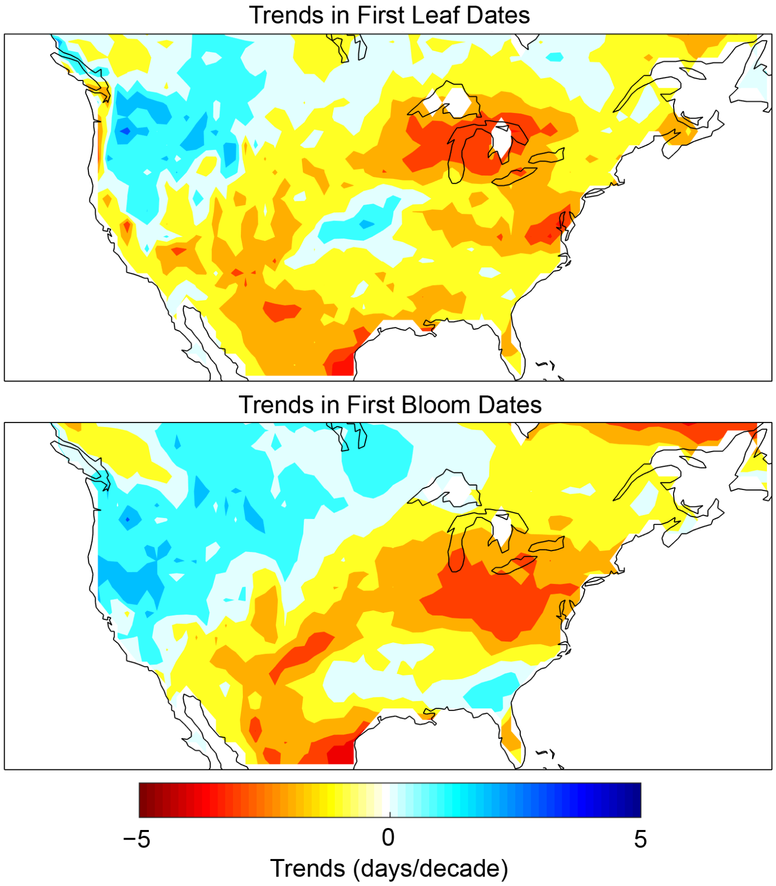


Figure 7.3: These maps show observed changes in timing of the start of spring over the period 1981–2010, as represented by (top) an index of first leaf date (the average date when leaves first appear on three indicator plants) and (bottom) an index of first bloom date (the average date when blossoms first appear on three indicator plants). Reds and yellows indicate negative values (a trend toward earlier dates of first leaf or bloom); blues denote positive values (a trend toward later dates). Units are days per decade. Indices are derived from models driven by daily minimum and maximum temperature throughout the early portion of the growing season. Source: adapted from Ault et al. 2015.[21]

One emerging trend is that the rate of phenological change varies across trophic levels (position in a food chain, such as producers and consumers),[25,26] resulting in resource mismatches and changes to species interactions. Migratory species are particularly vulnerable to phenological mismatch if their primary food source is not available when they arrive at their feeding grounds or if they lack the flexibility to shift to other food sources.[27,28,29]

Changes in range: Climate change is resulting in large-scale shifts in the range and abundance of species, which are altering terrestrial, freshwater, and marine ecosystems.[2,30,31,32,33] Range shifts reflect changes in the distribution of a population in response to changing environmental conditions and can occur as a result of directional movement or different rates of survival (Ch. 1: Overview, Figure 1.2h). The ability of a species to disperse affects the rate at which species can shift their geographic range in response to climate change and hence is an indicator of adaptive capacity.[34] Climate change has led to range contractions in nearly half of studied terrestrial animals and plants in North America; this has generally involved shifts northward or upward in elevation.[35] High-elevation species may be more exposed to climate change than previously expected[36] and seem particularly affected by range shifts.[37] In marine environments, many larval and adult fish have also shown distribution shifts—primarily northward, but also along coastal shelves and to deeper water—that correspond with changing conditions.[38]

Species vary in the extent to which they track different aspects of climate change (such as temperature and precipitation),[39,40,41] which has the potential to cause restructuring of communities across many ecosystems. This variation is increasingly being considered in research efforts in order to improve predictions of species range shifts.[42,43,44] Finally, habitat fragmentation and loss of connectivity (due to urbanization, roads, dams, etc.) can prevent species from tracking shifts in their required climate; efforts to retain, restore, or establish climate corridors can, therefore, facilitate movements and range shifts.[18,45,46,47]

Ecosystems

Climate-driven changes in ecosystems derive from the interacting effects of species- and population-level responses, as well as the direct impacts of environmental drivers. Since NCA3, there have been advances in our understanding of several fundamental ecosystem properties and characteristics, including: primary production, which defines the overall capacity of an ecosystem to support life; invasive species; and emergent properties and species interactions. Particular ecosystems that are experiencing specific climate change impacts, such as ocean acidification (Ch. 9: Oceans), sea level rise (Ch. 8: Coastal, KM 2), and wildfire (Ch. 6: Forests, KM 1), can be explored in more detail in sectoral and regional chapters (see also Ch. 1: Overview, Figures 1.2i, 1.2g, and 1.2k).

Changing primary productivity: Almost all life on Earth relies on photosynthetic organisms. These primary producers, such as plants and phytoplankton, are responsible for producing Earth's oxygen, are the base of most food webs, and are important components of carbon cycling and sequestration. Diverse observations suggest that global terrestrial primary production has increased over the latter 20th and early 21st centuries.[48,49,50,51] This change has been attributed to a combination of the fertilizing effect of increasing atmospheric CO_2, nutrient additions from human activities, longer growing seasons, and forest regrowth, although the precise contribution of each factor remains unresolved (Ch. 6: Forests, KM 2; Ch. 5: Land Changes, KM 1).[50,51,52] Regional trends, however, may differ significantly from global averages. For example, heat waves, drought, insect outbreaks, and forest fires in some U.S. regions have killed millions of trees in recent years (Ch. 6: Forests, KM 1 and 2).

Marine primary production depends on a combination of light, which is prevalent at the ocean's surface, and nutrients, which are available at greater depths. The separation between surface and deeper ocean layers has grown more pronounced over the past century as surface waters have warmed.[53] This has likely increased nutrient limitation in low- and midlatitude oceans. Direct evidence for declines in primary productivity, however, remains mixed.[54,55,56,57,58,59,60]

Invasive species: Climate change is aiding the spread of invasive species (nonnative organisms whose introduction to a particular ecosystem causes or is likely to cause economic or environmental harm). Invasive species have been recognized as a major driver of biodiversity loss.[61,62,63] The worldwide movement of goods and services over the last 200 years has resulted in an increasing rate of introduction of nonnative species globally,[64,65] with no sign of slowing.[66] Global ecological and economic costs associated with damages caused by nonnative species and their control are substantial (more than $1.4 trillion annually).[61] The introduction of invasive species, along with climate-driven range shifts, is creating new species interactions and novel ecological communities, or combinations of species with no historical analog.[67,68] Climate change can favor nonnative invading species over native ones.[69,70] Extreme weather events aid species invasions by decreasing native communities' resistance to their establishment and by occasionally putting native species at a competitive disadvantage, although these relationships are complex and warrant further study.[71,72,73,74] Climate change can also facilitate species invasions through physiological impacts, such as by increasing per capita reproduction and growth rates.[69,75,76]

Changing species interactions and emergent properties: Emergent properties of ecosystems refer to changes in the characteristics, function, or composition of natural communities. This includes changes in the strength and intensity of interactions among species, altered combinations of community members (known as assemblages), novel species interactions, and hybrid or novel ecosystems.[78] There is mounting evidence that in some systems (such as plant–insect food webs), higher trophic levels are more sensitive than lower trophic levels to climate-induced changes in temperature, water availability,[79,80,81] and extreme events.[82] Predator responses to these stressors can lead to higher energetic needs and increased consumption,[83] shifts or expansion in seasonal demand on prey resources, or resource mismatches.[84,85] Some predators may be able to adapt to changing conditions by switching to alternative or novel food sources[86] or adjusting their behavior to forage in cooler habitats to alleviate heat stress.[87] Such changes at higher trophic levels directly affect the energetic demands and mortality rates of prey[88] and have important impacts on ecosystem functioning, such as biological activity and productivity (as indicated by community respiration rates),[89] and on the flow of energy and nutrients within communities and across habitats. For example, in Alaska, brown bears have recently altered their preference for salmon to earlier-ripening berries, changing both salmon mortality rates and the transfer of oceanic nutrients to terrestrial habitats.[90] Warming is changing community composition, as species with lower tolerances to disturbance[91] and nonoptimal conditions[92] are outcompeted. Declining diversity in life histories as a result of climate change is also expected to result in more uniform, less varied population structures, in turn resulting in increased competition and potentially contributing to local extinctions and reduced community resilience.[29,93]

Lionfish are an invasive species in the Atlantic, and their range is projected to expand closer to the U.S. Atlantic coastline in the future as a result of climate change. Photo credit: G.P. Schmahl, NOAA Flower Garden Banks National Marine Sanctuary.

Projected Range Expansion of Invasive Lionfish

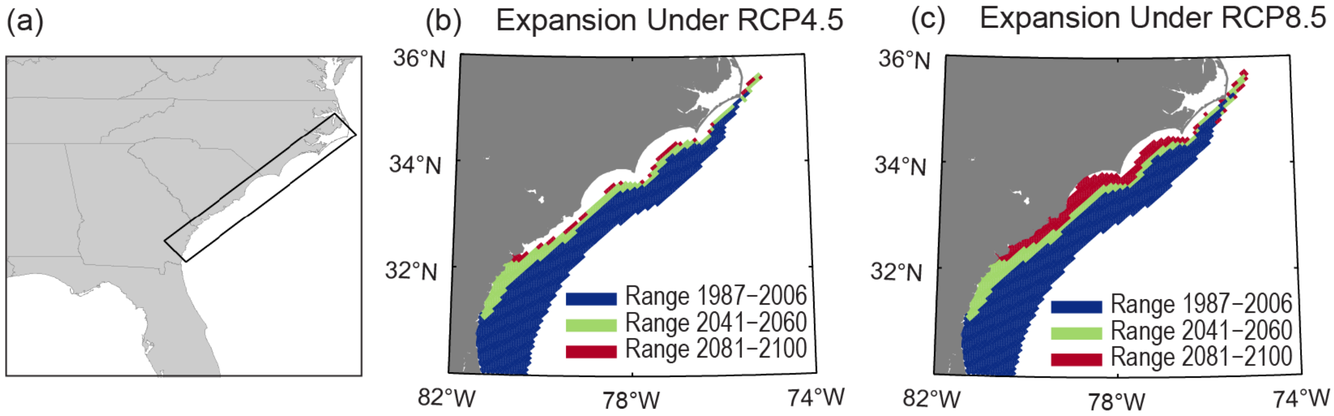


Figure 7.4: Lionfish, native to the Pacific Ocean, are an invasive species in the Atlantic. Their range is projected to expand closer to (a) the U.S. Atlantic coastline as a result of climate change. The maps show projected range expansion of the invasive lionfish in the southeast United States by mid-century (green) and end of the century (red), based on (b) the lower and (c) higher scenarios (RCP4.5 and RCP8.5, respectively), as compared to their recently observed range (blue). The projected range shifts under a higher scenario (RCP8.5) represents a 45% increase over the current year-round range. Venomous lionfish are opportunistic, generalist predators that consume a wide variety of invertebrates and fishes and may compete with native predatory fishes. Expansion of their range has the potential to increase the number of stings of divers and fishers. Source: adapted from Grieve et al. 2016.[77]

Ecosystem Services

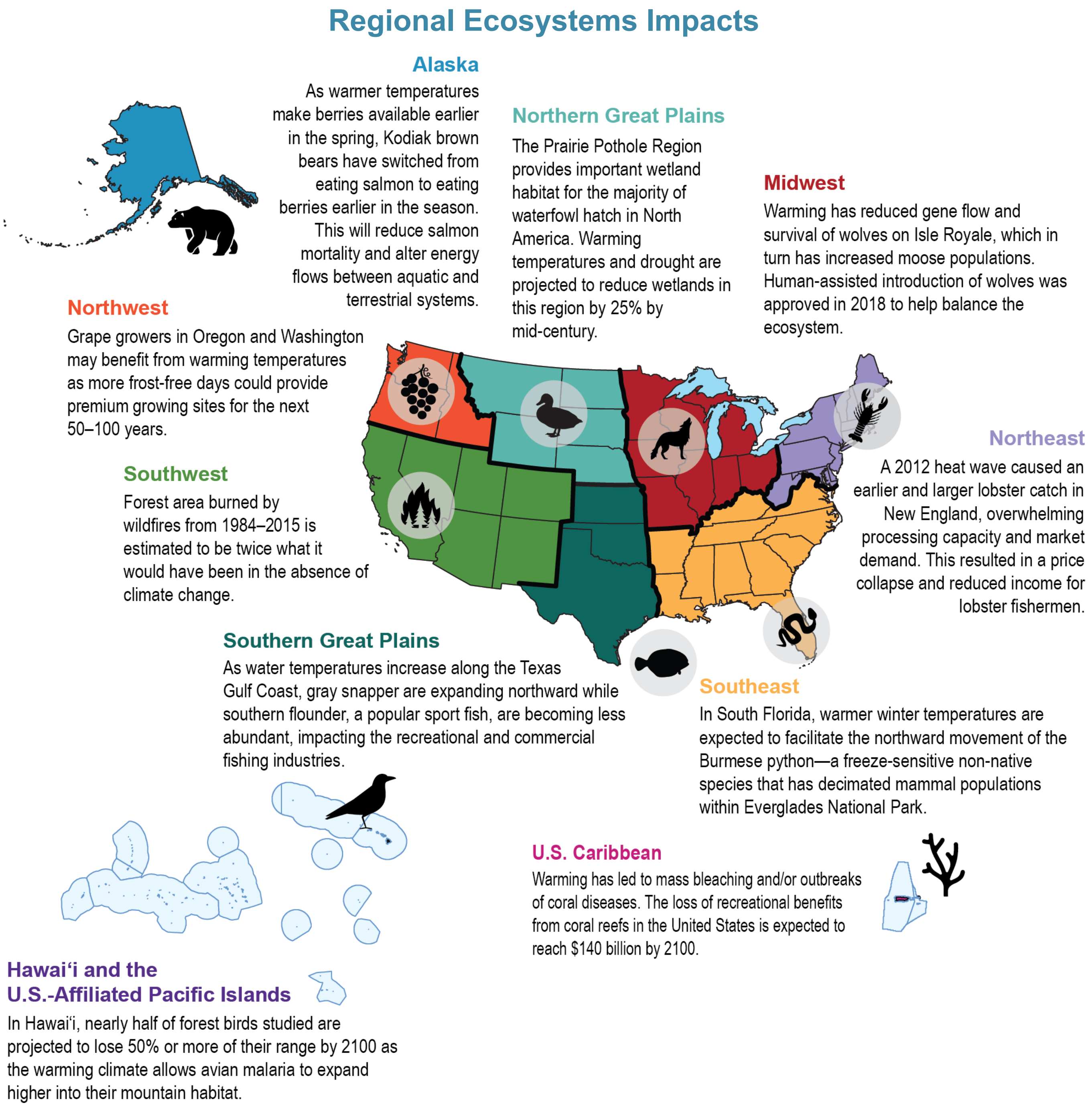
Increasing evidence since NCA3 demonstrates that climate change continues to affect the availability and delivery of ecosystem services, including changes to provisioning, regulating, cultural, and supporting services. Humans, biodiversity, and ecosystem processes interact with each other dynamically at different temporal and spatial scales.[94] Thus, the climate-related changes to ecosystems and biodiversity discussed in this and other chapters of this report all have consequences for numerous ecosystem services. In addition, these climate-related impacts interact with other non-climate stressors, such as pollution, overharvesting, and habitat loss, to produce compounding impacts on ecosystem services.[95,96]

The adaptive capacity of human communities to deal with these changes will partly determine the magnitude of the resulting impacts to ecosystem services. For example, the shifting range of fish stocks (Ch. 9: Oceans, KM 2), an example of a provisioning ecosystem service, may require vessels to travel further from port, invest in new fishing equipment, or stop fishing altogether; each of these responses implies increasing levels of costs to society.[97] A reduction in biodiversity that impacts the abundance of charismatic and aesthetically valuable organisms, such as coral reefs, can lead to a reduction in wildlife-related ecotourism and may result in negative economic consequences for the human communities that rely on them for income.[3] Climate change can also impact ecosystem services such as the regulation of climate and air, water, and soil quality.[98] Although climate change impacts on ecosystem services will not be uniformly negative, even apparently positive impacts of climate change can result in costly changes. For example, in areas experiencing longer growing seasons (Ch. 10: Ag & Rural, KM 3), farmers would need to shift practices and invest in new infrastructure (Ch. 12: Transportation, KM 1 and 2) in order to fully realize the benefits of these climate-driven changes. Moreover, different human communities and segments of society will be more vulnerable than others based on their ability to adapt; jurisdictional borders, for instance, may limit human migration in response to climate change.[99]

Oyster reefs exemplify the myriad ways in which ecosystem components support ecosystem services, including water quality regulation, nutrient and carbon sequestration, habitat formation, and shoreline protection. These services are reduced when oyster reefs are impacted by climate change through, for example, sea level rise[100,101] and ocean acidification.[102] A recent study estimated that the economic value of the non-harvest ecosystem services provided by oyster reefs ranges from around $5,500 to $99,400 (in 2011 dollars) per year per hectare. The value of shoreline protection varied depending on the location but had the highest possible value of up to $86,000 per hectare per year (in 2011 dollars).[103] Coral reefs, which provide shoreline protection and support fisheries and recreation, are also threatened by ocean warming and acidification. The loss of recreational benefits associated with coral reefs in the United States is projected to be $140 billion by 2100 (in 2015 dollars) under a higher scenario (RCP8.5) (Ch. 9: Oceans, KM 1).[104]

Regional Summary

All regions and ecosystems of the United States are experiencing the impacts of climate change. However, impacts will vary by region and ecosystem: not all areas will experience the same types of impacts, nor will they experience them to the same degree (Ch. 2: Climate, KM 5 and 6). Regional variation in climate impacts are covered in detail in other sectoral and regional chapters of the Fourth National Climate Assessment. However, in Figure 7.5, a wide range of regional examples are provided at multiple scales to demonstrate the varied ways in which biodiversity, ecosystems, and ecosystem services are being impacted around the United States.



Regional Ecosystems Impacts

Alaska

As warmer temperatures make berries available earlier in the spring, Kodiak brown bears have switched from eating salmon to eating berries earlier in the season. This will reduce salmon mortality and alter energy flows between aquatic and terrestrial systems.

Northern Great Plains

The Prairie Pothole Region provides important wetland habitat for the majority of waterfowl hatch in North America. Warming temperatures and drought are projected to reduce wetlands in this region by 25% by mid-century.

Midwest

Warming has reduced gene flow and survival of wolves on Isle Royale, which in turn has increased moose populations. Human-assisted introduction of wolves was approved in 2018 to help balance the ecosystem.

Northwest

Grape growers in Oregon and Washington may benefit from warming temperatures as more frost-free days could provide premium growing sites for the next 50–100 years.

Southwest

Forest area burned by wildfires from 1984–2015 is estimated to be twice what it would have been in the absence of climate change.

Northeast

A 2012 heat wave caused an earlier and larger lobster catch in New England, overwhelming processing capacity and market demand. This resulted in a price collapse and reduced income for lobster fishermen.

Southern Great Plains

As water temperatures increase along the Texas Gulf Coast, gray snapper are expanding northward while southern flounder, a popular sport fish, are becoming less abundant, impacting the recreational and commercial fishing industries.

Southeast

In South Florida, warmer winter temperatures are expected to facilitate the northward movement of the Burmese python—a freeze-sensitive non-native species that has decimated mammal populations within Everglades National Park.

U.S. Caribbean

Warming has led to mass bleaching and/or outbreaks of coral diseases. The loss of recreational benefits from coral reefs in the United States is expected to reach $140 billion by 2100.

Hawai‘i and the U.S.-Affiliated Pacific Islands

In Hawai‘i, nearly half of forest birds studied are projected to lose 50% or more of their range by 2100 as the warming climate allows avian malaria to expand higher into their mountain habitat.

Figure 7.5: This figure shows selected examples of impacts to biodiversity, ecosystems, and ecosystem services that are linked to climate change throughout the United States. See the online version at https://nca2018.globalchange.gov/chapter/7#fig-7-5 for more examples and references. Source: adapted from Groffman et al. 2014.

Key Message 1

Impacts on Species and Populations

Climate change continues to impact species and populations in significant and observable ways. Terrestrial, freshwater, and marine organisms are responding to climate change by altering individual characteristics, the timing of biological events, and their geographic ranges. Local and global extinctions may occur when climate change outpaces the capacity of species to adapt.

Climate change continues to alter species' characteristics, phenologies, abundances, and geographical ranges, but not all species are affected equally. Generalists (species that use a wide range of resources) are better able to adapt to or withstand climate-driven changes,[90] while specialists (species that depend on just a few resources), small or isolated populations, and species at the edge of their ranges have limited abilities to adjust to unfavorable or new environmental conditions.[27,105,106]

Species' survival depends on the presence and flexibility of traits to adapt to climate change; traits may occur within the existing genetic structure of a population (that is, plasticity) or arise through evolution. Changes in individual characteristics are one of the most immediate mechanisms an organism has to cope with environmental change, and species have demonstrated both plastic and evolutionary responses to recent climate change.[9,10,11,12] For example, snowshoe hares rely on coat color to camouflage them from predators, but earlier spring snowmelts have increased the number of white animals on snowless backgrounds. While individual animals have exhibited some ability to adjust the rate of molting, they have limited capacity to adjust the timing of color change.[9] Consequently, evolution in the timing of molting may be needed to ensure persistence under future climate conditions.

Shifts in range and phenology also indicate species' ability to cope with climate change through the presence and flexibility of particular traits (for example, behavior and dispersal abilities). In studies spanning observational periods of up to 140 years, terrestrial animal communities have shifted ranges an average of 3.8 miles per decade.[107] Larger shifts of up to 17.4 miles per decade have been recorded for marine communities[17,38,108] in observations spanning up to a century. Birds in North America have shifted their ranges in the last 60 years, primarily northward.[109] Pollinators have been affected, too, with decreases in abundance and shifts upslope seen over the past 35 years.[110] Models suggest that shifts in species' ranges will continue, with freshwater and marine organisms generally moving northward to higher latitudes and to greater depths and terrestrial species moving northward and to higher elevations.[111,112] However, this capacity to adapt to climate change through range shifts is not infinite: many organisms have limited dispersal ability and newly suitable habitat in which to colonize, and all organisms are limited in the range of environments to which they can adapt.

White snowshoe hares stand out in stark contrast against snowless backgrounds, leaving them more vulnerable to predators than their brown counterparts. Photo credit: L. S. Mills research photo by Jaco and Lindsey Barnard, University of Montana Mills Research Lab.

Shifts in phenology have been well documented in terrestrial, marine, and freshwater systems.[113] As with range shifts, changes to phenology are expected to continue as the climate warms.[114] Changes in phenology can have significant impacts on ecosystems and the services they provide, as evidenced by shifts in the production and phenology of commercially important marine groundfish,[38,115] inland fish species,[116] migratory fish such as salmon,[10,117,118] and invertebrates such as northern shrimp and lobster (Ch. 18: Northeast, KM 2 and Box 18.1).[119,120]

The many components of climate change (for example, rising temperatures, altered precipitation, ocean acidification, and sea level rise) can have interacting and potentially opposing effects on species and populations, which further complicates their responses to climate change.[41,121,122] In addition, species are responding to many other factors in addition to climate change, such as altered species interactions and non-climate stressors such as land-use change (Ch. 5: Land Changes, "State of the Sector" and KM 2) and resource extraction (for example, logging and commercial fishing).

Compounding stressors can result in species lagging behind temperature change and occupying nonoptimal conditions.[123] For example, iconic species of salmon have lost access to much of their historical habitat due to barriers or degradation caused by pollution and land-use change, leading to significant losses in spawning and cold water habitats that could have supported adaptation and provided refuge against increasing climate impacts.[124,125]

The rate and magnitude of climate impacts can exceed the abilities of even the most adaptable species and potentially lead to tipping points, which result in abrupt system changes and local extinctions.[126,127] For example, climate change appears to have contributed to the local extinction of populations of the Federally Endangered Karner blue butterfly in Indiana (Ch. 21: Midwest, KM 3). Compounded climate stress arises when populations with limited capacity to adapt also experience high exposure to climate change, posing substantial risks to certain ecosystems and the services they provide to society. Bull trout in the Northwest, for example, show the least genetic diversity in the same regions where summer temperature and winter streamflows are projected to be the highest due to climate change (Figure 7.2).[15] Further decline of salmon and trout will impact a cherished cultural resource, as well as popular sport and commercial fisheries. Identifying the most vulnerable species and understanding what makes them relatively more at risk than other species are, therefore, important considerations for prioritizing and implementing effective management actions.[35,127,128,129]

Key Message 2

Impacts on Ecosystems

Climate change is altering ecosystem productivity, exacerbating the spread of invasive species, and changing how species interact with each other and with their environment. These changes are reconfiguring ecosystems in unprecedented ways.

Climate change impacts also occur at the ecosystem scale, changing fundamental ecosystem characteristics, properties, and related ecosystem services; altering important trophic relationships; and affecting how species and populations interact with each other.

Because primary producers are the base of the food web, climate impacts to primary production can have significant effects that radiate throughout the entire ecosystem. While climate models project continued increases in global terrestrial primary production over the next century,[130,131] these projections are uncertain due to a limited understanding of the impacts of continued CO_2 increases on terrestrial ecosystem dynamics;[132,133,134] the potential effects of nutrient limitation;[135] the impacts of fire[136] and insect outbreaks;[137] and an incomplete understanding of the impacts of changing climate extremes.[138,139] Furthermore, even without these factors, projections suggest decreasing primary production in many arid regions due to worsening droughts, similar to responses observed in the Southwest United States in recent years.[140,141,142] Modest to moderate declines in ocean primary production are projected for most low- to midlatitude oceans over the next century,[143,144,145] but regional patterns of change are less certain.[60,143,145] Most models project increasing primary productivity in the Arctic due to decreasing ice cover. This trend is supported by satellite-based observations of the primary productivity–ice cover relationship over the last 10–15 years.[146,147,148] Projections also suggest that changes in productivity will not be equal across trophic levels: changes in primary productivity are likely to be amplified at higher levels of the food web.[149,150,151] For example, small changes in marine primary productivity are likely to result in even larger changes to the biomass of fisheries catch.[152]

Varying phenological responses to climate change can also impact the food web and result in altered species interactions and resource mismatch.[17,153] Such mismatches can decrease the fitness of individuals, disrupt the persistence and resilience of populations, alter ecosystems and ecosystem services, and increase the risk of localized extinctions.[16,26,113,154,155] In marine ecosystems, rapid phenological changes at the base of the food web can create a mismatch with consumers,[156] disrupting the availability of food for young fish and changing the food web structure.[24,156]

In both terrestrial and aquatic environments, migratory species face the potential for resource mismatch. For example, a majority of migratory songbirds in North America have advanced their phenology in response to climate change, but for several species, such as the yellow-billed cuckoo and the blue-winged warbler, these changes have been outpaced by advancing vegetation in their breeding grounds and stopover sites.[28] The resulting mismatch between consumers and their food or habitat resources can result in population declines.[155]

In addition to changes in productivity and phenology, novel species interactions as a result of climate change can cause dramatic and surprising changes. For example, range expansions of tropical herbivorous fishes have changed previously kelp-dominated systems into kelp-free sites.[157] These novel combinations of species are expected to outcompete and potentially eliminate some native species, posing a significant threat to the long-term stability of iconic ecosystems and the services they provide.[157] A recent survey of 136 freshwater, marine, and terrestrial studies suggests that species interactions are often the immediate cause of local extinctions related to climate change.[158]

Climate change impacts to ecosystem properties are difficult to assess and predict because they arise from multiple and complex interactions across different levels of food webs, habitats, and spatial scales. Modeling and experimental studies are some of the few ways to assess complicated ecological interactions, especially in marine systems where direct observations of plants, fish, and animals are difficult.[67,159,160,161] There is strong consensus that trophic mismatches and asynchronies will occur, yet these are mostly predicted consequences, and few examples have been documented.[13,84,162,163] While theory and management principles for novel ecosystems are new, strongly debated, and largely descriptive, they are also crucial for understanding and anticipating widespread ecosystem changes in the future.[164,165,166] For example, it remains largely uncertain which members of historical ecological communities and ecosystems will adapt in place or move into new locations to follow optimal ecological and environmental conditions.[167] Such uncertainties complicate management decisions regarding where and when human intervention is advisable to assist persistence.

It is also unclear how the restructuring of ecosystems will manifest in terms of the functioning and delivery of ecosystem services.[167,168] For example, along the Northeast Atlantic coast, native fiddler and blue crabs have shifted their ranges north and are now found in New England coastal habitats where they were previously absent.[169,170] These two species join an assemblage of native and invasive crab species, which are responding to changes in environmental and ecological conditions in different ways. In some locations, purple marsh crabs are benefiting from lower abundances of blue crabs and other predators, in part due to overfishing; this results in population explosions of purple marsh crabs that damage marsh habitats through herbivory (plant eating) and burrowing activities.[171] Because salt marshes provide a range of ecosystem services, including coastal protection, erosion control, water purification, carbon sequestration, and maintenance of fisheries, marsh destruction can negatively impact human communities.[172] Thus, climate impacts to ecosystems can have important consequences for ecosystem services and the people who depend on them.

Key Message 3

Ecosystem Services at Risk

The resources and services that people depend on for their livelihoods, sustenance, protection, and well-being are jeopardized by the impacts of climate change on ecosystems. Fundamental changes in agricultural and fisheries production, the supply of clean water, protection from extreme events, and culturally valuable resources are occurring.

Climate change is affecting the availability and delivery of ecosystem services to society through altered provisioning, regulating, cultural, and supporting services.[95]

A reduced supply of critical provisioning services (food, fiber, and shelter) has clear consequences for the U.S. economy and national security and could create a number of challenges for natural resource managers.[104] Although an extended growing season resulting from phenological shifts may have positive effects on the yield and prices of particular crops,[173] net changes to agricultural productivity will vary regionally (Figure 7.6) and will be affected by other climate change impacts, such as drought and heat stress.[174,175] In addition, early springs with comparatively late (but climatically normal) frosts can directly affect plant growth and seed production and indirectly disrupt ecosystem services such as pollination. By the middle of this century, early onset of spring could occur one out of every three years; however, if the date of last freeze does not change at the same rate, large-scale plant damage and agricultural losses, [176,177,178] as well as changes to natural resource markets,[119] are possible. Shellfish harvests are also projected to decline significantly through the end of the century due to ocean acidification, with cumulative estimated losses of $230 million under RCP8.5 and $140 million under RCP4.5 (discounted at 3%) (see the Scenario Products section of App. 3 for more information on scenarios).[104]

The degree to which climate change alters species' ranges can create jurisdictional conflict and uncertainty.[97] For example, fisheries management is typically done within defined boundaries and governed by local or international bodies, and terrestrial resource extraction typically occurs on private property or leased public lands with legislated boundaries.[180] Local extinctions and range shifts of marine species have already been documented (Ch. 9: Oceans, KM 2), as species' ranges shift with changing habitat and food conditions. Some species have moved out of historical boundaries and seasonal areas and into places that have no policy, management plan, or regulations in place to address their presence and related human use. Furthermore, unique life histories and genetic resources will likely be lost altogether as range shifts and the spread of invasive species interact with ecological complexity. Examples include loss of genetic diversity and the evolution of traits that increase rates of dispersal.[181,182] Managers may also need to respond to an alteration in the timing of spawning and migration of fish species in order to avoid overly high levels of fish mortality.[183]

Climate change can affect important regulating services such as the capture and storage of carbon,[126] which can help reduce greenhouse

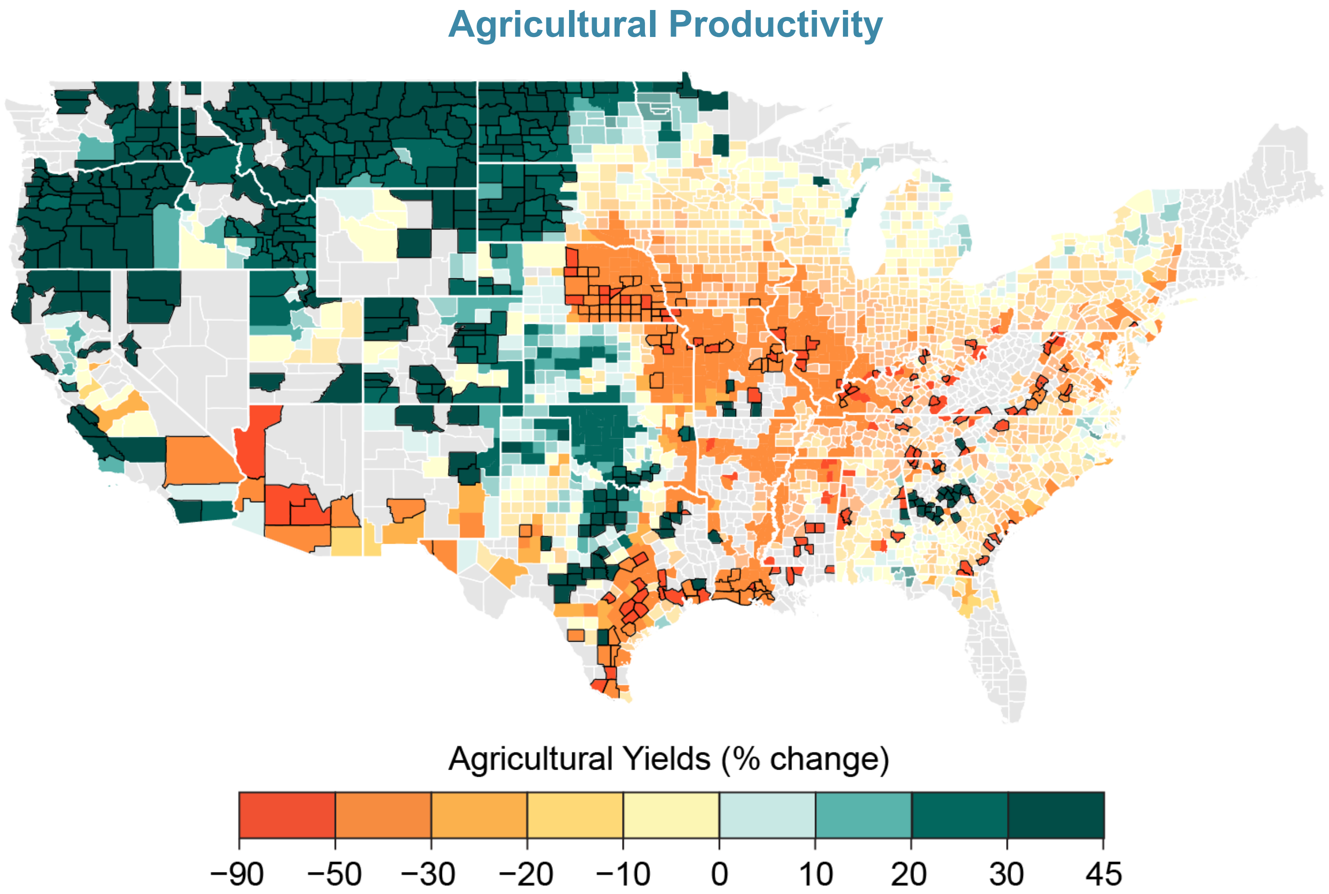


Figure 7.6: The figure shows the projected percent change in the yield of corn, wheat, soybeans, and cotton during the period 2080–2099. Units represent average percent change in yields under the higher scenario (RCP8.5) as compared to a scenario of no additional climate change. Warmer colors (negative percent change) indicate large projected declines in yields; cooler colors (green) indicate moderate projected increases in yields. Source: adapted from Hsiang et al. 2017.[179] Data were not available for the U.S. Caribbean, Alaska, or Hawai'i and U.S.-Affiliated Pacific Islands regions.

gas concentrations in the atmosphere and thereby contribute to climate change mitigation.[184] Climate change impacts, such as changes to the range and abundance of vegetation, to the incidence of wildfire and pest outbreaks, and to the timing and species composition of phytoplankton blooms, can all impact carbon cycling and sequestration (Ch. 5: Land Changes, KM 1; Ch. 6: Forests, KM 2; Ch. 9: Oceans, KM 2; Ch. 29: Mitigation, Box 29.1). Disease regulation is also an important ecosystem service that can be impacted by climate change. Pests and diseases are expected to expand or shift their ranges as the climate warms, and the evolution of immune responses will be important for both human and animal health (Ch. 18: Northeast, KM 4; Ch. 21: Midwest, KM 4; Ch. 26: Alaska, KM 3; Ch. 6: Forests, KM 1; Ch. 14: Human Health, KM 1).[185,186] Other examples of regulating ecosystem services that could be impacted by climate change include coastal protection from flooding and storm surge by natural reefs (Ch. 8: Coastal, KM 2),[187] the supply of clean water (Ch. 3: Water, KM 1)[188] and controls on the timing and frequency of wildfires (Ch. 6: Forests, KM 1).[189]

Some cultural ecosystem services are also at risk from climate change. By the end of the century (2090), cold water recreational fishing days are predicted to decline, leading to a loss in recreational fishing value of $1.7 billion per year under RCP4.5 and $3.1 billion per year under RCP8.5 by 2090.[104] Climate change is also predicted to shorten downhill and cross-country ski seasons.[104] In northwestern Wyoming and western Montana, the cross-country ski season is projected to decline by 20%–60% under RCP4.5 and 60%–100% under RCP8.5 by 2090 (Ch. 22: N. Great Plains, KM 3). Climate change also threatens Indigenous peoples' cultural relationships with ancestral lands (Ch. 15: Tribes, KM 1). In addition, biodiversity and ecosystems are valuable to humans in and of themselves through their "existence value," whereby people derive satisfaction and value simply from knowing that diverse and healthy ecosystems exist in the world.[190] For example, a recent study found that the average U.S. household is willing to pay $33–$73 per year for the recovery or delisting of one of eight endangered or threatened species they studied.[191] However, climate change could have a positive impact on recreational activities that are more popular in warmer weather. For example, demand for biking, beachgoing, and other recreational activities has been projected to increase as winters become milder.[95,192]

Finally, climate change is impacting supporting services, which are the services that make all other ecosystem services possible. Climate change impacts include alterations in primary production and nutrient cycling.[48,193] Novel species assemblages associated with climate change can result in changes to energy and nutrient exchange (for example, altered carbon use in streams as new detritus-feeding or predator communities emerge) within and among ecological communities.[193] Because supporting services underpin all other ecosystem services, climate-induced changes to these services can have profound effects on human well-being.

Key Message 4

Challenges for Natural Resource Management

Traditional natural resource management strategies are increasingly challenged by the impacts of climate change. Adaptation strategies that are flexible, consider interacting impacts of climate and other stressors, and are coordinated across landscape scales are progressing from theory to application. Significant challenges remain to comprehensively incorporate climate adaptation planning into mainstream natural resource management, as well as to evaluate the effectiveness of implemented actions.

Climate change is affecting valued resources and ecosystem services in complex ways, as well as challenging existing management practices. While natural resource management has traditionally focused on maintaining or restoring historical conditions, these goals and strategies may no longer be realistic or effective as the climate changes.[194] Climate-driven changes are most effectively managed through highly adaptive and proactive approaches that are continually refined to reflect emerging and anticipated impacts of climate change (Ch. 28: Adaptation, Figure 28.1).[194] Decision support tools, including scenario planning[195,196,197] and structured decision-making,[198] can help decision-makers explore broad scenarios of risk and develop actions that account for uncertainty, optimize tradeoffs, and reflect institutional capacity.

Systems that are already degraded or stressed from non-climate stressors have lower adaptive capacity and resilience (Ch. 28: Adaptation, KM 3); therefore, some of the most effective actions that managers can take are to strategically restore and conserve areas that support valued species and habitats. However, these actions will be most effective when they consider future conditions in addition to historical targets.[4] New guidance on habitat restoration actions that can help to reduce impacts from climate change[199,200,201] is now being incorporated into regional and local restoration plans (Ch. 24: Northwest, KM 2). Limiting the spread of invasive species can also help maintain biodiversity, ecosystem function, and resilience.[202,203,204] In 2016, the U.S. Federal Government recommended specific management actions for the early detection and eradication of invasive species.[205]

Understanding and reestablishing habitat connectivity across terrestrial, freshwater, and marine systems are other key components in helping ecosystems adapt to changing environmental conditions.[45,46,201,206] Identifying and conserving climate change refugia (that is, areas relatively buffered from climate change that enable persistence) in ecological corridors can help species stay connected.[207,208] For example, areas of particularly cold water have been identified in the Pacific Northwest that, if well-connected and protected from other stressors, could act as critical habitat for temperature-sensitive salmon and trout populations.[209,210,211] More active approaches like assisted migration, whereby species are actively moved to more suitable habitats, and genetic rescue, where genetic diversity is introduced to improve fitness in small populations,[212] may be considered for species that have limited natural ability to move or that face extreme barriers to movement due to habitat fragmentation and development (Ch. 5: Land Changes, "State of the Sector" and KM 2).[124] For any assisted migration, there could be unforeseen and unwanted consequences. Developing policies to analyze and manage the potential consequences of assisted migration would not guarantee successful outcomes, but is likely to minimize unintended consequences.[213,214]

Climate change impacts have been incorporated into national and regional management plans that seek to mitigate harmful impacts and to address future management challenges, while also accounting for other non-climate stressors. Federal agencies with responsibilities for natural resource management are increasingly considering climate change impacts in their management plans, and many have formulated climate-smart adaptation plans for future resource management (such as the National Oceanic and Atmospheric Administration [NOAA], National Park Service [NPS], and U.S. Fish and Wildlife Service [USFWS]).[215,216,217,218,219,220] For example, the National Marine Fisheries Service recognizes climate change as a specific threat to marine resources, has developed regional action plans (e.g., Hare et al. 2016[221]), and is undertaking regional vulnerability analyses to incorporate climate change impacts in decision-making.[129,215,217] Agencies within the Department of the Interior are also increasingly developing and using climate change vulnerability assessments as part of their adaptation planning processes.[222] For example, USFWS has considered climate change in listing decisions, biological opinions, and proposed alternative actions under the Endangered Species Act (e.g., USFWS 2008, 2010[223,224]). In addition, federal agencies have been challenged to develop policies and approaches that consider ecosystem services and related climate impacts within existing planning and decision frameworks.[225] For example, ecosystems can be managed to help mitigate climate change through carbon storage on land and in the oceans (Ch. 29: Mitigation, Box 29.1; Ch. 5: Land Changes, KM 1)[200,226,227] and to buffer ocean acidification,[228] which could help reduce pressure on ecosystems. USFWS has been acquiring and restoring ecosystems to increase biological carbon sequestration since the 1990s.[229]

At the local and regional levels, efforts to restore ecosystems, increase habitat connectivity, and protect ecosystem services are gaining momentum through collaborations among state and tribal entities, educational institutions, nongovernmental organizations, and partnerships. For example, the Great Lakes Climate Adaptation Network, NOAA's Great Lakes Integrated Sciences and Assessments Program, the Huron River Watershed Council, and five Great Lakes cities worked together to develop a vulnerability assessment template that incorporates adaptation and climate-smart information into city planning (Ch. 21: Midwest, Case Study "Great Lakes Climate Adaptation Network"). Significant work remains, however, before climate change is comprehensively addressed in natural resource management at local and national scales. Improved projections of climate impacts at local and regional scales would likely improve ecosystem management, as would predictive models to inform effective adaptation strategies.[230,231,232] Yet such tools are often hampered by a lack of sufficient data at the appropriate scale.[232] In addition, institutional barriers (such as a focus on near-term planning, fixed policies and protocols, jurisdictional restrictions, and an established practice of managing based on historical conditions) have constrained agencies from comprehensively accounting for climate impacts.[194] Finally, more rigorous evaluation of adaptation efforts would allow managers to fully assess the effectiveness of proposed adaptation measures.[194]

Acknowledgments

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Opening Image Credit

Bear catching salmon: Lisa Hupp/U.S. Fish and Wildlife Service.

Traceable Accounts

Process Description

Topics for the chapter were selected to improve the consistency of coverage of the report and to standardize the assessment process for ecosystems and biodiversity. Chapter leads went through the detailed technical input for the Third National Climate Assessment and pulled out key issues that they felt should be updated in the Fourth National Climate Assessment. The chapter leads then came up with an author team with expertise in these selected topics. To ensure that both terrestrial and marine issues were adequately covered, most sections have at least one author with expertise in terrestrial ecosystems and one with expertise in marine ecosystems.

Monthly author calls were held beginning in December 2016, with frequency increasing to every other week as the initial chapter draft deadline approached. During these calls, the team came up with a work plan and fleshed out the scope and content of the chapter. After the outline for the chapter was created, authors reviewed the scientific literature, as well as the technical input that was submitted through the public call. After writing the State of the Sector section, authors pulled out the main findings to craft the Key Messages.

Key Message 1

Impacts on Species and Populations

Climate change continues to impact species and populations in significant and observable ways (*high confidence*). Terrestrial, freshwater, and marine organisms are responding to climate change by altering individual characteristics, the timing of biological events, and their geographic ranges (*likely, high confidence*). Local and global extinctions may occur when climate change outpaces the capacity of species to adapt (*likely, high confidence*).

Description of evidence base

Changes in individual characteristics: Beneficial effects of adaptive capacity depend on adequate genetic diversity within the existing population and sufficient population sizes. In addition, successful adaptive responses require relatively slow or gradual environmental change in relation to the speed of individual or population-level responses.[13] Empirical evidence continues to suggest that plastic changes and evolution have occurred in response to recent climate change[10,11,12,233] and may be essential for species' persistence.[186,234,235] However, adaptation is only possible if genetic diversity has not already been eroded as a result of non-climate related stressors such as habitat loss.[15] Additionally, projections suggest that climate change may be too rapid for some species to successfully adapt.[35,236] Adaptive capacity, and by extension the ability to avoid local or even global extinctions, is likely to vary among species and even populations within species.

Changes in range: Shifts in species' ranges have been documented in both terrestrial and aquatic ecosystems as species respond to climate change.[35,39] Approximately 55% of terrestrial and marine plant and animal species studied in temperate North America have experienced range shifts.[35] Climate change has led to contractions in the latitudinal or elevational ranges of 41% (97 of 238) of studied terrestrial plant and animal species in North America and Hawai‘i in the last 50–100 years.[35] Range shifts in terrestrial animal communities average 3.8 miles per decade.[107] In marine communities, range shifts of up to 17.4 miles per decade have been documented.[17] Planktonic organisms in the water column (that is, passively floating organisms in a body of water) more closely track the trajectory of preferred environmental conditions, resulting in more extensive range shifts; these organisms have exhibited rates of change from 4.3 miles per decade for species with broad environmental tolerances to 61.5 miles per decade for species with low tolerance of environmental change over a 60-year period.[237] Walsh et al. (2015)[38] documented significant changes in the center of distribution over two decades of 43% of planktonic larvae of 45 fish species.

These shifts have been linked to climate velocity—the rate and direction of change in temperature patterns.[30,39,238,239] Marked differences in observed patterns of climate velocity in terrestrial and aquatic ecosystems have been observed.[29,240] Climate velocity in the ocean can be greater than that on land by a factor of seven.[17]

Changes in phenology: In marine and freshwater systems, the transition from winter to spring temperatures is occurring earlier in the year, as evidenced by satellite measures of sea surface temperature dating back to 1981.[23] In addition, the timing of sea ice melt is occurring earlier in the spring at a rate of about 2 days per decade and has advanced by 25–30 days since 1979 in some regions.[24] Shifts in phenology have been well documented in terrestrial, marine, and freshwater systems.[113] As with range shifts, changes to phenology are expected to continue as the climate warms.[114]

Extinction risks: The rate and magnitude of climate impacts can exceed the abilities of even the most adaptable species, potentially leading to tipping points and abrupt system changes. In the face of rapid environmental change, species with limited adaptive capacity may experience local extinctions or even global extinctions.[126,127]

Major uncertainties

Changes in individual characteristics: Species and populations everywhere have evolved in response to reigning climate conditions, demonstrating that evolution will be necessary to survive climate change. Nonetheless, there is very limited evidence for evolutionary responses to recent climate change. As reviewed by Crozier and Hutchings (2014),[10] only two case studies document evolutionary responses to contemporary climate change in fish, as opposed to plasticity without evolution or preexisting adaptation to local conditions, and both cases involved the timing of annual migration.[241,242] In the case of the sockeye salmon, for example, nearly two-thirds of the phenotypic response of an earlier migration date was explained by evolutionary responses rather than individual plastic responses.[241]

Changes in range: Although the evidence for shifting ranges of many terrestrial and aquatic species is compelling, individual species are responding differently to the magnitude and direction of change they are experiencing related to their life history, complex mosaics of microclimate patterns, and climate velocity.[243,244,245,246,247] Additionally, projections of future species distributions under climate change are complicated by the interacting effects of multiple components of climate change (such as changing temperature, precipitation, sea level rise, and so on) and effects from non-climate stressors (such as habitat loss and degradation); these multiple drivers of range shifts can have compounding or potentially opposing effects, further complicating projections of where species are likely to be found in the future.[41]

Description of confidence and likelihood

There is *high confidence* that species and populations continue to be impacted by climate change in significant and observable ways.

There is *high confidence* that terrestrial, freshwater, and marine organisms are *likely* responding to climate change by altering individual characteristics, the timing of biological events, and their geographic ranges.

There is *high confidence* that local and global extinctions are *likely* to occur when climate change outpaces the capacity of species to adapt.

Key Message 2

Impacts on Ecosystems

> Climate change is altering ecosystem productivity, exacerbating the spread of invasive species, and changing how species interact with each other and with their environment (*high confidence*). These changes are reconfiguring ecosystems in unprecedented ways (*likely, high confidence*).

Description of evidence base

Primary productivity: Diverse observations suggest that global terrestrial primary production has increased over the latter 20th and early 21st centuries,[48,49,50,51] and climate models project continued increases in global terrestrial primary production over the next century.[130,131] Modest to moderate declines in ocean primary production are projected for most low- to midlatitude oceans over the next century,[143,144,145] but regional patterns of change are less certain.[60,143,145]

Projections also suggest that changes in productivity will not be equal across trophic levels: changes in primary productivity are likely to be amplified at higher levels of the food web;[149,150,151] for example, small changes in marine primary productivity are likely to result in even larger changes to the biomass of fisheries catch.[152]

Changes in phenology: Synchronized timing of seasonal events across trophic levels ensures access to key seasonal food sources,[25,248] particularly in the spring, and is especially important for migratory species dependent on resources with limited availability and for predator–prey relationships.[29] The match–mismatch hypothesis[249] is a mechanism explaining how climate-induced phenological changes in producers and consumers can alter ecosystem food web dynamics.[114] For example, Chevillot et al. (2017)[250] found that reductions in temporal overlap of juvenile fish and their zooplankton prey within estuaries, driven by changes in temperature, salinity, and freshwater discharge rates, could threaten the sustainability of nursery functions and affect the recruitment of marine fishes. Secondary consumers may be less phenologically responsive to climate change than other trophic groups,[114] causing a trophic mismatch that can negatively impact reproductive success and overall population levels by increasing vulnerability to starvation and predation.[16,155] Long-distance migratory birds, which have generally not advanced their phenology as much as lower trophic levels,[113] can be particularly vulnerable.[27] A recent study found that 9 out of 48 migratory bird species examined did not keep pace with the changing spring phenology of plants (termed green-up) in the period 2001–2012.[28] Trophic mismatch and an inability to sufficiently advance migratory phenology such that arrival remains synchronous with peak resource availability can cause declines in adult survival and breeding success.[28,155]

Invasive species: Changes in habitat and environmental conditions can increase the viability of introduced species and their ability to establish.[69,75,76] Climate change may be advantageous to some nonnative species. Such species are, or could become, invasive, as this advantage might allow them to outcompete and decimate native species and the ecosystem services provided by the native species.

Invasive species' impacts on ecosystems are likely to have a greater negative impact on human communities that are more dependent on the landscape/natural resources for their livelihood and cultural well-being.[251,252] Thus rural, ranching, fishing, and subsistence economies are likely to be negatively impacted. Some of these communities are economically vulnerable (for example, due to low population density, low median income, or reduced tax revenues) and therefore have limited resources and ability to actively manage invasive species.[253,254] Climate change and invasive species have both been recognized as two of the most significant issues faced by natural resource managers.[61,62] For example, the invasive cheatgrass (*Bromus tectorum*) is predicted to increase in abundance with climate change throughout the American West, increasing the frequency of major economic impacts associated with the management and rehabilitation of cheatgrass-invaded rangelands.[255,256] Ecological and economic costs of invasive species are substantial, with global costs of invasive species estimated at over $1.4 trillion annually.[61] Annual economic damages from climate change are complex and are projected to increase over time across most sectors that have been examined (such as coral reefs, freshwater fish, shellfish) (Ch. 29: Mitigation, Figure 29.2).

Species interactions and emergent properties: Human-caused stressors such as land-use change and development can also lead to novel environmental conditions and ecological communities that are further degraded by climate impacts (Ch. 11: Urban, KM 1) .[13,163] Studies of emergent properties have progressed from making general predictions to providing more nuanced evaluations of behavioral mechanisms such as adjusting the timing of activity levels to avoid heat stress [6,81,87] and predation,[88] tolerances to variable temperature fluctuations and water availability,[79,80,82,257] adaptation to changes,[82,258] turnover in community composition,[259,260] and specific traits such as dispersal ability.[67,85]

Changes in community composition vary relative to invasion rates of new species, local extinction, and recruitment and growth rates of resident species, as well as other unknown factors.[260] In some cases, such as Pacific Northwest forests, community turnover has been slow to date, likely due to low exposure or sensitivity to the direct and indirect impacts of climate change,[259] while in other places, like high-latitude systems, dramatic shifts in community composition have been observed.[261] Differential responses within and across communities are expected due to individual sensitivities of community members. For example, as a result of the uncertainties associated with range shifts, the impact of individual species' range shifts on ecosystem structure and function and the potential for the creation of novel community assemblages have medium certainty. The interplay of physical drivers resulting in range shifts and the ways in which interactions of species in new assemblages shape final outcomes affecting ecosystem dynamics is uncertain, although there is more certainty in how ecosystem services will change locally. There is still high uncertainty in the rate and magnitude at which community turnover will occur in many systems; still, there is widespread agreement of high turnover and major changes in age and size structure with future climate impacts and interactions with other disturbance regimes.[259,260,261]

Climate-induced warming is predicted to increase overlaps between some species that would normally be separated in time. For example, tree host species could experience earlier bud burst, thus overlapping with the larval stage of insect pests; this increase in synchrony between normally disparate species can lead to major pest outbreaks that alter community composition, productivity, ecological functioning, and ecosystem services.[262] Direct climate impacts, such as warmer winters and drought-induced stress on forests, can interact with dynamics of pest populations to render systems more susceptible to damage in indirect ways. In the case of the bark beetle, for example, forests that have experienced drought are more vulnerable to damage from beetle attacks.[138,263] Other potential outcomes of novel species assemblages are changes in energy and nutrient exchange (for example, altered carbon use in streams as new detritus-feeding or predator communities emerge)[193] and respiration[89] within and among ecological communities. Abrupt and surprising changes or the disruption of trophic interactions have the potential for negative and irreversible impacts on food webs and ecosystem productivity that supports important provisioning services including fisheries and forest harvests for food and fiber. Abrupt changes in climate have been observed over geological timescales and have resulted in mass extinctions, decreased overall biodiversity, and ecological communities largely composed of generalists.[67]

Major uncertainties

Primary productivity: There is still high uncertainty in how climate change will impact primary productivity for both terrestrial and marine ecosystems. For terrestrial systems, this uncertainty arises from an incomplete understanding of the impacts of continued carbon dioxide increases on plant growth;[132,133,134] underrepresented nutrient limitation effects;[135] effects of fire[136] and insect outbreaks;[137] and an incomplete understanding of the impacts of changing climate extremes[138,139] on primary production. Direct evidence for declines in marine primary production is limited. The suggestion that phytoplankton pigment has declined in many ocean regions,[55] indicating a decline in primary production, was found to be inconsistent with primary production time series[59] and potentially sensitive to analysis methodology.[56,58,264] Subsequent work accounting for methodological criticisms still argued for a century-scale decline in phytoplankton pigment but acknowledged large uncertainty in the magnitude of this decline and that some areas show marked increases.[54] There is growing consensus for modest to moderate productivity declines at a global scale in the marine realm.[143,144,145] Considerable disagreement remains at regional scales.[143] For both the terrestrial and marine case, however, projections clearly support the potential for marked primary productivity changes.

Phenology: Models of phenology, particularly those leveraging advanced statistical modeling techniques that account for multiple drivers in phenological forecasts,[265] enable extrapolation across space and time, given the availability of gridded climatological and satellite data.[21,266,267,268] However, effective characterization of phenological responses to changes in climate is often constrained by the availability of adequate in situ (ground-based) organismal data. Experimental manipulation of ecological communities may be insufficient to determine sensitivities; for example, E. M. Wolkovich et al. (2012)[269] compared observational studies to warming experiments across four continents and found that warming predicted smaller advances in the timing of flowering and leafing by 8.5- and 4.0-fold, respectively, than what has been observed through long-term observations.

The majority of terrestrial plant phenological research to date has focused on patterns and variability in the onset of spring, with far fewer studies focused on autumn.[270] However, autumn models have large biases in describing interannual variation.[271,272] Additional research is needed on autumnal responses to environmental variation and change, which would greatly expand inferences related to the carbon uptake period, primary productivity, nutrient cycling, species interactions, and feedbacks between the biosphere and atmosphere.[273,274,275,276] While broad-based availability of phenological data has improved greatly in recent years, more extensive, long-term monitoring networks with consistently implemented protocols would further improve scientific understanding of phenological responses to climate change and would better inform management applications.[277]

Invasive species: There is some uncertainty in knowing how much a nonnative species will impact an environment, if and when it is introduced, although there are methods available for estimating this risk.[278,279] For example, the U.S. Department of Agriculture conducts Weed Risk Assessment,[280] and the U.S. Fish and Wildlife Service publishes Ecological Risk Screening Summaries (https://www.fws.gov/fisheries/ans/species_erss_reports.html). New technologies, such as genetic engineering, environmental DNA, and improved detection via satellites and drones, offer promise in the fight against invasive species.[281] New technologies and novel approaches to both invasive species management and mitigation and adapting to climate change could reduce negative impacts to livelihoods, but there is some uncertainty in whether or not the application of new technologies can gain social acceptance and result in practical applications.

Species interactions and emergent properties: Climate change impacts to ecosystem properties are difficult to assess and predict, because they arise from interactions among multiple components of each system, and each system is likely to respond differently. One generalization that can be made arises from fossil records, which show climate-driven mass extinctions of specialists followed by novel communities dominated by generalists.[67] Although there is widespread consensus among experts that novel interactions and ecosystem transitions will result from ecological responses to climate change,[85] these are still largely predicted consequences, and direct evidence remains scarce; thus, estimates of how ecosystem services will change remain uncertain in many cases.[13,67,84,128,159,161,162,163,258,282,283] Modeling and experimental studies are some of the few ways to assess complicated ecological interactions at this time. New and more sophisticated models that can account for multispecies interactions, community composition and structure, dispersal, and evolutionary effects are still needed to assess and make robust predictions about system responses and transitions.[161,258,282]

High uncertainty remains for many species and ecosystems due to a general lack of basic research on baseline conditions of biotic interactions; community composition, structure, and function; and adaptive capacity; as well as the interactive, synergistic, and antagonistic effects of multiple climate and non-climate stressors.[67,128,283] Improved understanding of predator–prey defense mechanisms and tolerances are key to understanding how novel trophic interactions will manifest.[257]

Description of confidence and likelihood

There is *high confidence* that climate-induced changes are occurring within and across ecosystems in ways that alter ecosystem productivity and how species interact with each other and their environment.

There is *high confidence* that such changes can *likely* create mismatches in resources, facilitate the spread of invasive species, and reconfigure ecosystems in unprecedented ways.

Key Message 3

Ecosystem Services at Risk

> The resources and services that people depend on for their livelihoods, sustenance, protection, and well-being are jeopardized by the impacts of climate change on ecosystems (*likely, high confidence*). Fundamental changes in agricultural and fisheries production, the supply of clean water, protection from extreme events, and culturally valuable resources are occurring (*likely, high confidence*).

Description of evidence base

Similar to the Third National Climate Assessment, results of this review conclude that climate change continues to affect the availability and delivery of ecosystem services to society through altered agricultural and fisheries production, protection from storms and flooding in coastal zones, a sustainable harvest, pollination services, the spread of invasive species, carbon storage, clean water supplies, the timing and intensity of wildfire, the spread of vector-borne diseases, and recreation.[1,29,104,113,152,284,285]

Provisioning services: Regional changes in critical provisioning services (food, fiber, and shelter) have been observed as range shifts occur. These result in spatial patterns of winners and losers for human communities dependent on these resources. For example, as the distribution of harvestable tree species changes over time in response to climate change, timber production will shift in ways that create disconnects between resource availability and ownership rights.[286]Although fisheries are more often treated as common property resources (with attendant problems related to the overuse and mismanagement of common resources),[287] disconnects emerge with respect to the definitions of management units and jurisdictional conflict and uncertainty.[97] Shifting distribution patterns can potentially affect access to both harvested and protected natural resources, cultural services related to the rights of Indigenous peoples and to recreation, and the aesthetic appreciation of nature in general (Ch. 15: Tribes, KM 1).[288]

Additionally, changes in physical characteristics in response to climate change can impact ecosystem services. In the ocean, the combination of warmer water and less dissolved oxygen can be expected to promote earlier maturation, smaller adult body size, shorter generation times, and more boom–bust population cycles for large numbers of fish species.[289] These changes would have profound ecosystem effects, which in turn would affect the value of ecosystem services and increase risk and volatility in certain industries.

Altered phenology can also impact ecosystem services. Based on standardized indices of the timing of spring onset,[21] 2012 saw the earliest spring recorded since 1900 across the United States.[21,290] Much of the central and eastern parts of the contiguous United States experienced spring onset as much as 20 to 30 days ahead of 1981–2010 averages, and accelerated blooming in fruiting trees was followed by a damaging, but climatically normal, hard freeze in late spring, resulting in widespread reductions in crop productivity.[20] Mid-century forecasts predict that spring events similar to that of 2012 could occur as often as one out of every three years; because last freeze dates may not change at the same rate, more large-scale plant tissue damage and agricultural losses are possible.[177,178] Early springs with episodic frosts not only directly affect plant growth and seed production but can also indirectly alter ecosystem functions such as pollination.[291,292]

Potential asynchronies may impact some pollination services, although other pollinator–plant relationships are expected to be robust in the face of shifting phenology.[291,293,294,295] For example, broad-tailed hummingbirds in Colorado and Arizona have advanced their arrival date between 1975 and 2011, but not sufficiently to track changes in their primary nectar sources.

Regulating services: Average carbon storage in the contiguous United States is projected to increase by 0.36 billion metric tons under RCP4.5 and 3.0 billion metric tons under RCP8.5.[104] However, carbon storage is projected to decrease for U.S. forests (Ch. 6: Forests, KM 2). Increases in overall carbon storage are projected for the Northwest, and decreases are projected for the Northeast and Midwest.[104] Furthermore, shorter winters and changing phenology may affect the incidence and geographic extent of vector-borne diseases (Ch. 14: Human Health, KM 1).[284,296,297,298,299] Other examples of regulating ecosystem services that are impacted by climate include coastal protection from flooding and storm surge by natural reefs (Ch. 8: Coastal, KM 2),[187] the supply of clean water (Ch. 3: Water, KM 1),[188] and controls on the timing and frequency of wildfires (Ch. 6: Forests, KM 1).[189]

Cultural services: Climate change is expected to impact recreation and tourism in the United States, as well as cultural resources for Indigenous peoples (Ch. 15: Tribes, KM 1).[95,104,192] While some changes may be positive (such as increased biking and hiking access in colder seasons or cold-weather areas), other changes will have negative impacts (such as reduced skiing opportunities).[95,104]

Supporting services: Climate change is impacting supporting services, which are the services that make all other ecosystem services possible. Climate change impacts include alterations in primary production and nutrient cycling.[48,193]

Major uncertainties

One of the major challenges to understanding changes in ecosystem services due to climate change arises from matching the scale of the ecosystem change to the scale at which humans are impacted. Local conditions may vary greatly from changes expected at larger geographic scales. This uncertainty can work in both directions: local estimates of changes in ecosystems services can be overestimated when local impacts of climate change are less than regional-scale impacts. However, estimates of local impacts on ecosystem services can be *under*estimated when local impacts of climate change exceed regional projections. Another major source of uncertainty is related to the emergent properties of ecosystems related to climate change. Since observation of human impacts of these emergent ecosystem properties is lacking, it is difficult to predict how humans will be impacted and how they might adapt.

Description of confidence and likelihood

There is *high confidence* that the resources and services that people depend on for livelihoods, sustenance, protection, and well-being are *likely* jeopardized by the impacts of climate change on ecosystems.

There is *high confidence* that fundamental changes in agricultural and fisheries production, the supply of clean water, protection from extreme events, and culturally valuable resources are *likely* occurring.

Key Message 4

Challenges for Natural Resource Management

Traditional natural resource management strategies are increasingly challenged by the impacts of climate change (*high confidence*). Adaptation strategies that are flexible, consider interacting impacts of climate and other stressors, and are coordinated across landscape scales are progressing from theory to application. Significant challenges remain to comprehensively incorporate climate adaptation planning into mainstream natural resource management, as well as to evaluate the effectiveness of implemented actions (*high confidence*).

Description of evidence base

Climate change is increasingly being recognized as a threat to biodiversity and ecosystems. For example, a recently developed threat classification system for biodiversity[300] has been adopted by the International Union for Conservation of Nature, which stands in contrast to previous frameworks that did not include climate change as a threat.[301] Moving away from traditional management strategies that aim to retain existing species and ecosystems and implementing climate-smart management approaches are likely to be the most effective ways to conserve species, ecosystems, and ecosystem services in the future.[194]

Ecosystem-based management strategies, where decisions are made at the ecosystem level,[217] and programs that consider climate change impacts along with other human-caused stressors are becoming more established and seek to optimize benefits among diverse societal goals.[302] A number of regional to national networks have been implemented, including the Department of the Interior's (DOI) Climate Adaptation Science Centers[303] and the NOAA Regional Integrated Sciences and Assessment Programs,[304] that bring together multiple stakeholders to develop approaches for dealing with climate change. Landscape Conservation Cooperatives (LCCs) were established by DOI Secretarial Order 3289 in 2009 to provide transboundary support and science capacity for adaptive resource management. The U.S. Fish and Wildlife Service (Service) is no longer providing dedicated staff and funding to support the governance and operations of the 22 LCCs, consistent with its FY2018 and FY2019 budget requests. The Service will continue to support cooperative landscape conservation efforts as an equal partner, working with states and other partners on priority conservation and management issues. Federal and state agencies with responsibilities for natural resources have begun to implement proactive and climate-smart management approaches. Recent examples (within the last 10 years) include the development of the National Marine Fisheries Service's Climate Science Strategy[215,217] and its commitment to ecosystem-based fisheries management;[216] the National Park Service's Climate Change Response Program;[305] the Forest Adaptation Planning and Practices collaborative, led by the Northern Institute of Applied Climate Science;[306] the National Fish, Wildlife and Plants Climate Adaptation Strategy;[218] the Southeast Conservation Adaptation Strategy,[307] initiated by states of the Southeastern Association of Fish and Wildlife Agencies, the federal Southeast Natural Resource Leaders Group, the Southeast and Caribbean Landscape Conservation Cooperatives, and the Southeast Aquatic Resources Partnership; and a range of individual state plans.[302] These newly formed collaborative programs better account for the various climate impacts on, and interactions between, ecosystem components, while optimizing benefits among diverse societal goals.

In addition, federal agencies are developing policies and approaches that consider ecosystem services and related climate impacts within existing planning and decision frameworks.[225] For example, NOAA's Fisheries Ecosystem-Based Fisheries Management Policy specifically considers climate change and ecosystem services. By framing management strategies and actions within an ecosystem services context, communication about the range of benefits derived from biodiversity and natural ecosystems can be improved, and managers, policymakers, and the public can better envision decisions that support climate adaptation. Restoration efforts can also help conserve important ecosystem services (Ch. 21: Midwest, Figure 21.7).

An example of an effective, collaborative effort to manage climate impacts took place in Puerto Rico during a recent drought. In order to better manage the impacts of the drought on the environment, people, and water resources, Puerto Rico developed a special task force composed of government officials, federal partners, and members of academia to evaluate the progression, trends, and effects of drought in the territory. Weekly reports from the task force provided recommended actions for government officials and updated the public about the drought (Ch. 20: U.S. Caribbean, Box 20.3).

Changes in Individual characteristics: Maintaining habitat connectivity is important to ensure gene flow among populations and maintain genetic diversity, which provides the platform for evolutionary change. Additionally, assisted migration can be used to increase genetic diversity for less mobile species, which is important to facilitate evolutionary changes.[213]

Changes in range: Climate-induced shifts in plant and animal populations can be most effectively addressed through landscape-scale and ecosystem-based conservation and management approaches. Increasing habitat connectivity for terrestrial, freshwater, and marine systems is a key climate adaptation action that will enable species to disperse and follow physiological niches as environmental conditions and habitats shift.[206] More active approaches like seed sourcing and assisted migration may be considered for planted species or those with limited natural dispersal ability.[308] However, for any assisted migration, there could be unforeseen and unwanted consequences. Although a provision to analyze and manage the potential consequences of assisted migration would not guarantee successful outcomes, developing such policies is warranted toward minimizing unintended consequences.[213,214] Systems that are already degraded or stressed from non-climate factors will have lower adaptive capacity and resilience to climate change impacts; therefore, restoration and conservation of land, freshwater, and marine areas that support valued species and habitats are key actions for natural resource managers to take. In addition, climate change refugia—areas relatively buffered from climate change that enable persistence—have become a focus of conservation and connectivity efforts to maintain highly valued vulnerable ecosystems and species in place as long as possible.[207,208]

Changes in phenology: Direct management of climate-induced phenological shifts or mismatches is challenging, as managers have few if any direct measures of control on phenology.[248] However, research into how species' phenologies are changing has the potential to support improved conservation outcomes by identifying high-priority phenological periods and informing changes in management actions accordingly. In Vermont grassland systems, for example, research on grassland bird nesting phenology identified the timing of haying as a critical stressor. In response, the timing of haying has been modified to accommodate the nesting phenology of several declining species, including the bobolink, demonstrating the potential for phenological data to support a successful conservation program.[309,310] Such monitoring and research efforts will become increasingly important as climate change results in further phenological shifts. Managing for phenological heterogeneity can also be an effective bet-hedging strategy to manage for a wide range of potential changes.[248]

Invasive species: Focusing efforts on the prevention, eradication, and control of invasive species and the implementation of early detection and rapid response (EDRR) can be considered an adaptation strategy to help maintain healthy ecosystems and preserve biodiversity such that natural systems are more resistant and resilient to climate change and extreme weather events.[202,203] Once an invasive species is established, EDRR is much more effective than efforts to control invasive species after they are widely established.[205] The current U.S. National Invasive Species Council Management Plan[311] recognizes the stressors of land-use change and climate change and calls for an assessment of national EDRR capabilities.

Major uncertainties

Better predictive models are necessary to create effective adaptation strategies, but they can be hampered by a lack of sufficient data to adequately incorporate important biological mechanisms and feedback loops that influence climate change responses.[232] This can be most effectively addressed if resource management approaches and monitoring efforts increasingly expand programs, especially at the community or ecosystem level, to detect and track changes in species composition, interactions, functioning, and tipping points, as well as to improve model inputs.[312,313,314]

Changes in individual characteristics: Although genetic diversity is important for evolution and potentially for increasing the fitness of individuals, it does not guarantee that a species will adapt to future environmental conditions. Failure to adapt may occur when a species or population lacks genetic variability in a particular trait that is under selection (such as heat tolerance) as a result of climate change,[7] despite having high overall genetic diversity.

Changes in Range: Although potential strategies for adaptation to range shifts can be readily identified, the lack of experience implementing these approaches to meet this issue results in uncertainty in the efficacy of different approaches. Another big uncertainty is the incomplete information on the ecology and responses of species and ecosystems to climate change.

Changes in phenology: Phenological sensitivity may also be an important component of organismal adaptive capacity[315] and thus species' vulnerability to climate change, although additional research is required before resource managers can utilize known relative vulnerabilities to prioritize management activities.

Invasive species: There is some uncertainty in the optimal management approach for a given species and location. Best practices for management actions are often context specific; one approach will not fit all scenarios. Management of climate change and invasive species needs to explore such variables as the biology of the target species, the time of year or day for maximizing effectiveness, the ecological and sociocultural context, legal and institutional frameworks, and budget constraints and timeliness.[281]

Description of confidence and likelihood

There is *high confidence* that traditional natural resource management strategies are increasingly challenged by the impacts of climate change.

There is *high confidence* that adaptation strategies that are flexible, consider the emerging and interactive impacts of climate and other stressors, and are coordinated across local and landscape scales are progressing from theory to application.

There is *high confidence* that significant challenges remain to comprehensively incorporate climate adaptation planning into mainstream natural resource management, as well as to evaluate the effectiveness of implemented actions.

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