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Review

Climate change effects on biodiversity, ecosystems, ecosystem services, and natural resource management in the United States

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HIGHLIGHTS

- Climate change is affecting ecosystems at multiple scales.
- Individual/species: changes in morphology and behavior, phenology, and range shifts observed
- Ecosystems: shifts in productivity, species interactions, and emergent properties observed
- Together, these changes are impacting ecosystem services and human well-being.
- Natural resource managers need proactive, flexible approaches to deal with changes.

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ABSTRACT

Climate change is a pervasive and growing global threat to biodiversity and ecosystems. Here, we present the most up-to-date assessment of climate change impacts on biodiversity, ecosystems, and ecosystem services in the U.S. and implications for natural resource management. We draw from the 4th National Climate Assessment to summarize observed and projected changes to ecosystems and biodiversity, explore linkages to important ecosystem services, and discuss associated challenges and opportunities for natural resource management. We find that species are responding to climate change through changes in morphology and behavior, phenology, and geographic range shifts, and these changes are mediated by plastic and evolutionary responses. Responses by species and populations, combined with direct effects of climate change on ecosystems (including more extreme events), are resulting in widespread changes in productivity, species interactions, vulnerability to biological invasions, and other emergent properties. Collectively, these impacts alter the benefits and services that natural ecosystems can provide to society. Although not all impacts are negative, even positive changes can require costly societal adjustments. Natural resource managers need proactive, flexible adaptation strategies that consider historical and future outlooks to minimize costs over the long term. Many organizations are beginning to explore these approaches, but implementation is not yet prevalent or systematic across the nation.

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Contents

1. Introduction

Climate change is a pervasive and growing global threat to biodiversity and ecosystems (Díaz et al., 2019). Climate change affects individual species and the way they interact with other organisms and their habitats, which alters the structure and function of ecosystems and the goods and services that natural systems provide to society (Díaz et al., 2019). Understanding the direction and magnitude of ecological responses allows human communities to better anticipate these changes and adapt as necessary.

Periodic assessments of current and future climate change impacts on ecosystems are important for developing and updating natural resource management plans and evaluating adaptation actions (West et al., 2009). The National Climate Assessment (NCA) is a key assessment in the United States, required by the Global Change Research Act to summarize current and projected impacts of climate change on a variety of sectors and regions in the U.S. every four years (USGCRP, 2018). Here, we draw upon the recently published Fourth NCA (NCA4) Volume II to present the most up-to-date assessment of climate change impacts on biodiversity, ecosystems, and ecosystem services in the U.S. (USGCRP, 2018). We synthesize, extend, and integrate the NCA4 chapters focused on natural resources: "Ecosystems, Ecosystem Services, and Biodiversity" (Ch. 7); "Forests" (Ch.6); "Oceans and Marine Resources" (Ch. 9); "Coastal Effects" (Ch. 8); and "Tribes & Indigenous Peoples" (Ch.15) (USGCRP, 2018).

We provide a more in-depth, technical analysis of topics of interest to scientists and practitioners, and review climate change impacts at multiple scales, including: 1) the individual organisms, populations, and species of biodiversity which comprise ecosystems; 2) the properties and processes that characterize ecosystems; and 3) the goods and services that ecosystems provide which support human economies and well-being (Fig. 1). Further, we explore natural resource management challenges posed by climate change and present examples of on-the-ground adaptation actions. Many topics covered in this review are complex and deserve a review of their own. However, by covering multiple scales in one place, we provide a holistic overview of how climate change is affecting different ecosystems and how these changes may in turn affect human well-being, including impacts to vulnerable communities, tribes, and Indigenous peoples.

2. Individuals, populations, and species

Although climate change impacts are widespread, they are not uniform, and accumulating evidence indicates that climate change responses vary as a function of relative vulnerability due to differences in exposure, sensitivity, and adaptive capacity (Beever et al., 2016; Foden and Young, 2016; Glick et al., 2011; Kovach et al., 2019). Below, we discuss major impacts observed at the scale of individuals, populations, and species, and review the mechanisms driving changes.

2.1. Behavior and morphology

One way that organisms cope with changes in their environment is by altering their behavior or morphology. Behavioral responses to climate change can result from changes in temperature and manifest before changes at the population and species level, such as distribution changes or population declines (Beever et al., 2017). Behavioral responses include seeking shade or refuge, altering feeding times, changing site use, and shifting circadian or circannual rhythms (e.g., hibernation, migration; Beever et al., 2017; Bradshaw and Holzapfel, 2007; McCann et al., 2017).

Morphological changes commonly entail changes in body size (Cheung et al., 2013; Eastman et al., 2012; Ozgul et al., 2010). For example, increasing summer temperatures have been associated with reduced body size and increased wing length in North American migratory birds (Weeks et al., 2019). In ectotherms, where metabolic rate is sensitive to temperature (Gardner et al., 2011), warmer temperatures can lead to faster growth rates but can ultimately lead to smaller body size (Atkinson, 1994). This direct impact of temperature on growth has been observed, for example, in American lobster (*Homarus americanus*; Le Bris et al., 2017) and Atlantic cod (*Gadus morhua*; Pershing et al., 2016) during recent warming in the northwest Atlantic. Morphological responses, however, are complex and highly variable: changes in phenotype may not be observed if genetic change is counteracted by environmental effects (Conover et al., 2009). Moreover, short term benefits may not be adaptive in the long term (Section 2.4).

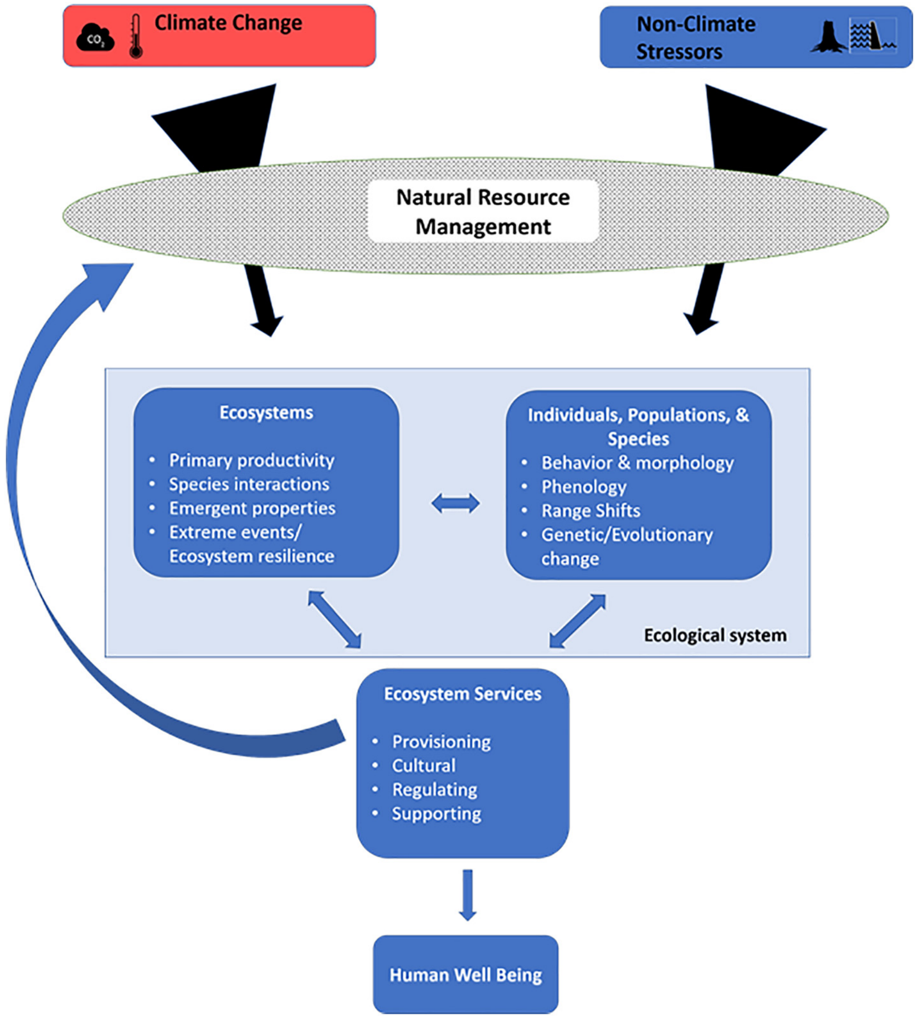


Fig. 1. Climate change and non-climate stressors interact and affect ecological systems at multiple scales. These combined stressors affect individuals, populations, and species, as well as ecosystem processes and properties. The relative impact of climate change versus other stressors varies depending on the species or ecosystem. Diverse biological communities and functioning ecosystems are critical to maintaining the ecosystem services (Millennium Ecosystem Assessment, 2005) that support human well-being (Díaz et al., 2019). Natural resource management affects biodiversity, ecosystems and their services and can moderate or exacerbate climate change and non-climate stressors.

2.2. Phenology

Phenology, or the seasonal timing of recurring biological events, is a critical part of ecological relationships (Rudolf, 2019), and a primary indicator of species responses to climate change (Staudinger et al., 2019). Across much of the terrestrial U.S., broad changes in seasonality are evidenced by an earlier start to spring compared to 20th-century averages (Ault et al., 2015; Monahan et al., 2016). Although changes in phenology are well documented, trends are far from homogenous (Cohen et al., 2018), a result of high variability in climate drivers and phenological responses across habitat types (Chmura et al., 2019; Fu et al., 2015; Pearson, 2019). Migratory birds provide clear examples of phenological shifts, with extensive documentation of earlier migration (Lehikoinen et al., 2019) and earlier breeding (Lany et al., 2016) in response to rising temperatures and altered precipitation patterns.

Phenological shifts in marine and aquatic habitats are less well documented in comparison to terrestrial systems, largely due to difficulty detecting and tracking aquatic organisms (Staudinger et al., 2019). Nonetheless, there have been clear, directional shifts in the timing of seasonal aquatic and marine abiotic drivers, including earlier transitions from winter to spring temperatures (Thomas et al., 2017) and earlier ice melting and runoff (Post, 2017; Staudinger et al., 2019). Marine phytoplankton can respond rapidly to such abiotic changes, resulting in altered timing of phytoplankton blooms (Wasmund et al., 2019), which in turn can create a mismatch with secondary consumers and change the food web structure (Post, 2017; Sundby et al., 2016). Phenological changes have also been observed in freshwater and riparian systems, including advances in the winter spawning phenology of coho (*Oncorhynchus kisutch*) and chum salmon (*O. keta*) in the Pacific Northwest, which has driven phenological changes in bald eagle (*Haliaeetus leucocephalus*) populations (Rubenstein et al., 2019).

Differential shifts in phenology among interacting organisms could drive population declines through reduced reproductive success and/or increased predation or competition (Visser and Gienapp, 2019; Wann et al., 2019; Zimova et al., 2016). Additionally, phenology changes in species with multiple life stages are complex and shifts that are beneficial for one life stage may be detrimental to another (Campbell et al., 2019; Schluter et al., 1991). However, few species have had documented population-level consequences of mistimed reproduction, perhaps due to mitigating effects of density-dependence and greater ability to alter prey or behavior (Dunn and Møller, 2014; Staudinger et al., 2019). Asynchronous phenological shifts have the potential to disrupt the functioning, persistence, and resilience of population dynamics, ecosystems, and ecosystem services (Asch et al., 2019; Mayor et al., 2017; Staudinger et al., 2019; Visser and Gienapp, 2019).

2.3. Geographic range shifts

Climate change is driving large-scale shifts in species distribution, abundance, and reorganization of terrestrial and aquatic ecosystems (Lenoir and Svenning, 2015; Pacifici et al., 2017; Staudinger et al., 2012). Geographic range shifts are widespread across taxa and ecosystems: a recent review of plant and animal species in temperate North America found 55% have either contracted the warm edge or expanded the cool edge of their range (Wiens, 2016). Documented shifts poleward, upslope, and deeper average tens of kilometers per decade (Burrows et al., 2011; Chen et al., 2011). Northern Hemisphere birds, for example, are decreasing in abundance along species' southern and lower elevational range edges (Ralston et al., 2017; Tayleur et al., 2015).

Marine organisms have also demonstrated range shifts, in some cases at faster rates than observed in terrestrial systems and at pace with climate velocities (García Molinos et al., 2015; Poloczanska et al., 2013). The majority of marine taxa surveyed in a 2013 review, for example, shifted in directions consistent with climate velocity (Pinsky et al., 2013). This response, however, is not uniform, with some fish demonstrating a lag effect, potentially due to species-specific sensitivities (Alabia et al., 2018). Arctic marine environments are experiencing changes to sea ice cover, increasing temperatures, and ocean acidification, resulting in range shifts for marine fish, arthropods, and marine mammals (Mecklenburg et al., 2016; Taylor et al., 2017; U.S. Environmental Protection Agency, 2016). Some temperate marine ecosystems are 'tropicalizing', with herbivorous tropical fish expanding poleward, causing decreases in macroalgal plant communities (Vergés et al., 2014).

Despite evidence for widespread range shifts, fewer shifts have been documented than expected from projections, and some shifts are counterintuitive to expectations from projections based solely on temperature changes (Crimmins et al., 2011; Foster and D'Amato, 2015; Morley et al., 2017; Rowe et al., 2015). Indirect effects of climate change and interactive ecological and evolutionary processes can complicate predictions (Estrada et al., 2016; MacLean and Beissinger, 2017; Pacifici et al., 2017). Microclimates, complex topography, and factors such as land use change also need to be considered to accurately predict shifts (Elsen and Tingley, 2015; Guo et al., 2018; Hannah et al., 2014; Kleisner et al., 2016, 2017; Sirami et al., 2017). Moreover, documenting range shifts is challenging, requiring baseline information on historical ranges that is missing for many species, ecosystems, and geographic areas. Additionally, life stages that are most responsive to climate may not be the focus of monitoring or might show lag effects (Alexander et al., 2018). Limited and occasionally conflicting evidence could actually indicate that some species are able to adapt in place, at least for now (Beever et al., 2015; Berg et al., 2010; Jurgens and Gaylord, 2018). Although range shifts are generally regarded as a primary mechanism by which species can effectively adapt to climate change, shifts should be considered in the context of entire ecosystems: an adaptive shift for one species may negatively impact recipient communities (Wallingford et al., in review) (Box 1).

2.4. Mechanisms and rate of change

An organism's response to climate change can be driven by genetic (evolutionary) or non-genetic (plastic) processes (e.g., Franks et al., 2014; Kingsolver and Buckley, 2017). This distinction is important because the mechanism determines the rate of response and whether individuals, populations, and species will be able to keep pace with rapidly changing conditions (Boutin and Lane, 2014). Plastic responses occur within an individual's lifetime and are almost immediate, whereas evolutionary change requires multiple generations (Harrisson et al., 2014; Hendry et al., 2011). Current research is starting to explore the role of epigenetic responses, wherein environmental drivers alter gene expression and can be passed to future generations, occur between generations, and are considered intermediate responses (Jeremias et al., 2018). The distinction between plastic/epigenetic responses and evolutionary change is not always clear, as an organism's ability to respond through these mechanisms can be heritable and subject to evolutionary pressure (Banta and Richards, 2018; Grenier et al., 2016).

Some rapid responses reflect a long history of genetic adaptation to natural variability in climate, and may facilitate persistence during directional climate change by allowing populations to persist long enough for genetic adaptation to occur (Fox et al., 2019; Snell-Rood et al., 2018). While often effective at increasing survival in the short term, some plastic responses are not beneficial over the long term (Ghalambor et al., 2007): they may entail tradeoffs with fecundity (e.g., smaller body sizes typically produce fewer eggs and more boom/bust population dynamics; Waples and Audzijonyte, 2016), or they may lead to interactions with other species or habitats that ultimately lower survival (Bonamour et al., 2019; Schlaepfer et al., 2002). Negative effects of plastic responses are often delayed and difficult to measure, so tracking long-term demographic responses to ensure populations of concern are truly coping with climate change is important.

The pace of climate change often exceeds average rates of evolutionary change (De Meester et al., 2018). However, evolution can happen in very few generations if populations survive strong selection and favorable genetic variation is already present (Hendry, 2017).Strong selection typically involves high mortality, so populations face extirpation before they can effectively adapt via evolution (Bay et al., 2018). Indeed, recent meta-analyses demonstrate that even species demonstrating adaptive phenotypic responses may be adapting too slowly to keep pace with climate change (Radchuk et al., 2019).

Substantial theoretical and empirical work has focused on predicting and measuring rates of response to climate change in recent years (Bell, 2013; Carlson et al., 2014; Gomulkiewicz et al., 2018; Kopp and Matuszewski, 2014; Pelletier and Coltman, 2018). Rapid trait changes are common and well documented, but most cases are consistent with plastic rather than evolutionary mechanisms (Eastman et al., 2012; Merilä and Hendry, 2014). Although examples do exist of evolutionary responses across multiple taxa (Boutin and Lane, 2014; Charmantier and Gienapp, 2014; Crozier and Hutchings, 2013; Franks et al., 2014), the comparative lack of evidence may be due to complex selection and genetic landscapes, methodological constraints that hinder measurement of genetic change (Merilä, 2012), and altered species interactions which may outpace evolutionary responses (Section 3.2). Evolutionary rates are complicated to predict because selection acts on many traits simultaneously, possibly with opposing costs and benefits in different life stages or habitats (Crozier et al., 2008). However, because responses vary in the extent to which they reduce extinction risk, tracking multiple responses and understanding their limitations is critical for successful resource management.

3. Ecosystems

Observed ecosystem-level changes in response to climate change are due to direct impacts from changing climate drivers and interacting effects of species- and population-level responses. Here, we focus on several key ecosystem-level characteristics and properties affected by climate change: primary production; species interactions and emergent properties, including biological invasions; and the impact of extreme events on ecosystem resilience.

3.1. Primary productivity

Almost all life on Earth relies on primary producers, photosynthetic organisms that are the foundation of most food webs and are responsible for producing Earth's oxygen and regulating important components of carbon cycling and sequestration. Climate change has had varying effects on primary production across spatial and temporal scales (Lipton et al., 2018). Changes in primary production are likely to be amplified at higher trophic levels (Chust et al., 2014; Lefort et al., 2015; Stock

Box 1
Examples of climate-driven changes to ecosystems.

Terrestrial

Photo: U.S. Geological Survey

Photo: U.S. Forest Service

The 2012–2017 drought across California resulted in direct physiological stress to trees and facilitated bark beetle outbreaks, causing an unprecedented mortality of 129 million trees in Sierra Nevada forests (Asner et al., 2016; Cal Fire, 2018; Stephens et al., 2018). High levels of mortality among ponderosa pine led to increases in the relative proportion of incense cedar (*Calocedrus decurrens*), which has increased the likelihood of high-intensity surface fires and large wildfires (Stephens et al., 2018). The combined effects of drought, insects, and altered community composition has drastically changed this ecosystem.

Marine

Photo: NOAA

Photo: New York State Department of Environmental Conservation

Non-native invasive species such as European green crab (*Carcinus maenas*) are now present off the California coast, alongside recent "invasions" (due to climate-driven range expansion) of the Humboldt squid (*Dosidicus gigas*) (Epstein and Smale, 2017; Grosholz et al., 2000; Zeidberg and Robison, 2007). Both Humboldt squid and green crab are voracious predators that feed on a variety of native prey (Field et al., 2013; Grosholz et al., 2000). Although ultimate synergistic impact on California marine communities is not yet known, impacts from these species that have already been observed separately include prey population reductions, alteration of the resource base available to migratory shorebirds, and potential fundamental modification of ecosystem structure.

et al., 2014), resulting in further changes to ecosystem function and potentially substantial changes to entire ecosystems.

Globally, terrestrial primary production increased during the late 20th and early 21st centuries due to the fertilizing effect of increasing atmospheric CO_2, nutrient additions from human activities, longer growing seasons, and forest regrowth (Campbell et al., 2017; Domke et al., 2018; Graven et al., 2013; Wenzel et al., 2016; Zhu et al., 2016). However, regional trends vary, and different components of climate change may have opposing impacts on production; while increased atmospheric CO_2 can increase vegetation growth (e.g., Norby et al., 2002), excess or lack of nutrients, water deficits, and air pollution can limit growth (Norby et al., 2010; Oren et al., 2001; Pan et al., 2009). Warming and increased atmospheric CO_2 may also affect belowground biogeochemical processes, such as carbon and nitrogen cycling (Melillo et al., 2017), which can affect terrestrial production (Campbell et al., 2009).

Climate-driven changes to forest primary productivity vary by forest type and elevation. Primary production will likely decrease in forests where soil water availability is limited during the growing season (Latta et al., 2010), but will likely increase in energy-limited forests where snow and cold temperatures restrict the growing season (Latta et al., 2010; Marcinkowski et al., 2015; Wang et al., 2017). However, even in energy-limited forests, drought and extreme temperatures could limit growth increases (Anderegg et al., 2015; Hember et al., 2017). It is also unclear if fertilization effects will continue as forests age (Norby et al., 2010).

In marine and aquatic systems, phytoplankton is responsible for nearly all primary production and generates almost half of the total global primary production. Phytoplankton growth rates affect CO_2 uptake from seawater and organic carbon export to the deep ocean, and also impact fisheries productivity (Tyrrell, 2019). Like terrestrial systems, climate change impacts to marine primary production vary regionally; warming in temperate and tropical oceans can increase stratification, limiting upwelling of deep nutrients that stimulate new production (IPCC, 2013). In contrast, reduced ice cover at higher latitudes increases sunlight availability to the ocean surface, increasing phytoplankton growing seasons and annual primary production (Wasmund et al., 2019). Understanding how these changes impact the food web is crucial for maintaining sustainable fisheries.

3.2. Species interactions, emergent properties, and biological invasions

Variability in species' exposure and responses to climate change are primary drivers of altered species interactions. Emergent properties of ecosystems, including community characteristics such as food-web structure and function that are mediated by species interactions, are changing as species shift their distributions (Section 2.3) and phenologies (Section 2.2) in response to climate impacts (Breeggemann et al., 2016). Higher trophic levels, for example, are expected to be more sensitive to climate change because of changes in predatory demand and search and encounter rates (Abbott et al., 2014; Daly and Brodeur, 2015; Dell et al., 2014). However, functional responses vary and depend on species composition, abiotic conditions (Davis et al., 2017; McCluney and Sabo, 2016; Verdeny-Vilalta and Moya-Laraño, 2014), body size (Ewald et al., 2013), and predator-prey interactions (Peers et al., 2014; Van Zuiden et al., 2016). Collectively, these changes are resulting in novel (i.e., species composition or function is completely transformed) or hybrid (i.e., some historical characteristics persist but structure and composition lie outside the historical range of variability) ecosystems and altered interspecific relationships with no historical analog (Hobbs et al., 2009).

Emergent ecosystem properties are more difficult to predict than direct impacts to individual species because they develop from interactions radiating throughout the system. Modeling is commonly used to evaluate changes in species interactions, but high uncertainty remains for many species and ecosystems due to lack of baseline research on biotic interactions, community structure and function, adaptive capacity, and interactions of climate and non-climate stressors (Beever et al., 2016; Blois et al., 2013; Rosenblatt and Schmitz, 2014). A growing number of studies are assessing how direct and indirect climate impacts may alter ecosystem properties. For example, fossil records have shown that ecosystems respond similarly to past climate change events by becoming dominated with generalist species (Blois et al., 2013) which may be an indicator of what could be expected under contemporary climate change. Research is also providing more nuanced evaluations of behavioral changes, including phenological, reproductive, and foraging changes (Beever et al., 2016), such as how increasing temperatures are increasing ratsnake predation on birds in the southeastern U.S. (DeGregorio et al., 2015). Finally, studies are suggesting that possessing population-specific traits (Dell et al., 2014; Rasmann et al., 2014) or local adaptations (Davis et al., 2017; Herstoff and Urban, 2014) may allow species to transition and persist in novel environments (Cannizzo and Griffen, 2016). More sophisticated models that account for multi-species interactions, community structure, dispersal, and evolution are needed to make robust predictions, although complex models may not always increase predictive capability (Alexander et al., 2016; Herstoff and Urban, 2014; Novak et al., 2011; Young, 2014).

Of additional concern is that climate change is facilitating the introduction and spread of non-native invasive species. Global economic costs of invasive species are currently estimated to be over $1.4 trillion annually and climate change has the potential to intensify these impacts (Burgiel et al., 2014). Many non-native invasive species are opportunistic generalists that can take advantage of changing conditions, colonize disturbed areas, and out-compete species, thereby altering community composition, dominance, production, and increasing extinction risk in some cases (e.g., Schmitt et al., 2019; Yeruham et al., 2020). For example, disturbance along with warming temperatures, was found to be important for plant invasions at cold, high-altitude regions in South America and Scandinavia (Lembrechts et al., 2016). Moreover, many non-native invasive plants respond more positively than native plants to increasing CO_2, nitrogen deposition, and temperature, likely increasing their competitiveness under increasing climate change (Liu et al., 2017). Stronger competitive abilities will likely lead to higher non-native invasive plant abundance and declines of native species abundances and community diversity (Bradley et al., 2019). Infiltration of non-native species into natural communities has already negatively impacted biodiversity (Bradley et al., 2019). Although new interactions resulting from invasive and native range-shifting species often negatively impact ecosystems (Carey et al., 2012; Valéry et al., 2009; Vergés et al., 2016; Wallingford et al., in review) and related services (Blois et al., 2013), species responses can have counter-intuitive outcomes. For example, the introduction of a non-native invasive bryozoan in the Gulf of Maine is thought to have resulted in substantial expansion of a native nudibranch species due to increased availability of a novel food source (Dijkstra et al., 2013). In some cases, climate change could also indirectly benefit native species by reducing populations of invasive species (Wenger et al., 2011).

3.3. Extreme events and ecosystem resilience

Climate change has altered the duration, magnitude, and frequency of extreme events, including droughts, forest fires, and heatwaves (Jay et al., 2018). Many of these events have significant impacts on ecosystems and interact with other climate-driven changes, reducing ecological resilience.

More extreme droughts and wildfires, driven by rising temperatures and altered precipitation patterns, affect ecosystem structure and function, particularly in forested ecosystems. Over the last two decades, warming and more variable precipitation have increased forest drought severity in the West, Southeast, and the Lake States (Clark et al., 2016), reducing tree growth and increasing mortality (Peters et al., 2015). However, responses vary (Choat et al., 2012) and can be lagged in long-lived species (Walter et al. 2013). Drought weakens tree defenses, increasing susceptibility to other disturbances, including insects, pathogens, invasive species (Trottier et al., 2017), and wildfires (Littell et al., 2016; Logan and Powell, 2009; Weed et al., 2013; see Box 1). While drought impacts have direct long-term consequences, drought-facilitated disturbances can result in more immediate changes to forest ecosystem structure and function (Loehman et al., 2017).

Earlier spring warming (Westerling et al., 2006), increased vapor pressure deficit (Abatzoglou and Williams, 2016), and reduced summer precipitation (Dennison et al., 2014; Holden et al., 2018) have increased fire season length and area burned across the western U.S. (Abatzoglou and Kolden, 2013; Gergel et al., 2017; Luce et al., 2014; McKenzie and Littell, 2017; Westerling, 2016). Climate changes have interacted with forest management practices to create large, dense forest with high fuel loads, especially in lower-elevation ponderosa pine (*Pinus ponderosa*) and dry mixed-conifer forests in the West (Keane et al., 2002). Fire frequency and area burned will likely increase in fire-prone forests (Barbero et al., 2015; Liu et al., 2015); by the 2050s, annual area burned in the U.S. might increase by 2–6 times compared to present (Kitzberger et al., 2017; Litschert et al., 2012; Ojima et al., 2014), However, frequency and severity will depend on topography, fuel levels, and fire suppression efforts (Abt et al., 2015; Butry et al., 2010).

In the North Atlantic, storms are getting stronger due to rising ocean temperatures and sea level rise (Elsner et al., 2008; Malmstadt et al., 2010). There is also evidence that tropical cyclones are bringing more extreme rainfall, even if wind speeds have not increased (Patricola and Wehner, 2018). Increased storm intensity can impact ecosystems and human communities through extreme flooding, erosive waves, and higher storm surge, making recovery from extreme events more challenging. Rising ocean temperatures have also led to periods of extraordinarily warm conditions across the globe, known as marine heatwaves (Hobday et al., 2016, 2018). The U.S. experienced significant heatwaves in the northwest Atlantic in 2012 (Mills et al., 2013) and 2016 (Pershing et al., 2018) and the northeast Pacific in 2014–2015 (Bond et al., 2015). Rising ocean temperatures are driving widespread coral bleaching, contributing to coral cover loss, impacting fish communities, and increasing exposure of nearby shores to waves (Eakin et al., 2019).

4. Ecosystem services

Diverse biological communities and functioning ecosystems are critical to maintaining ecosystem services that support human well-being (Díaz et al., 2019). Therefore, climate change impacts to species, populations, and ecosystems affect the availability and delivery of ecosystem services, including changes to provisioning, regulating, supporting, and cultural services.

4.1. Provisioning services

Climate-induced changes in provisioning services, the material goods that people obtain from ecosystems and biodiversity, can have profound impacts on human economies and well-being. For example, climate impacts to forested watersheds, including increased temperatures, changes to precipitation and snowfall, and disturbances such as wildfires, are altering freshwater supply for municipalities, agriculture, and power generation (Barnett et al., 2008; Stewart et al., 2005). Surface water shortages are likely in dry years in some locations (Li et al., 2017). Rising stream temperatures also affect water quality (Warziniack et al., 2018). Similarly, wildfires can increase sediment deposition and debris in streams, lakes, and reservoirs (Luce et al., 2012). These changes will stress water supplies, potentially increasing water treatment costs (Warziniack et al., 2018).

Changes in water supply, along with other climate change impacts, can alter agricultural production. Droughts and other extreme events can decrease crop yield and quality (Gowda et al., 2018), with production declines projected for several important crop species as temperatures rise (Zhao et al., 2017). In contrast, changes to growing season length can have both positive and negative effects on crop yield and prices (U.S. Environmental Protection Agency, 2016),

In marine systems, fish and invertebrate harvesting contributes $212 billion in sales annually to the US economy (National Marine Fisheries Service, 2018), and climate change is affecting the availability, distribution (section 2.3), and quality of commercially important species (Kleisner et al., 2016; Peer and Miller, 2014; Pershing et al., 2015; Walsh et al., 2015). Rising ocean temperatures also decrease oxygen levels, which may reduce average fish body size by 14–24% by 2050 (Cheung et al., 2013). In freshwater systems, rising stream temperatures will negatively affect some harvested species (Crozier et al., 2019; Isaak et al., 2012). Future warming is expected to reduce the catch potential of all U.S. regions except the Arctic (Lam et al., 2016).

4.2. Regulating services

Biodiversity and ecosystems provide important regulation services, such as sequestering carbon, moderating the impacts of extreme events (section 3.3), maintaining soil and air quality, and controlling disease spread.

Carbon storage is an important service that will become increasingly important as climate change accelerates. Although forest area has increased nationally since 2000 (EPA, 2017; Oswalt et al., 2014), it is unclear whether carbon storage from afforestation will continue to outweigh emissions from deforestation (Coulston et al., 2015). Moreover, carbon storage in many forests will likely decrease due to higher temperatures, increased water stress and disturbances (section 3.1), and lower rates of CO_2 uptake in aging forests when compared to regrowth forests after past disturbances (Oswalt et al., 2014; Pugh et al., 2019; USDA, 2016; Wear and Coulston, 2015). Coastal wetlands are highly productive ecosystems that store carbon (Davis et al., 2015; Howard et al., 2017), and also provide natural defenses against erosion, waves, flooding, and storm surge (Arkema et al., 2013). As human development or sea level rise degrade coastal wetlands, their capacity to provide these services diminishes.

Ecosystems also regulate the distribution, abundance, and life cycles of disease carrying organisms (Corvalan et al., 2005). Climate change is affecting the ability of ecosystems to provide this service as species ranges (section 2.3), abundances, and habitat conditions shift. For example, Aedes mosquitoes, which transmit diseases such as dengue, are expanding their geographic distribution in the southern U.S., increasing disease risk (Ebi and Nealon, 2016).

4.3. Supporting services

Supporting ecosystem services facilitate basic ecosystem function, such as primary productivity (see section 3.1), nutrient cycling, and maintenance of genetic diversity. As temperatures rise, decomposition of soil organic matter generally increases, potentially increasing soil carbon losses and altering C:N balances (Davidson and Janssens, 2006). These changes are impacted by biotic interactions, including indirect changes to soil microbial community composition (Crowther et al., 2011).

The same activities responsible for climate change (e.g., fossil fuel combustion) result in increased nitrogen deposition, which has significant impacts on terrestrial and aquatic ecosystems, including through eutrophication (Galloway et al., 2008). The combination of higher nutrient loading and rising temperatures is increasing the frequency, duration, and extent of cyanobacteria responsible for harmful algal blooms, which can negatively impact human and animal health (Hilborn and Beasley, 2015). Estimates suggest that by the end of this century, conditions may allow blooms of the toxic alga *Alexandrium catanella* to be up to two months earlier and persist for up to an additional month (Moore et al., 2008; Sandifer and Sutton-Grier, 2014), with resulting impacts on aquaculture, recreation, and other activities.

4.4. Cultural services

Cultural services are the non-material benefits that people gain from biodiversity and ecosystems, such as cultural identity, recreation, and mental and physical health. Despite their importance to human well-being, cultural services have been understudied compared to other ecosystem services (Runting et al., 2017). Indigenous peoples were among the earliest voices connecting culture and environmental change through science, scholarship, and other forms of expression (ACIA, 2004; Maynard, 1998).

There is growing evidence that human health benefits from exposure to natural ecosystems (Donatuto et al., 2014; Sandifer et al., 2015); conversely, climate-driven extremes such as increased temperatures and storms can decrease mental and physical health (Bell et al., 2016; Obradovich et al., 2018). Indirect economic costs (such as lost livelihoods) can also cause adverse socio-psychological impacts (Becker et al., 2015; Morris and Deterding, 2016; Shen and Aydin, 2014).

Although quantifying the value of ecosystems to cultural services is difficult, studies suggest that Americans place a high cultural value on natural systems: for example, a recent survey found that nearly 49 million adults nationwide participated in ocean and coastal recreation, spending more than 1.2 billion days along the coasts and over $141 billion in ocean recreation-related goods and services (National Marine Fisheries Service, 2018). As climate change alters the ability of ecosystems to provide jobs, recreational opportunities, and restorative experiences, communities will experience declines in mental and physical health and potential losses of nature-based tourism dollars (Sandifer and Sutton-Grier, 2014).

5. Vulnerability of human communities

The adaptive capacity of human communities to deal with changes in ecosystem services will partly determine the magnitude of impacts on well-being. While some human communities have been proactive in identifying and planning for changes, others are more vulnerable due to a reduced ability to adapt.

Tribes and Indigenous peoples in the U.S. (groups whose exercise of self-determination as governing entities pre-dates the establishment of the U.S.; Jantarasami et al., 2018) have over 800 climate change initiatives and have led or participated in numerous climate change studies; many have developed their own climate change plans (Jantarasami et al., 2018). Since 1998, tribes and Indigenous peoples

Table 1
Example management responses to changing biodiversity, ecosystems, and ecosystem services that can increase resilience, use updated technology or infrastructure, or be incorporated into governance approaches.

	Increasing ecosystem resilience	Utilizing technology and infrastructure	Improved governance
Individuals, populations, species	Maintaining population sizes, connectivity, and gene flow to allow for shifting ranges and increases in evolutionary resilience of populations and species	Matching individual genotypes with future environments under projected climate change increases adaptability of species	Considering climate change impacts on threatened and endangered species in listing decisions can improve overall understanding of vulnerability
Ecosystems	Reduction of non-climate stressors, such as pollution and invasive species to minimize climate change impacts	Adopting use of natural and nature-based infrastructure to improve resilience of natural communities, leveraging programs in place addressing other stressors	Implementing use of boundary organizations (e.g., North American Marine Protected Areas Network) can promote dialogue of diverse stakeholders in ecosystems that cross multiple jurisdictional boundaries and look for efficiencies in addressing multiple stressors
Ecosystem services	Maintain biodiversity and ecological redundancy to minimize losses in valuable services	Forecasting environmental conditions to prepare for economic changes in a particular industry (e.g., fishery)	Promoting consideration of ecosystem services and related climate impacts within federal planning and decision frameworks

have collaborated on the NCA, focusing on Indigenous concerns, knowledge of vulnerability, and goals for adaptation and mitigation.

Although tribes and Indigenous peoples continue to exercise self-governance, federal policies provide uneven levels of political engagement and support. Indigenous leadership is critical to addressing climate change; however, federal, state, and local governments pose barriers to tribal and Indigenous mitigation and adaptation efforts (Jantarasami et al., 2018). Historical and contemporary land-reduction, land-use restrictions, and poorly implemented treaty rights and consultation requirements exacerbate economic and health risks, which in many cases are associated with threats to Indigenous cultural maintenance. For example, climate-driven range shifts in culturally important species pose challenges to tribes and Indigenous peoples when tribal land areas are small and have limited connectivity (Rapp et al., 2019). Indigenous peoples face risks related to resettlement due to the impacts of climate change, such as coastal erosion and sea ice loss in Alaska. Despite a history of forced relocations, there are structural barriers for Indigenous peoples to participate in current policy processes trying to plan for climate-driven resettlement (Jantarasami et al., 2018).

Across the U.S., coastal communities are also particularly vulnerable to climate change impacts from rising sea levels and more intense storms, which are exacerbating high tide and storm surges, erosion, and saltwater intrusion. High tide flooding is already forcing some cities to install costly pump stations to clear floodwaters and mobilize emergency responders to routinely close flooded streets.

Society's most vulnerable populations, including children, the elderly, economically disadvantaged, homeless, and those with preexisting mental illness tend to be the most heavily impacted by climate changes and resulting impacts to ecosystem services (Dodgen et al., 2016).

6. Implications for natural resource management

Natural resource management traditionally focuses on maintaining or restoring to historical conditions (e.g., National Park System Advisory Board, 2012). While historical context may still motivate management decisions, restoring to historical baselines may not be realistic as the climate changes (Stein et al., 2014). In some cases, management practices to resist change may be effective; in others, managers may choose to accept ecosystem changes or to alter management practices to direct changes in order to minimize loss of valued species and services as ecosystems transform (Aplet and Mckinley, 2017; Millar and Stephenson, 2015; Stein et al., 2013).

Adaptive and proactive approaches that are continually updated to reflect emerging and anticipated climate change impacts will be needed (Bradford et al., 2018; Holsman et al., 2019; Stein et al., 2014; Table 1). For example, the U.S. has a rigorous, science-based system for detecting changes in fish abundance, productivity, and catch, which informs fishery management decisions such as seasonal and spatial closures, annual quotas, and stock rebuilding plans (Pinsky and Mantua, 2014). Collection of this type of information is important for future assessment and updating of management objectives (Stein et al., 2014). NOAA Fisheries has developed adaptation strategies that incorporate climate and ecosystem-related factors into fishery decision-making (Busch et al., 2016; Hare et al., 2016a; Link et al., 2015). Decision support tools, including scenario planning (Cobb and Thompson, 2012; Mahmoud et al., 2009; Peterson et al., 2003) and structured decision-making (Gregory et al., 2012) can help decision-makers explore broad scenarios of risk and develop and prioritize actions that account for uncertainty, optimize tradeoffs, and reflect institutional capacity. Below, we discuss strategies for increasing resilience of ecosystems and human communities.

6.1. Increasing ecosystem resilience

To create effective adaptation strategies, managers need to understand which species are most at risk and why. One way to determine relative risk is through climate change vulnerability assessments that examine species exposure, sensitivity, and adaptive capacity to climate change, and exposure to non-climate stressors (Glick et al., 2011; Hare et al., 2016b; Spencer et al., 2019; Staudinger et al., 2015). Managers can then take proactive steps to increase resilience (Table 1).

Systems that are already degraded from non-climate stressors have lower resilience; therefore, restoring and conserving areas that support valued resources are important. Many strategies for reducing other stressors are things that managers already know, such as restoring populations and habitats, increasing connectivity, and reducing stress from disease, pollution and invasive species (Box 2). For example, prescribed burning and reducing forest stand density can lower wildfire risk in some forest types and can increase resistance and resilience to drought and insect outbreaks (Bottero et al., 2017; Sohn et al., 2016; Vernon et al., 2018). Similarly, in aquatic systems, effective strategies include reconnecting floodplains and side channels, ensuring effective passage for aquatic organisms, and maintaining large trees in forested riparian areas for shade and recruitment to streams (Peterson and Halofsky, 2018; Pollock et al., 2014).

Limiting invasive species spread can help maintain biodiversity, ecosystem function, and resilience (Fischer et al., 2006; Katsanevakis et al., 2014; Oliver et al., 2015). Dialogue between managers, scientists, and policymakers can help ensure that climate change mitigation does not exacerbate invasive species spread (Beaury et al., 2019). Similarly, invasive species policies that explicitly address climate change will enable proactive management (Pyke et al., 2008). Managers may also benefit from considering potential negative effects from native species range expansions (Burgiel et al., 2014; Carey et al., 2012; Giakoumi et al., 2019; Wallingford et al., in review).

Restoring habitat and increasing connectivity to enable species to disperse across the landscape and follow physiological niches is another

Box 2
Examples of on-the-ground adaptation.

Restoring meadows in the Sierra Nevada

Photo: Toni Lyn Morelli

The Sierra Nevada region is critical to the California water supply. Snow in the mountains melts slowly during spring and summer, providing water for ecosystems and people. Climate change is projected to cause more winter precipitation to fall as rain and earlier snowmelt, leading to decreased summer water flows (Viers et al., 2013). Increased frequency and severity of floods is also anticipated. Well-functioning mountain meadows can attenuate floods and increase groundwater storage (National Wildlife Federation, 2010), and some have been identified as climate change refugia for wildlife (Morelli et al., 2017). However, historic land use changes have degraded approximately 40–60% of Sierra meadows. In 2015, Federal, state, and NGO partners restored four meadows with high ecological value located in areas projected to experience the most significant changes in hydrology (Fair and Hunt, 2015; National Wildlife Federation, 2010).

Nature-based infrastructure

Photo: Linda Walters

The use of nature-based designs for coastal resilience structures like living shorelines tends to be more effective at withstanding extreme events (Powell et al., 2019). For example, during Tropical Storm Irene in 2011, stream-designed road crossings survived a category 3 hurricane while nearly 1000 traditional culverts were damaged or destroyed (Sutton-Grier et al., 2018). In another example, living shorelines fared much better under a category 1 hurricane in North Carolina than traditional bulk heads (Gittman et al., 2014).

key climate adaptation action (Anderson et al., 2015; Mcguire et al., 2016; Timpane-Padgham et al., 2017). For example, the recent recovery plan for Atlantic salmon (*Salmo salar*) included identifying vacant habitats, creating redundant populations, and revisiting critical habitat designations to ensure sufficient climate resilient habitats under future conditions (USFWS and NMFS, 2019). Additionally, conserving climate change refugia (areas relatively buffered from contemporary climate change that enable persistence of valued resources), has become a focus of conservation efforts for highly valued vulnerable ecosystems and species (Keppel et al., 2015; Morelli et al., 2016).

Restoring populations can be an effective way to increase genetic diversity and potential for species to evolve and adapt to changing climatic conditions (Sgrò et al., 2011). More active approaches such as diverse seed sourcing, translocation of genes or individuals to accelerate evolution, and assisted migration may be warranted for species with limited dispersal ability or that face movement barriers (Anderson et al., 2014; Isaac-Renton et al., 2014; Whiteley et al., 2015). Unforeseen and unwanted consequences are possible for any assisted migration, but developing policies to analyze and manage potential consequences could minimize unintended outcomes (Invasive Species Advisory Committee, 2017; Schwartz et al., 2012).

6.2. Leveraging technology and infrastructure

Human communities may need to adapt by updating technology and infrastructure (Table 1). Extreme events often motivate adaptation. For example, the inability of the lobster supply chain to handle the sudden influx of soft-shell lobster during the 2012 heatwave (Mills et al., 2013) led to increased domestic processing capacity and expanded marketing. These adaptations allowed the fishery to achieve record value during a subsequent heatwave in 2016 (Pershing et al., 2018). To-date, most documented cases of adaptation to climate impacts on the ocean have been reactive. However, it is now possible to forecast temperature, pH, and oxygen conditions several months in advance (Jacox et al., 2017; Siedlecki et al., 2016; Tommasi et al., 2017). Ensuring that these data products are distributed and used effectively will require considerable engagement with the user community (Hobday et al., 2019; Siedlecki et al., 2016).

In coastal ecosystems, there is growing interest in natural and nature-based infrastructure (NNBI) to increase coastal community resilience (Powell et al., 2019; Spalding et al., 2014; Sutton-Grier et al., 2015). NNBI strategies include restoring or creating coastal ecosystems like salt marsh, mangroves, oyster or coral reefs, beaches, and dunes to mitigate waves and erosion (Ferrario et al., 2014; Möller et al., 2014; Powell et al., 2019; Rodriguez et al., 2014; Zhang et al., 2012), but also include hybrid combinations of natural and built infrastructure such as living shorelines or using combinations of habitat restoration and flood walls (Box 2) (Gittman et al., 2014; Sutton-Grier et al., 2015). NNBI approaches provide co-benefits in terms of habitat, water quality, and recreation, and can be cheaper and survive extreme events better than traditional infrastructure (Gittman et al., 2014; Powell et al., 2019; Sutton-Grier et al., 2018). Although long-term planning may require some coastal communities to relocate due to prohibitively high cost or infeasibility of sea level rise protection, NNBI approaches can at least mitigate some short-term impacts and allow communities more time to consider options. NNBI approaches are often not as well known or trusted in comparison to traditional grey (e.g., seawall) approaches; therefore it is important to increase information on the performance of these techniques, communicate their ecosystem service benefits, and increase coordination and planning around shared socio-ecological goals (Powell et al., 2019).

6.3. Strengthening governance

Federal agencies that manage natural resources are increasingly considering climate change impacts in their management plans (e.g.

Busch et al., 2016; Link, 2016; National Fish Wildlife and Plants Climate Adaptation Partnership, 2012; National Park Service, 2013; Swanston and Janowiak, 2012; Table 1). For example, the National Marine Fisheries Service has developed guidance on how climate change information should be considered in Endangered Species Act (ESA) decisions (National Marine Fisheries Service, 2016). The U.S. Fish and Wildlife Service has also considered climate change in listing decisions, biological opinions, and proposed alternative actions under the ESA (e.g., U.S. Fish and Wildlife Service, 2008, 2010), although climate change is still not included for many species. Even when climate change has been listed as a threat, specific management actions are often lacking (Delach et al., 2019). Federal agencies have also been directed to promote consideration of ecosystem services and related climate impacts within existing planning and decision frameworks (Executive Office of the President of the United States, 2015).

Despite progress, 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 remain

Box 3
An integrated case study: climate change impacts on salmon across the U.S.

Individual, population, and species level responses

Bureau of Land Management

Photo: National Park Service

- In the Northwest, abnormally warm temperatures have led to losses of migrating and spawning salmon in the Columbia River (NOAA Fisheries, 2016).
- In Alaska, some salmon populations have benefited from warmer temperatures, earlier spring, and increased density of zooplankton prey (Schindler et al., 2005).
- Coho salmon on the west coast of the U.S. are expected to shift their range north by 2050 (Cheung et al., 2015). Under a high greenhouse gas emissions scenario, projected stream temperature increases could lead to a 22% reduction in salmon habitat in Washington by late century (Niemi et al., 2009).
- Sockeye salmon (*Oncorhynchus nerka*) in the Columbia River have been migrating earlier. Nearly two--thirds of this response was explained by evolutionary rather than plastic responses (Crozier et al., 2011).
- In the Penobscot River in the Gulf of Maine, adult Atlantic salmon (*Salmo salar*) have arrived as much as 2–3 weeks earlier to their freshwater spawning grounds between the late 1970s and early 2000s (Huntington et al., 2003; Juanes et al., 2004).

Ecosystem level responses

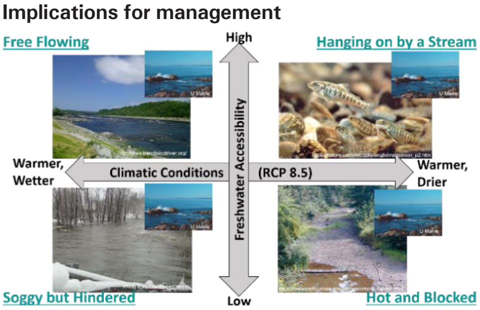
- Kodiak brown bears (*Ursus arctos middendorffi*) have responded to phenological shifts in sockeye salmon and red elderberry (*Sambucus racemosa*). During years with warmer springs, elderberry fruited earlier and overlapped with the salmon spawning run, causing bears to eat less salmon and more berries (Deacy et al., 2017).
- In the Pacific Northwest, warming stream temperatures are likely to reduce the amount of rearing habitat for Chinook salmon (*Oncorhynchus tshawytscha*), but will likely increase the range of invasive smallmouth bass (*Micropterus dolomieu*) (Lawrence et al., 2014).

Impacts to ecosystem services

Matt Nagle, Puyallup Tribal News

- As Kodiak brown bear diet shifted away from salmon (see panel 2), this reduced the distribution of marine derived nutrients being distributed into the surrounding terrestrial landscape, with implications for ecological function (Deacy et al., 2017).
- Shifts in availability and declines of salmon and other cold-water fishes impact cherished cultural resources, particularly in the Pacific Northwest where they are important to tribal nations such as the Nez Perce Tribe as cultural, subsistence, and economic resources. Tribes view salmon as an extension of life and an indicator of environmental health, and loss of salmon is equated with loss of tribal identity and culture (Colombi, 2012).

Implications for management



(Pictorial representation of scenarios used in Borggaard et al., 2019)

- Atlantic salmon and many distinct Pacific salmon population groups are federally protected species. Climate change is expected to exacerbate pre-existing anthropogenic stressors, which have reduced adaptive capacity (Crozier et al., 2019; Hare et al., 2016b). The Pacific Salmon Climate Vulnerability Assessment identified life stages that are most vulnerable to climate change and established a methodology for future status reviews to monitor and update recovery needs and prioritize recovery actions (Crozier et al., 2019).
- In the Yakima Basin, water resource managers, conservation groups, and state and federal agencies are enhancing reservoir storage capacity to ensure minimum flows for fish, allow passage above dams for access to cool, historical habitat, restore a more natural hydrograph, and improve riparian conditions for natural temperature and flow stabilization to bolster salmon runs and riparian habitat during droughts. Actions to redistribute water also impacted farmers, but agreements were made to sustain conditions needed to support salmon (NOAA Fisheries, 2015).
- NOAA used Atlantic salmon as a pilot case study for Scenario Planning - a structured process that embraces uncertainty and explores plausible alternative future conditions to help manage risk and prioritize actions - to explore actions to increase resilience to changing conditions in riverine and marine environments in response to declining population trends (Borggaard et al., 2019). Some outcomes from this effort have already been incorporated into the most recent revision of the Atlantic Salmon Recovery Plan (USFWS and NMFS, 2019).

a challenge (Kemp et al., 2015; Stein et al., 2014). Even with agency-level directives for climate adaptation, implementing actions on the ground can be difficult due to lack of funding and time, negative public perceptions, and difficulty transferring science between researchers and managers (Kemp et al., 2015). Boundary organizations that work at the interface of research and management, such as the U.S. Geological Survey Climate Adaptation Science Centers and the NOAA Regional Integrated Sciences and Assessment Programs, can help address some of these issues by bringing together multiple stakeholders and working with managers to develop adaptation plans.

Promoting local climate adaptation initiatives can also be an effective management strategy. Self-determination and self-governance of tribes and Indigenous peoples, as well as involvement of communities of color or natural resource users such as anglers in particular localities, supports the use of local knowledge and cultural practices that can track, adapt to and mitigate environmental change (Maldonado et al., 2013; Norton-Smith et al., 2016; Vinyeta et al., 2015). For many tribes and Indigenous peoples, their political rights are connected to cultural responsibilities to live sustainably (Borrows, 1997; De Chavez and Tauli-Corpuz, 2009). These cultural responsibilities often involve rich scientific traditions of observation and ecosystem stewardship (Shilling and Nelson, 2018; Trosper, 2009). Tribal and Indigenous governments have emphasized the importance of Indigenous scientists and knowledge keepers working collaboratively to observe changes and create adaptation strategies (Grossman and Parker, 2012; Houser et al., 2001). These governments are in unique positions to cooperate with local, state, and federal government to coordinate regional conservation and adaptation efforts that emphasize strategic foresight and sustainability (Krakoff, 2008; Morishima, 2014; Whyte et al., 2014).

7. Conclusion

Climate change is a pervasive and growing threat to biodiversity, ecosystems, and ecosystem services in the U.S. Climate impacts have been and will continue to be observed at the level of individuals, populations, and species through changes in behavior and morphology, phenology, and range shifts, and at the ecosystem level through changes in primary production, species interactions and emergent properties, and extreme events. Ecosystems and biodiversity underpin important services to people, thus these changes impact provisioning, regulating, supporting, and cultural services, with implications for human well-being. Effective management will require flexible, proactive approaches that account for potential climate change impacts (Box 3). Managers are beginning to implement these strategies, but face challenges due to lack of information and institutional barriers. Widespread incorporation of climate change into natural resource management is yet to be achieved, but examples are emerging that help increase awareness and provide case studies in different sectors. Moving forward, evaluations of effectiveness and demonstrative case studies of adaptation success stories are needed to promote and guide climate-smart management.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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