Fifth National Climate Assessment: Chapter 8

Ecosystems, Ecosystem Services, and Biodiversity

Chapter 8. Ecosystems, Ecosystem Services, and Biodiversity

Authors and Contributors

Federal Coordinating Lead Author

Shawn L. Carter, US Geological Survey, National Climate Adaptation Science Center

Chapter Lead Author

Pamela D. McElwee, Rutgers University

Agency Chapter Lead Authors

Kimberly J. W. Hyde, NOAA Fisheries, Northeast Fisheries Science Center

Jordan M. West, US Environmental Protection Agency, Office of Research and Development

Chapter Authors

Kofi Akamani, Southern Illinois University Carbondale

Amanda L. Babson, US National Park Service

Gillian Bowser, Colorado State University

John B. Bradford, US Geological Survey, Southwest Biological Science Center

Jennifer K. Costanza, USDA Forest Service

Theresa M. Crimmins, University of Arizona, USA National Phenology Network

Sarah C. Goslee, USDA Agricultural Research Service

Stephen K. Hamilton, Cary Institute of Ecosystem Studies

Brian Helmuth, Northeastern University

Serra Hoagland, USDA Forest Service

Fushcia-Ann E. Hoover, University of North Carolina at Charlotte

Mary E. Hunsicker, NOAA Fisheries, Northwest Fisheries Science Center

Roxolana Kashuba, US Environmental Protection Agency

Seth A. Moore, Grand Portage Band of Lake Superior Chippewa

Roldan C. Muñoz, NOAA Fisheries, Southeast Fisheries Science Center

Gyami Shrestha, Lynker

Maria Uriarte, Columbia University

Jennifer L. Wilkening, US Fish and Wildlife Service

Technical Contributors

Nazia N. Arbab, Rutgers University

Danielle Cholewiak, NOAA Fisheries, Northeast Fisheries Science Center

Pranay Kumar, Rutgers University

Victor O. Leshyk, Northern Arizona University

Katherine C. Malpeli, US Geological Survey, National Climate Adaptation Science Center

Richard S. Ostfeld, Cary Institute of Ecosystem Studies

GraceAnne K. Piselli, Northeastern University

José R. Ramírez-Garofalo, Rutgers University

Edward A.G. Schuur, Northern Arizona University

Jacquelyn Veatch, Rutgers University

Sarah Whipple, Colorado State University

Sauvanithi Yupho, Rutgers University, Department of Geography

Review Editor

Abigail York, Arizona State University

Cover Art

Taelyn B.

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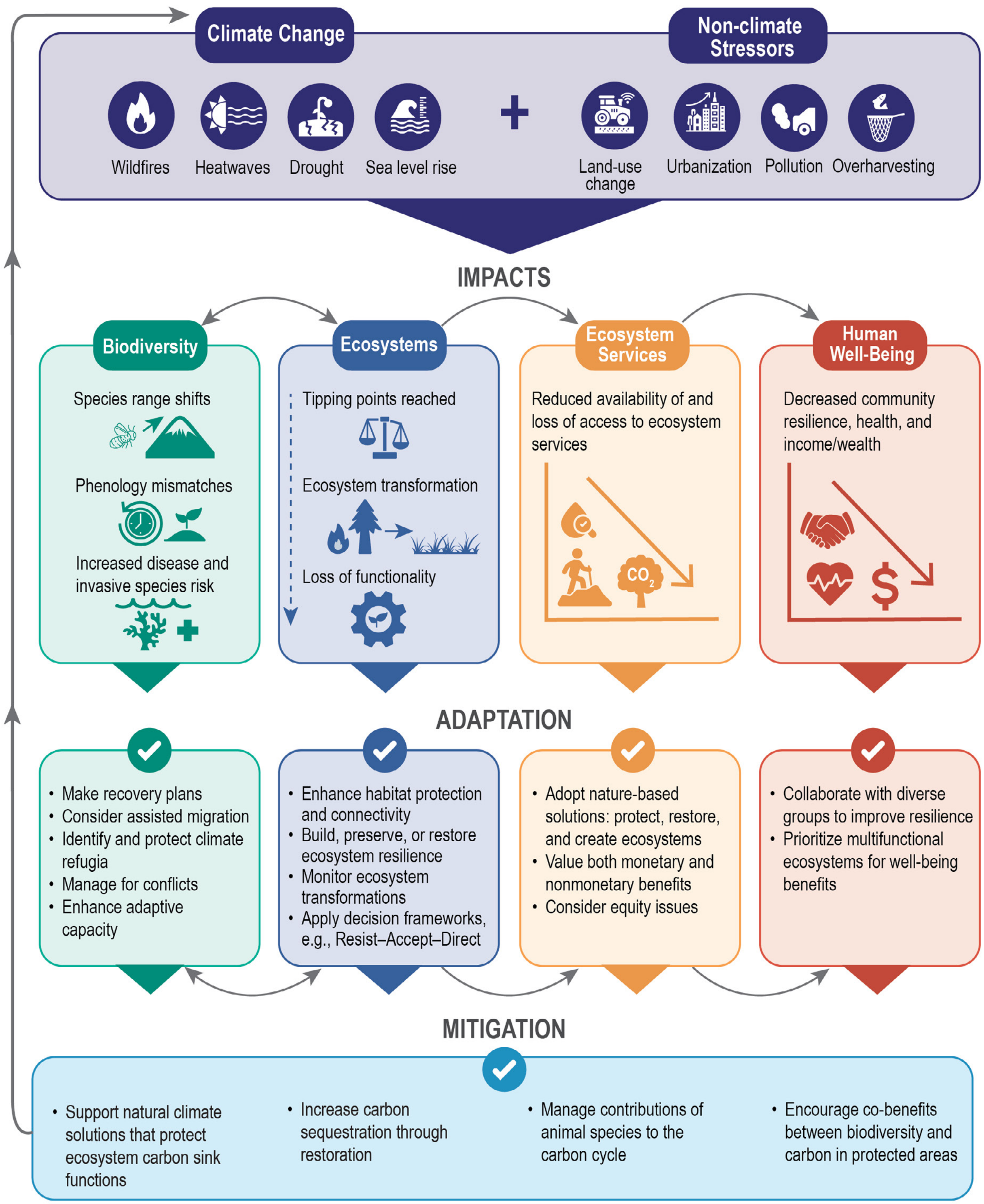
Introduction

Human well-being is dependent on natural and managed ecosystems, which provide crucial functions and resources for nearly everything we eat, make, and do.[1] Clean water and air, soils and nutrients for food production, timber for construction, and other supplies and services we depend on all come from nature. But many ecosystems are increasingly facing climate risks and impacts that alter ecological processes and functions and affect species across all levels of the food web. These changes in turn can result in reduced biodiversity and diminished ecosystem services (the benefits received from natural systems; Figure 8.1).[2,3] Relationships between humans and ecosystems, such as the kinship values that many Black, Indigenous and Tribal communities experience with regard to nature, are also endangered by these changes.[4,5]

Climate Change and Ecosystems, Biodiversity, and Ecosystem Services

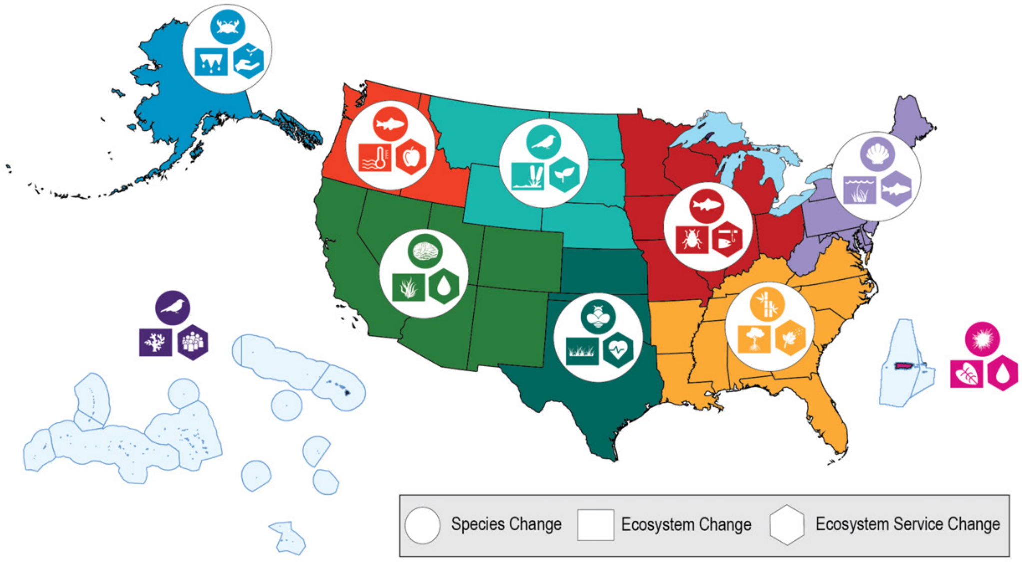


Climate and non-climate stressors together affect biodiversity, ecosystems, and the services they provide.

Figure 8.1. Species and ecosystems respond to pressures in different ways, such as shifting their locations or transforming into new, often degraded systems less able to provide ecosystem services.[6] Adaptation measures can help species and ecosystems cope with some climate impacts but are not always going to be effective or feasible, requiring increasingly difficult decisions on what resources to prioritize and what changes to accept.[7] Adapted from Lipton et al. 2018.[8]

Climate change impacts are already seen in the deterioration of ecosystem functions, as well as in changes in marine and terrestrial primary productivity (growth of plants and algae) and the balance between primary production and respiration (i.e., carbon balances).[2] Ecosystem degradation increases risks to human populations, such as in coastal areas where loss of wetlands increases damage from storms (KM 9.2). Other observed impacts include range shifts as species expand into new regions or disappear from unfavorable areas, altered timing of seasonal and life-cycle events, increased mortality and localized extinctions, and spread of diseases and invasive species (Figure 8.2).[9,10] These risks are projected to grow with additional degrees of warming (Figure 8.3),[11,12] as well as with increased atmospheric carbon dioxide, which contributes to the acidification of marine ecosystems (KM 10.1).[13]

Regional Impacts

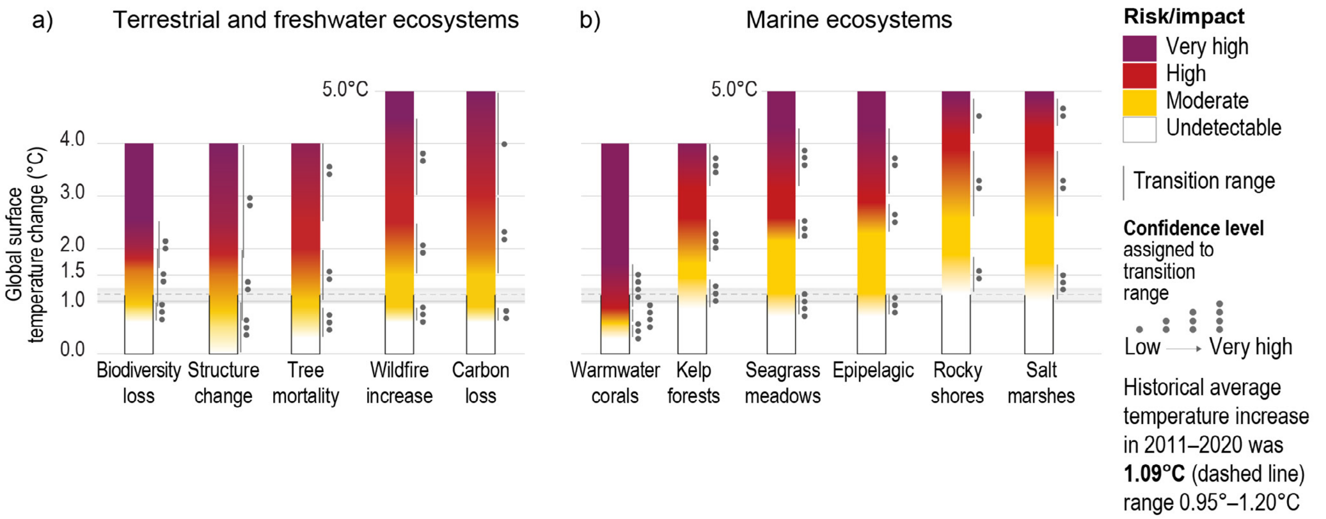


NCA Region	Species Change	Ecosystem Change	Ecosystem Service Change
Alaska	Commercial crab decline (KM 29.5)	Permafrost thaw and erosion (KM 29.5)	Cultural identity loss (Box 29.3)
Northern Great Plains	Grassland bird decline (KM 25.2)	Prairie wetlands threats (Box 25.2)	Delayed harvest of culturally important plants (KM 25.3)
Midwest	Brook trout decline (KM 24.2)	Increased agricultural pests (KM 24.1)	Recreational lake ice loss (Figure 24.6)
Northeast	Sea scallop decline (KM 21.2)	Coastal habitat loss (KM 21.2)	Impacts to fishing communities (KM 21.2)
Southeast	Rivercane loss (Box 22.3)	Coastal forest degradation (KM 22.1)	Increased pollen (KM 22.2)
US Caribbean	Sargassum seaweed increase (KM 23.4)	Tropical forest productivity declines (KM 23.2)	Reduction in water availability (KM 23.3)
Southern Great Plains	Pollinator disruptions (KM 26.2)	Decreased rangeland health (KM 26.1)	Extreme heat affecting human health (KM 26.3)
Southwest	Red abalone critically endangered (KM 28.2)	Kelp forest decline (KM 28.2)	Reduced water availability (KM 28.1)
Hawai‘i and US-Affiliated Pacific Islands	Avian extinctions (KM 30.4)	Coral reef loss (KM 30.1)	Cultural practices threats (Box 30.6)
Northwest	Invasive bass increase (KM 27.2)	Marine heatwaves (KM 27.2)	Reduced crop yields (KM 27.3)

All US regions are experiencing impacts of climate change on species, ecosystems, and ecosystem services.

Figure 8.2. Regional examples show the wide range of potential ecosystem impacts and their socioeconomic ramifications. Some changes may be occurring in more than one region (e.g., loss of coral reefs in both Hawai‘i and the US-Affiliated Pacific Islands [USAPI] and in the US Caribbean). Figure credit: Rutgers University and USGS.

Ecosystem Impacts and Risks



Ecosystem impacts and risks increase at higher levels of global warming.

Figure 8.3. As global surface temperatures increase relative to the preindustrial period (1850–1900), risks to ecosystems, such as changes in structure and function, become more acute beyond the 1.09°C (1.96°F) of warming that has already occurred (light gray dashed line). Maximum risk is reached below 4°C (7.2°F) of warming in some cases and between 4° and 5°C (9°F) in others. Very high risks to sensitive ecosystems, such as coral reefs, are anticipated above 2°C (3.6°F) and will be difficult to reverse. Adapted with permission from Figure SPM.3 in IPCC 2022.[2]

Ecosystem-based and climate-informed management that anticipates and adapts to changes can limit damage and increase resilience of ecosystems (Figure 6.7; KM 6.2).[14] Strategies include restoration, habitat protection and connectivity, assisted migration, and adaptive management.[15,16] However, there are limits to adaptive management, particularly for unique systems and species and the humans who depend on them.[2] For example, adaptive management may not be able to keep up with rising sea levels that submerge coastal communities and ecosystems (KM 9.1) or extreme heat that is intolerable to humans or other organisms (KM 15.1).

This chapter focuses on risks to terrestrial, freshwater, and marine ecosystems; more details on the following ecosystems can be found as noted: land (Ch. 6), forests (Ch. 7), coasts (Ch. 9), oceans (Ch. 10), and agroecosystems (Ch. 11).

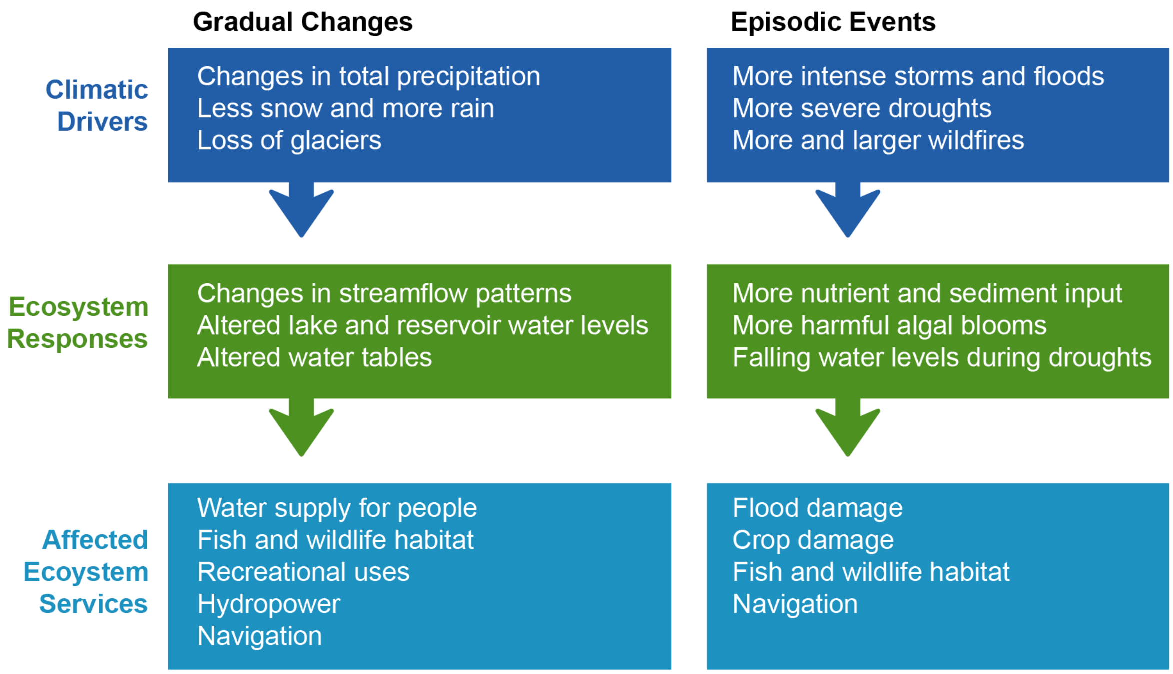
Key Message 8.1

Change Is Driving Rapid Ecosystem Transformations

Climate change, together with other stressors, is driving transformational changes in ecosystems, including loss and conversion to other states, and changes in productivity (*very likely*, *high confidence*). These changes have serious implications for human well-being (*very likely*, *high confidence*). Many types of extreme events are increasing in frequency and/or severity and can trigger abrupt ecosystem changes (*medium confidence*). Adaptive governance frameworks, including adaptive management, combined with monitoring can help to prepare for, respond to, and alleviate climate change impacts, as well as build resilience for the future (*medium confidence*).

Ecosystem changes can be driven by physical factors (e.g., thermal stress), biological responses (e.g., changing ranges), or both, often interacting with stressors from human activities. Multiple stressors, both gradual and episodic, can have complex interactive or amplifying effects on ecosystems (Figure 8.4);[17,18] for example, severe hurricanes can heighten forest vulnerability to drought and/or fire.[19,20]

Amplifying Climate Change Effects on Watersheds

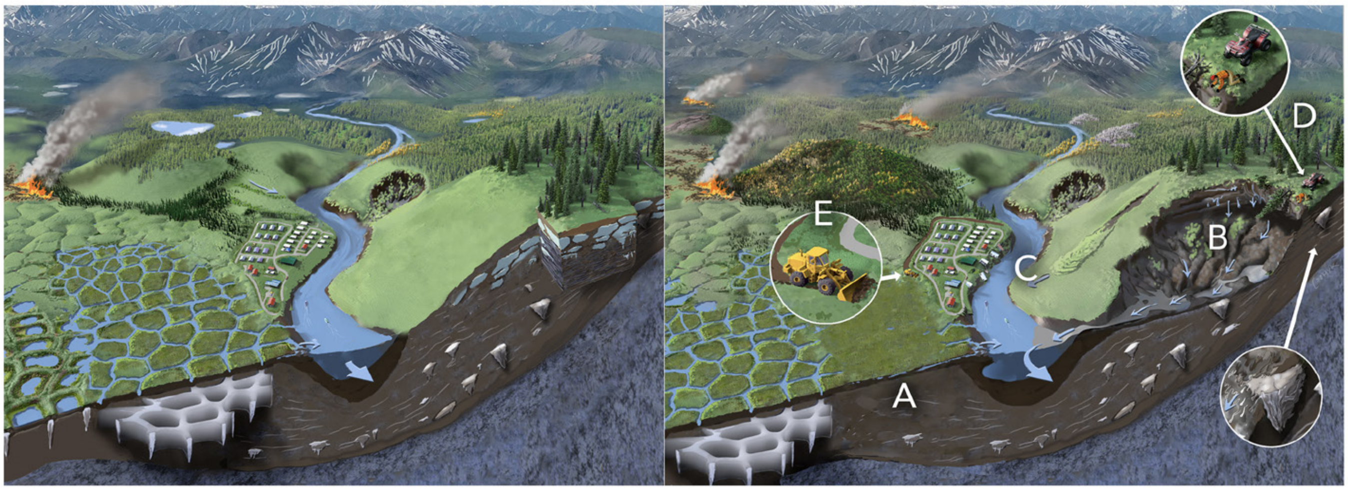


Climate effects on watersheds exemplify the amplifying impacts of gradual and episodic stressors.

Figure 8.4. Both gradual and episodic (short-lived) climatic drivers alter the transport of water, nutrients, and sediments from terrestrial watersheds to downstream water bodies. These drivers affect aquatic ecology and ecosystem services throughout the hydrological system, even in areas distant from drivers of change (e.g., more intense rainfall leading to leaching of fertilizers that stimulate harmful algal blooms downstream).[21] The frequency and intensity of episodic extreme events is projected to increase (KM 2.2), raising risks for many species (Figure 8.10). Figure credit: Cary Institute of Ecosystem Studies.

Many ecosystems are at increased risk of ecosystem tipping points (where rapid and unpredictable conversions to new states occur),[22] although it is difficult to predict how, where, and when these changes will occur.[23,24] Transformative changes in the composition, structure, function, and other properties of ecosystems result in a new stable state, or regime, with a different combination of species and communities, often resulting in reduced biodiversity and ecosystem services.[25,26] Restoring an ecosystem may be difficult or even impossible if a critical threshold or tipping point is crossed and a different system emerges, because changing or restoring the drivers that led to the altered state may not result in a return to the original state (Figure 8.5).[27]

Tipping Points and Regime Changes

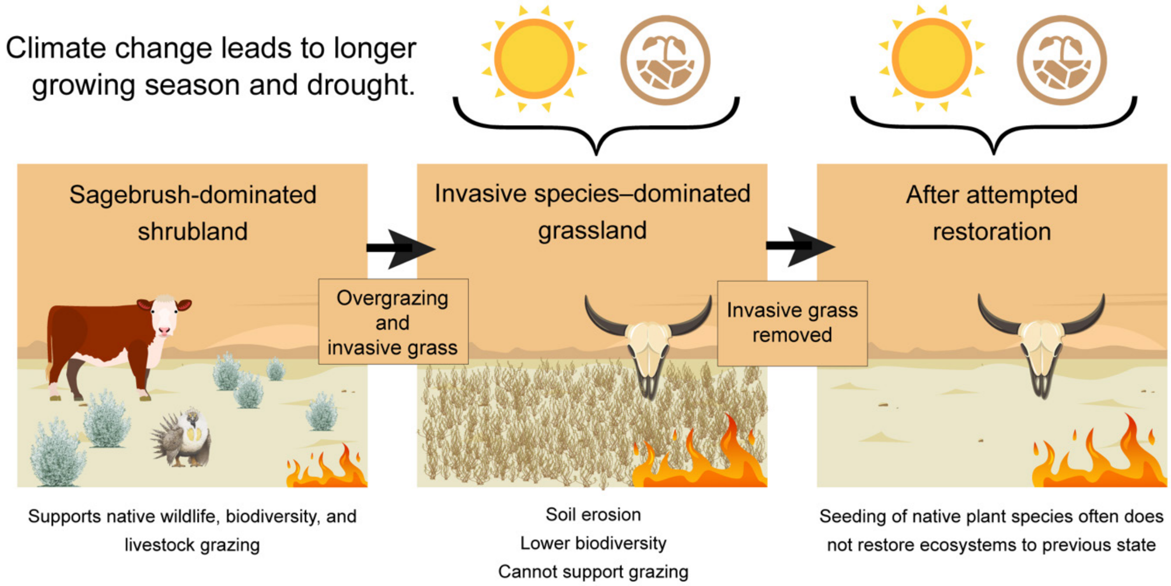


The Arctic faces substantial impacts from thawing permafrost that cannot be reversed.

Figure 8.5. Thawing of permafrost can cause irreversible tipping points in Arctic landscapes, transforming intact ecosystems (**left**) to severely altered ones (**right**), with impacts on people. A warming climate and fires lead to melting ground ice. Arctic and boreal forests contain permafrost soils with excess ice (more than is contained in soil pores), which form 3D networks in the ground. With warming, this ground ice can melt and the ground surface collapses (**A**). Fires, a natural part of the boreal disturbance cycle, are increasing in extent, frequency, and severity. Melting ice can lead to accumulation of water in ponds, lakes, and wetlands, but continued thawing can cause lakes to drain. Permafrost can also thaw abruptly, causing thaw slumps and bank failures (**B**). These geomorphological changes impact human infrastructure (**C**) and access to the land (**D**). Other risks (not pictured) include chemical and potentially disease mobilization that can threaten human health and ecosystems.[28,29] Human adaptation strategies to permafrost thaw include installing firebreaks around infrastructure (E). Adapted from Schuur et al. 2022[30] [CC BY 4.0].

Ecosystem changes can be gradual or relatively abrupt[31] and depend in part on ecosystem characteristics and key species.[32] Ecosystems with immobile or long-lived species such as corals or trees can often exhibit abrupt responses because they have limited capacity to keep pace.[33,34,35] Ecosystems with higher biodiversity have more species interactions and often exhibit slow changes at first followed by abrupt shifts.[15] Multiple stressors can lead to synergistic effects and trigger abrupt changes.[36] Examples include the co-occurrence of extreme heat, drought, and invasive grasses (Figure 8.6)[22] or wildfires followed by insect infestations (or vice versa; Focus on Western Wildfires).

Abrupt Changes in Ecosystem State

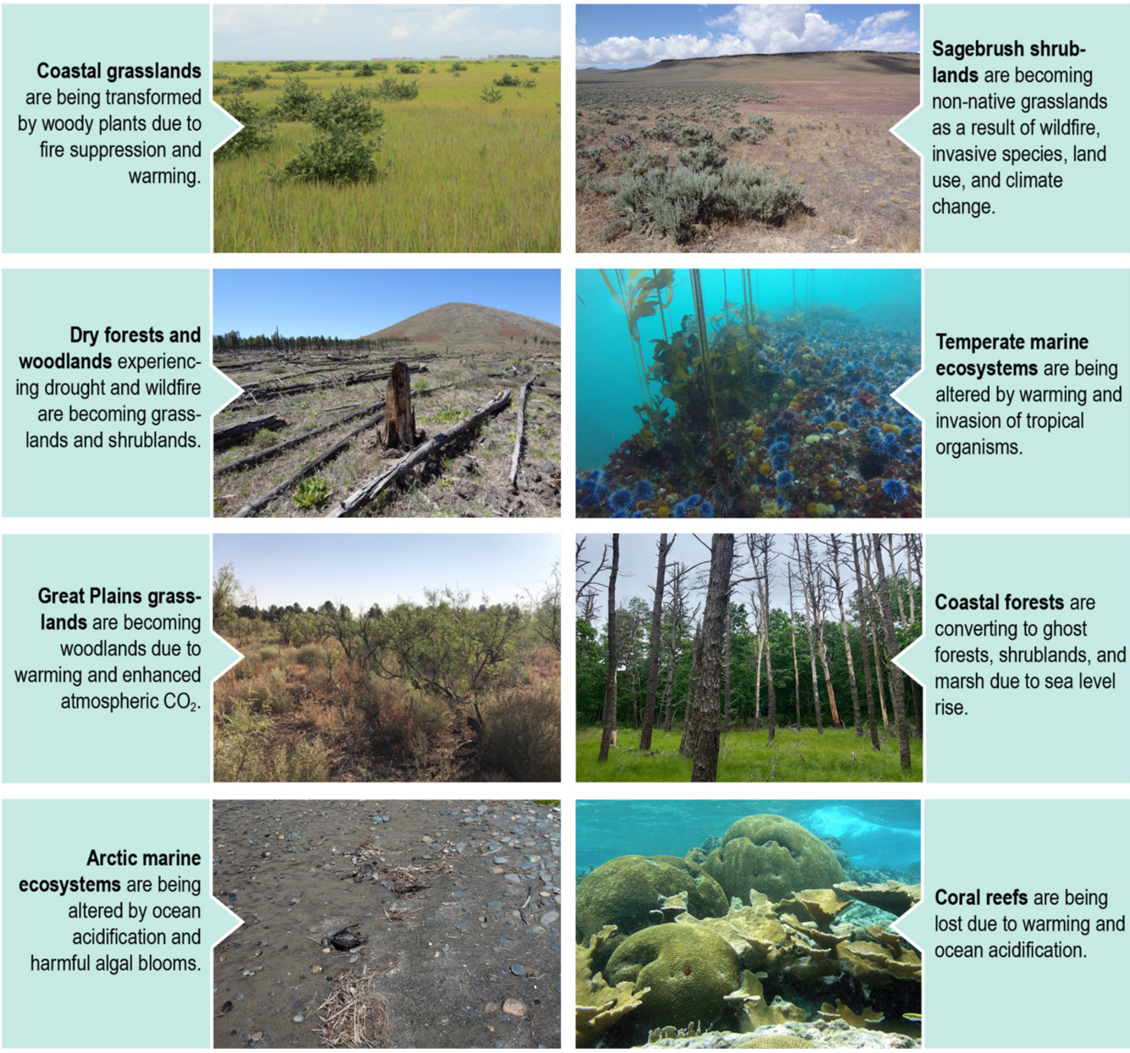


Climate change interacts with other stressors to cause synergistic effects, and resulting ecosystem changes can be abrupt and difficult to reverse.

Figure 8.6. In the western US, drought and longer, hotter growing seasons combined with invasive grasses and overgrazing have transformed sagebrush shrublands past a tipping point into annual grasslands that experience more frequent wildfires and no longer support native biodiversity and livestock grazing. Removing invasive grasses and seeding with native plants often does not restore the original shrubland ecosystem.[37] Adapted from Foley et al. 2015[38] [CC BY 4.0].

Vulnerability of ecosystems to climate change depends on exposure to the physical drivers of change and characteristics that affect species' sensitivity and capacity to adapt.[39] Examples of vulnerable ecosystems experiencing transformation are increasingly common (Figure 8.7). There is evidence that ecosystems with higher biodiversity are more resilient in the face of climate change,[40,41] indicating that better protection and reduced fragmentation and degradation of ecosystems are potential climate-adaptation strategies.[42]

Unique and Vulnerable Ecosystems



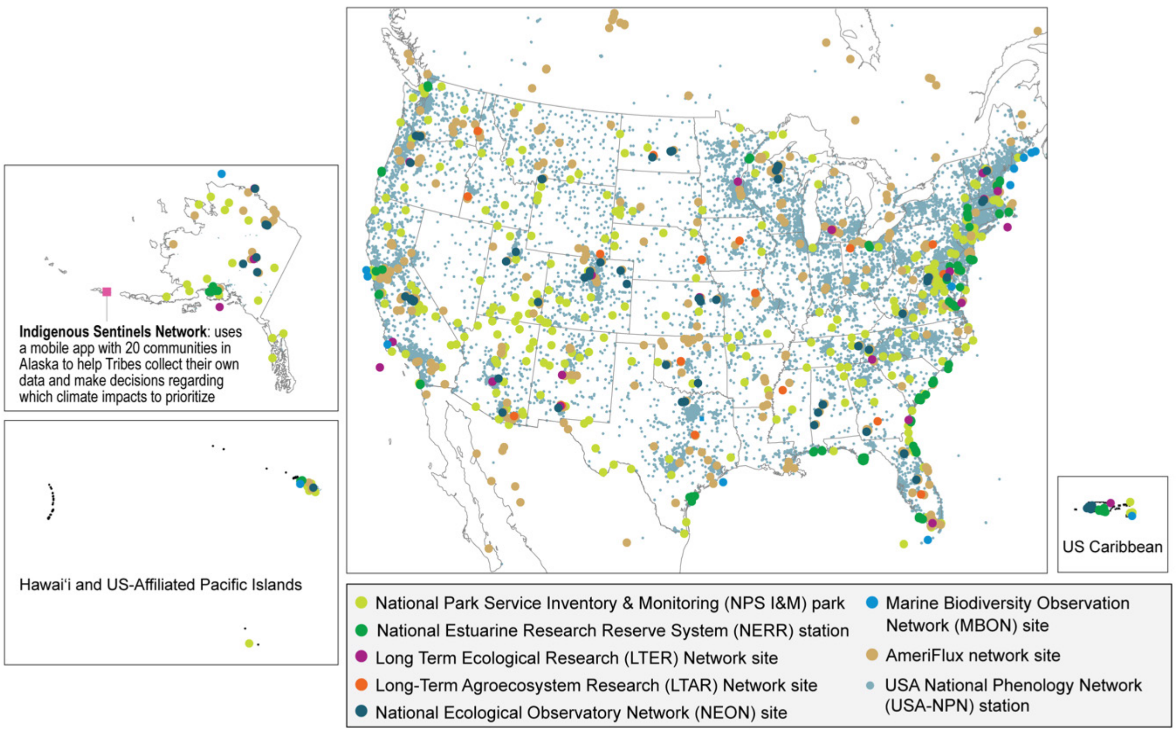
Transformations to ecosystems are already noticeable and widespread.

Figure 8.7. There are numerous and widespread examples of ecosystems transforming to altered states, with complex drivers and outcomes.[22,43,44,45,46] Climate-driven ecological transformations are occurring in all regions of the US and often negatively impact the services these ecosystems provide, including regulation of carbon and water cycles, wildlife habitat, and recreation. Figure credit: USDA Forest Service, USGS, and NOAA Fisheries. Photo credits (clockwise from top right): John Bradford, USGS; Steve Lonhart/NOAA; ©Elizabeth-Ann Jamison; Ilsa B. Kuffner, USGS; Sarah K. Schoen, USGS; ©Nicholas Smith; John Bradford, USGS; ©Anna Armitage.

Monitoring Transformations

Identifying and monitoring species or ecosystem traits that provide early warnings of vulnerability, system-wide decline, or tipping points can assist in reducing risks.[26,47,48,49] Numerous long-term monitoring networks (Figure 8.8) have been established in recent decades in direct response to climate and other changes.[27,50] Community-led ("citizen") science efforts such as iNaturalist[51] and the USA National Phenology Network,[52] alongside community-based monitoring networks[53] and Indigenous Knowledge holders (KM 16.3)[54] also collect observations across large areas[55] and have helped detect altered species distributions, abundances, and phenologies.[56,57,58]

Monitoring Ecosystem Changes



Monitoring programs are critically important for observing and projecting trends in resilience, species invasions, range shifts, declines, and extinctions.

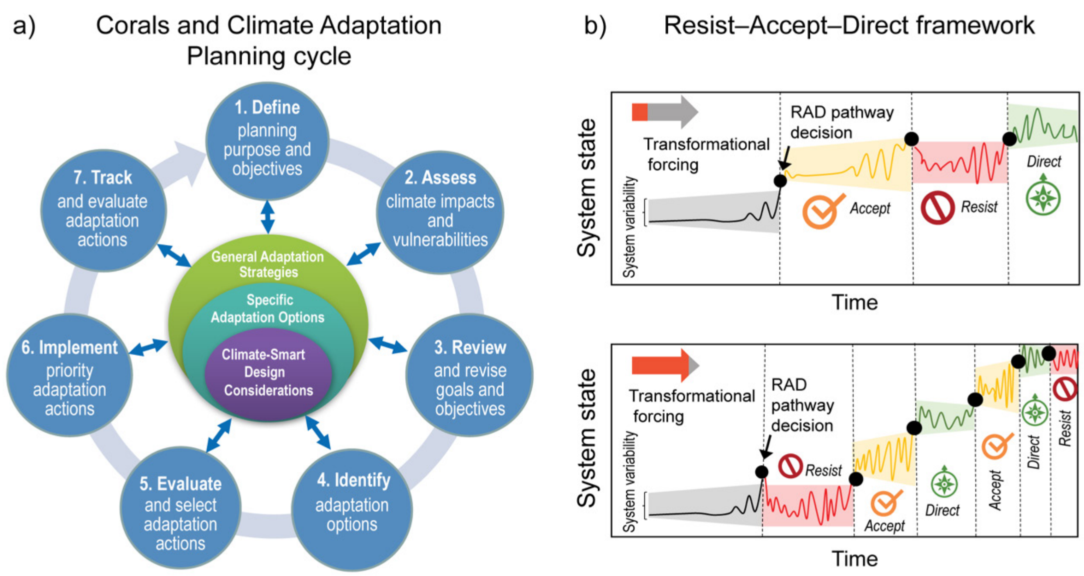
Figure 8.8. Federally operated networks (NPS I&M, NERR) and other long-term networks (LTER, LTAR, NEON, MBON, AmeriFlux) provide consistent and permanent observations at limited sites, whereas volunteer networks (USA-NPN, Indigenous Sentinels) offer more opportunistic observations across a wider landscape. Together, these networks provide critical data for understanding species and ecosystem changes, although gaps in coverage remain. Figure credit: Lynker and USGS.

Addressing Risks and Managing for Change

Climate change and other disturbances that transform ecosystems create growing management challenges.[14,59] Building, preserving, or restoring ecosystems is often the most practical and effective resilience strategy;[60,61] however, ecosystem transformation may still be inevitable.[62] Conventional resource management approaches are often ill-suited for managing uncertainties and related trade-offs.[63,64] In contrast, adaptive management iteratively plans, implements, and modifies strategies for managing resources under uncertainty. Successful adaptive management requires an overarching adaptive governance approach that provides institutional structures and decision-making processes for coordinating efforts across scales,[65] managing uncertainties and conflicts,[66,67] mobilizing diverse knowledges, and addressing stakeholder interests.[68,69,70]

Decision frameworks designed to anticipate ecosystem transformation can advance adaptative management processes (Figure 8.9).[71] As one example, the Resist–Accept–Direct (RAD) framework helps identify conditions where ecosystem management can resist a trajectory of change, accept change, or direct change toward desired future conditions (Figure 8.9b).[62,72] To engage the "direct" in their RAD planning, Tetlin National Wildlife Refuge in Alaska is combining scenarios, adaptive management, and adaptive pathway planning to engage managers and stakeholders to explore potential transformations, with one focus specifically on subsistence hunting.[73]

Adaptation and Transformation Planning Frameworks



Decision frameworks can help plan for the potential transformation of ecosystems.

Figure 8.9. Two examples of adaptive decision frameworks are the Corals and Climate Adaptation Planning cycle (**a**) and the Resist–Accept–Direct (RAD) framework (**b**). In (a), users are guided through assessment and design considerations to adjust climate-smart management interventions. In (b), the current ecosystem (gray) is affected by either moderate or strong transformational forcing that drives decisions (black dots) to resist (red time periods), accept (yellow time periods), and direct (green time periods) the trajectory of change. (a) Adapted from West et al. 2017, 2018[74,75] [CC BY 4.0]; (b) adapted from Lynch et al. 2022.[72]

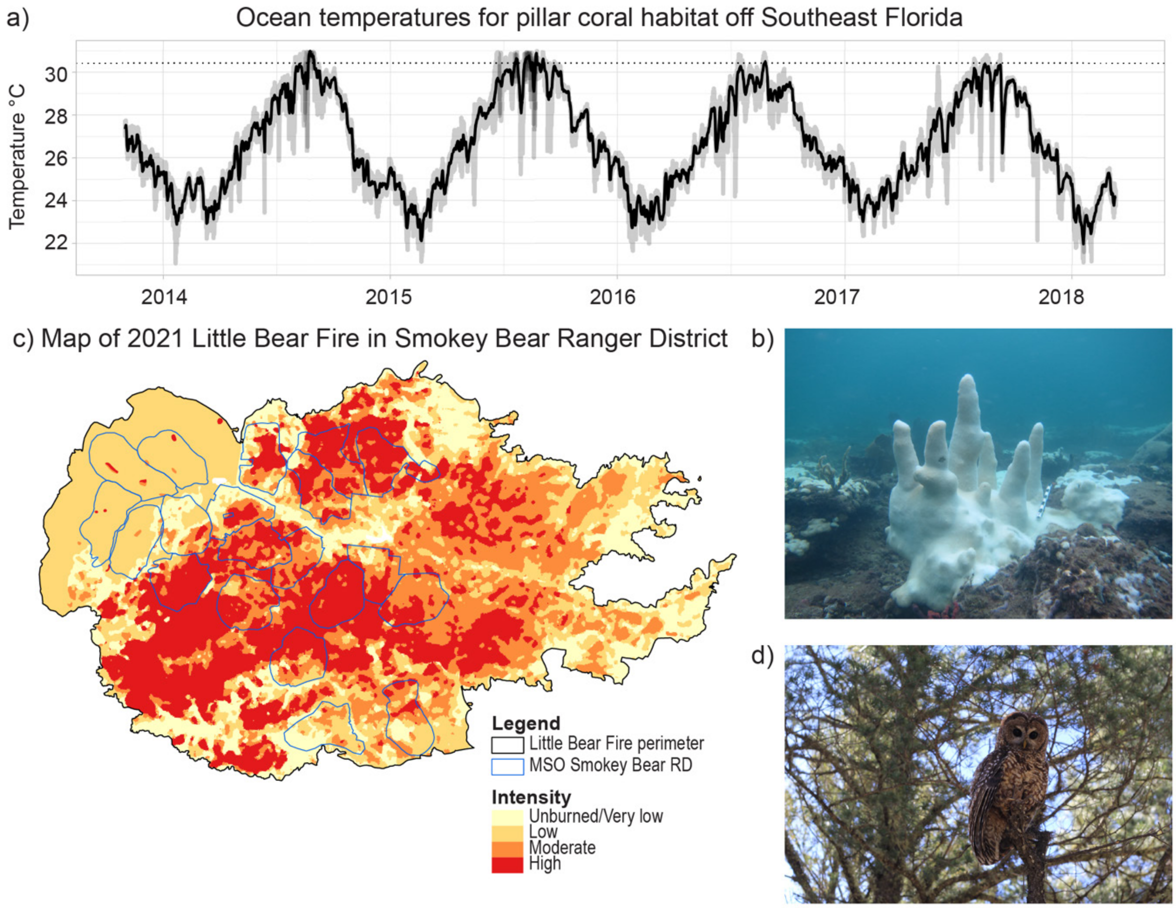
Key Message 8.2

Species Changes and Biodiversity Loss Are Accelerating

The interaction of climate change with other stressors is causing biodiversity loss, changes in species distributions and life cycles, and increasing impacts from invasive species and diseases, all of which have economic and social consequences (*very likely*, *high confidence*). Future responses of species and populations will depend on the magnitude and timing of changes, coupled with the differential sensitivity of organisms; species that cannot easily relocate or are highly temperature sensitive may face heightened extinction risks (*very likely*, *high confidence*). Identification of risks (e.g., extreme events) will help prioritize species and locations for protection and improve options for management (*very likely*, *high confidence*).

Climate-related stressors and other drivers of global change, such as land-use change, habitat destruction, and overexploitation, can create significant biodiversity changes and losses (Figure 8.1).[76,77] Even short-term extreme events such as heatwaves[78,79,80] can generate significant species impacts. For example, coral reefs are threatened by cumulative impacts of ocean warming and acidification, marine heatwaves resulting in bleaching and higher susceptibility to diseases, increasingly powerful tropical cyclones causing loss of structural complexity, hypoxia (low oxygen) events, overfishing, and pollution (Figure 8.10a, b; Box 10.1; KMs 9.2, 10.1).[81,82,83,84,85,86] Similarly, wildfires (Focus on Western Wildfires)[87] can create risks for some species both directly (Figure 8.10c, d) and indirectly through longer-term habitat changes.[88]

Extreme Event Impacts



Short-term extreme events can have severe impacts on threatened species.

Figure 8.10. Two examples of such impacts are as follows. (**a**) High water temperatures off Southeast Florida exceeded the maximum average monthly temperature (horizontal line in time series) in 2014–2015, resulting in severe bleaching of (**b**) pillar coral (*Dendrogyra cylindrus*) colonies and subsequent disease and death of all individuals. (**c**) Wildfires impacted more than 75% of breeding pairs (blue polygons) of (**d**) Mexican spotted owl (MSO; *Strix occidentalis lucida*) in Smokey Bear Ranger District, New Mexico, in 2012. Figure credits: (a) adapted from Jones et al. 2021[89] [CC BY 4.0]; (c) USDA Forest Service, NOAA Fisheries, and NOAA NCEI. Photo credits: (b) ©David Gilliam, Nova Southeastern University; (d) ©Serra J. Hoagland, USDA Forest Service.

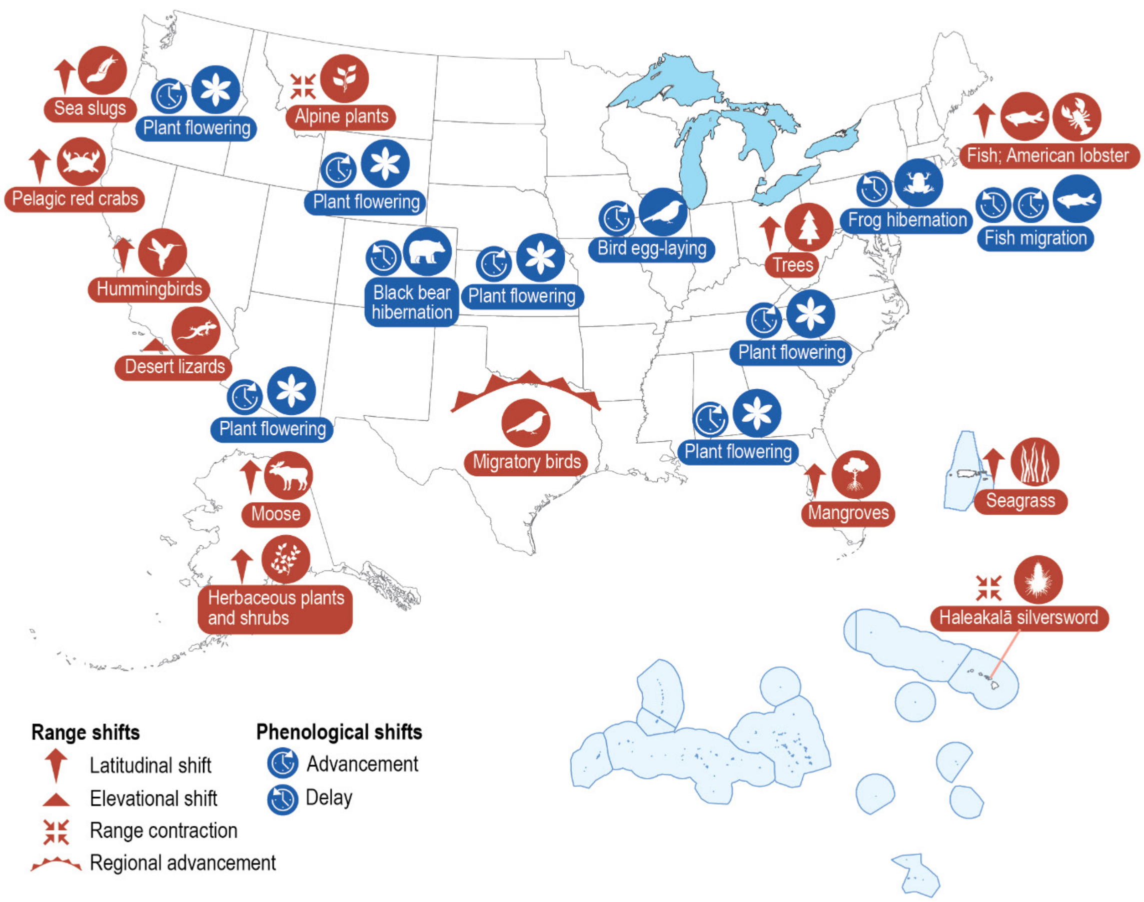
Changes in Phenology

Compounding the responses of species to extreme events, the timing of seasonal events such as leaf-out, flowering, migration, spawning, phytoplankton blooms, and egg hatching is changing in response to rising winter and spring temperatures and to the altered timing and amount of snowmelt and rainfall (Figures 8.8, A4.13).[58,90,91,92] Changes include earlier flowering and maturity in agricultural crops that affect planting and harvest times,[93,94,95,96,97] longer and more intense allergy seasons (KM 14.4),[98] and increased pest activity.[99,100] Changes are most pronounced at high latitudes and elevations and in urbanized areas.[101,102] Phenological mismatches emerge when the timing of activities in interacting species changes at different rates, such as food availability shifting to no longer match a dependent organism's needs.[103,104] Phenological changes are also impacting seasonal carbon cycling[105] and increasing vulnerability to spring frost damage (App. 4).[106] There are significant economic and social impacts of these changes, including tourism impacts and loss of culturally important species.[107,108]

Range Shifts

Elevational and latitudinal range shifts driven by climate change have already occurred for multiple species (Figure 8.11),[109,110,111] with range shifts of marine species more responsive and greater in magnitude than terrestrial ones (KM 10.1; Figure A4.12).[112] Mountaintop ranges are shrinking as species shift upslope, with high-elevation ones highly vulnerable.[113,114] Milder winters and warmer growing seasons are expected to expand ranges for some species.[115,116]

Observed Range Shifts and Changes in Phenology

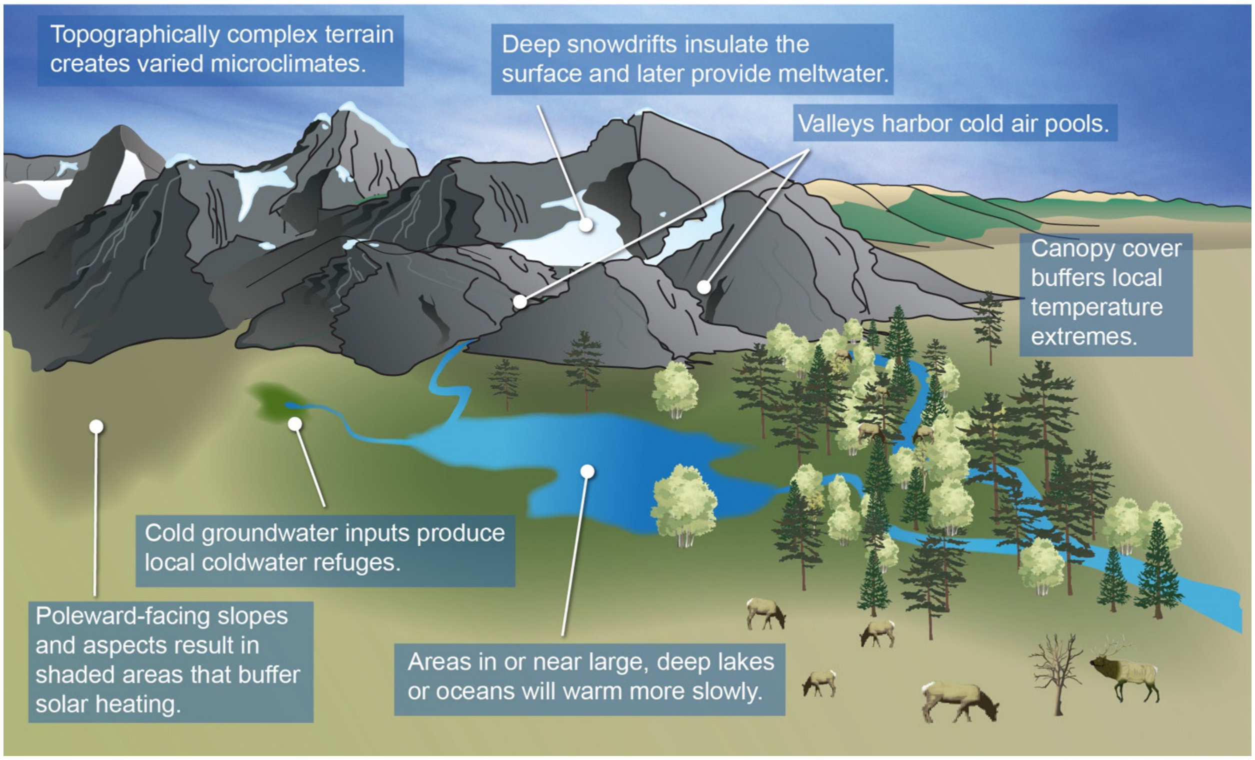


Climate change is leading to shifts in phenology and range for species across the United States.

Figure 8.11. Many plant and animal species are shifting to higher elevations, to more northern latitudes, or in multiple directions (here labeled "regional advancement"). The timing of seasonal activity is similarly shifting in response to warmer temperatures and changing precipitation regimes, in many cases occurring earlier in the year, although the direction and magnitude of changes are species-specific. Figure credit: University of Arizona and USFWS.

Conditions can change over very localized scales, creating complex "mosaic" patterns of environmental stressors.[117,118,119,120] Climate refugia occur in locations where environmental conditions are changing more slowly than in surrounding areas[121] or where local drivers override more regional-scale processes.[122] These refugia are expected to support organisms that can repopulate other depleted areas through dispersal via currents or land corridors[123] and are therefore a priority for conservation (Figure 8.12).[124,125] Identification of the many existing refugia expected to disappear under climate change is crucial.[126,127]

Environmental Mosaics and Climate Refugia



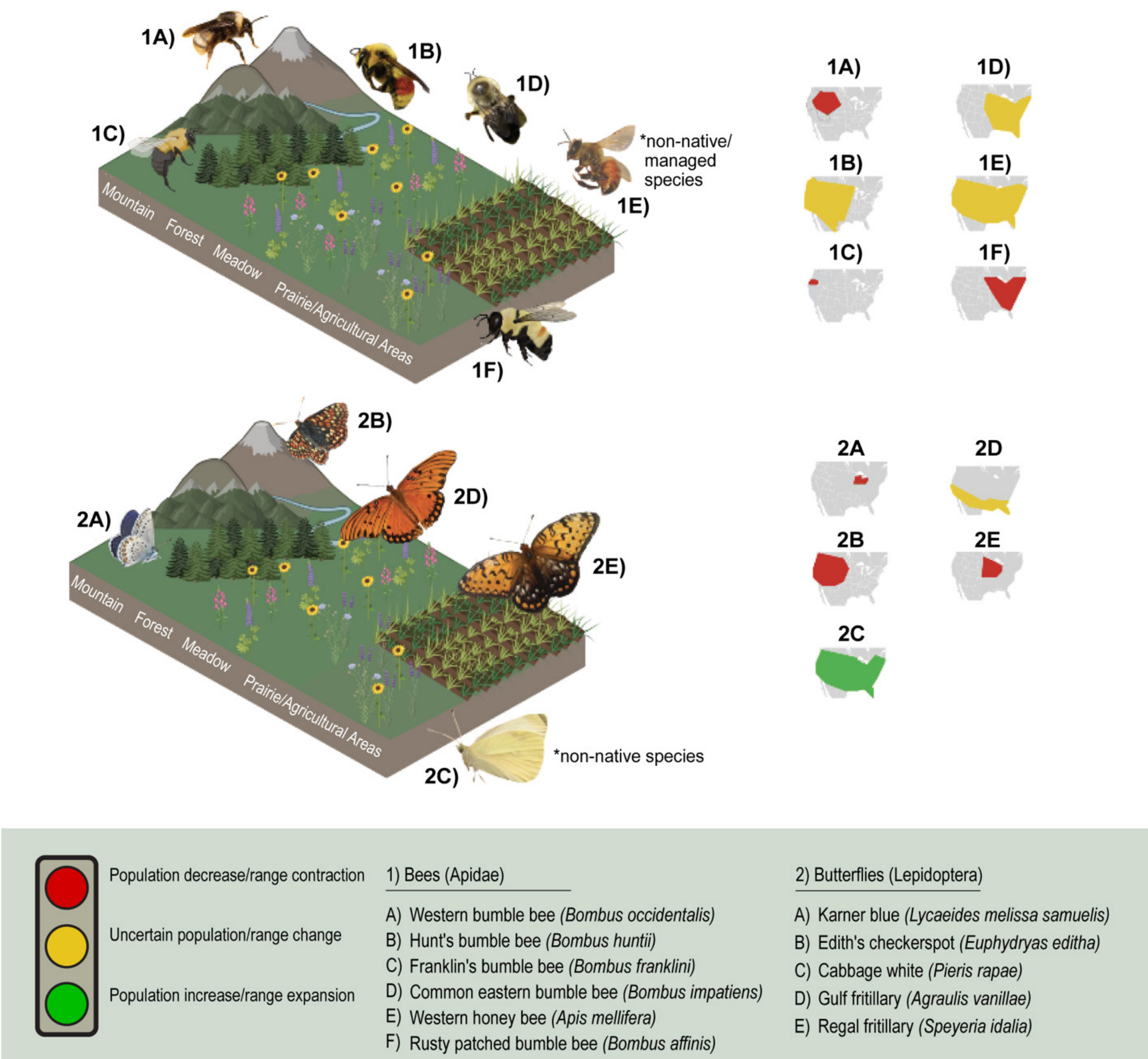
Climate refugia are locations where environmental conditions are changing more slowly than in the surrounding region.

Figure 8.12. Refugia help populations survive extreme events, and when connected via dispersal currents and corridors can serve as rescue sites.[122] Understanding variations in environmental exposures and organism sensitivities to extreme conditions helps forecast climate impacts[122,127] and inform management strategies.[128,129] Adapted from Morelli et al. 2016[130] [CC0 1.0].

Species Sensitivities and Extinction Risks

Understanding species sensitivities to climate impacts and adaptive capacity can help detect ecological tipping points (KM 8.1).[131,132] Large-bodied animals (Box 8.1)[133] and species occupying polar habitats are particularly at risk of local extinction due to physiological vulnerabilities.[134] In contrast, smaller-bodied species often have more widely variable responses to changing conditions (Figure 8.13).

Observed Pollinator Sensitivities



Insect pollinator responses to environmental stressors, even within the same taxonomic grouping, can vary widely.

Figure 8.13. Pollinator responses to changing climate conditions within a short time frame (the past 10–30 years) are leading to complex patterns of species movements across the landscape. Several species of bumble bees (**panel 1**) have had different responses over the past 10 years, from shifting in habitat within their ranges to range contractions and extinction risks. In **panel 2**, butterfly species are responding with declines and shifts within existing ranges or with range expansions nationwide. Figure credit: Colorado State University.

Box 8.1. Case Study: Climate Sensitivities of North Atlantic Right Whales

The North Atlantic right whale (*Eubalaena glacialis*) is one of the world's most endangered large whales, primarily due to historical commercial hunting, with fewer than 350 individuals remaining.[135] This species is vulnerable to climate change–driven extinction in part because of its large size, long lifespan, slow growth, delayed maturity, and small number of offspring.[136] Population recovery has been hindered by climate-driven changes in the distribution, availability, and quality of zooplankton, which has altered whale foraging patterns (KM 10.1).[133,137,138] As finding shelter and food becomes more difficult, the whales become more susceptible to disease, fishing gear entanglements, and vessel strikes, contributing to decreased body size and reproductive success (Figure 8.14).[139,140] Loss of these whales can have cascading effects on ecosystem composition and function.[141]

Threats to North Atlantic Right Whales

Climate change increases risks to the endangered North Atlantic right whale.

Figure 8.14. The whale known as Snow Cone is shown with her newborn calf near Cumberland Island, Georgia, in 2021. She was entangled in fishing rope for at least two years and is currently presumed deceased. Such threats are exacerbated as whales travel into new feeding areas because of changing oceanographic conditions. Photo credit: ©Georgia Department of Natural Resources/NOAA Permit #20556.

Disease Risks

Disease threats to wildlife, plants, and humans have emerged as a significant climate change risk.[142,143,144,145,146,147] Climate change promotes range expansions and population growth of disease-spreading (vector) species, increased host susceptibility via stress, and enhanced pathogen transmission (Table 8.1; KM 15.1),[148] with major economic consequences.[149,150] Diseases often thrive where other stressors are present; prevalence is projected to further increase as populations and ecosystems become stressed from temperature variation and extreme events, changes in habitats, altered migration patterns and ranges, biodiversity loss, and increases in invasive species (KMs 15.1, 30.4; Figure A4.16).[151,152,153,154]

Table 8.1. Climate-Impacted Disease Risks in Humans and Wildlife

Numerous wildlife and human diseases (KM 15.1) are expanding to new areas and species and becoming more common as climate change expands vector ranges and changes species interactions and habitat preferences. Sources: Islam et al. 2022; Gilbert 2021; Ogden et al. 2021; Sonenshine 2018; Keesing and Ostfeld 2021.[152,153,155,156,157]

Pathogen: Virus

Disease	Affected Organisms
West Nile virus	Birds and mammals
Viral hemorrhagic septicemia virus	Freshwater and marine fish
White spot syndrome virus	Aquatic crustaceans
Tomato spotted wilt virus	Plants

Example of impacts: Viral hemorrhagic septicemia damages wild and farm-raised fish such as rainbow trout, with patterns of spread and establishment being highly correlated with climatic variables (temperature, precipitation).[158]

Pathogen: Bacteria

Disease	Affected Organisms
Furunculosis	Trout and salmon
Enteric red mouth disease	Freshwater and marine fish
Citrus greening	Plants

Example of impacts: Citrus greening is a bacterial disease transmitted by an invasive insect (Asian citrus psyllid). Because the disease is highly sensitive to temperature, climate change is expected to allow it to spread farther.[159] Since 2005, Florida citrus production has declined 74%.[160]

Pathogen: Fungus

Disease	Affected Organisms
White-nose syndrome	Bats
Chytridiomycosis	Amphibians
Rapid ʻŌhiʻa death	Plants
Armillaria root rot	Plants

Example of impacts: Rapid ʻŌhiʻa death is a fungal disease that impacts ʻŌhiʻa lehua, a Hawaiian keystone species with important functional and cultural roles. Large-scale mortality is projected to worsen in a warmer and wetter climate.[161]

Pathogen: Parasite

Disease	Affected Organisms
Avian malaria	Birds
Proliferative kidney disease	Salmon
Brainworm	Moose, elk, caribou
Seagrass wasting disease	Aquatic plants

Example of impacts: Brainworm is a parasitic nematode spread via white-tailed deer, which are currently expanding farther northward. In moose, population declines due to brainworm are already affecting subsistence hunting among some Tribal communities.[162]

Pathogen: Unknown

Disease	Affected Organisms
Stony coral tissue loss disease	Corals
White band disease	Corals
Colony collapse disorder	Bees

Example of impacts: Stony coral tissue loss disease originated in Florida in 2014 and has spread throughout the Caribbean, with thermal stress implicated in reef vulnerability. The disease affects more than 30 coral species, including many important reef-builders. Rapid spread and high mortality rates have had serious economic consequences for tourism and fishing.[163]

Invasive Species Risks

Climate change has created uncertainty about where and how fast invasive species will spread, but there are both observed cases[164] and projections showing expected increases.[165] For example, cold-sensitive invasive species such as the kudzu vine (*Pueraria montana* var. *lobata*) can spread northward with warming.[166] Some invasive species are more successful than natives—particularly certain terrestrial plants[167] and aquatic species[168]—because they better tolerate or more rapidly adapt to changing conditions (Figure 8.15). Yet not all invasive species are favored by climate change; many invasive plants and vertebrates may experience decreased ranges while the ranges of many invasive invertebrates and pathogens are expected to increase.[169]

Invasive Species and Climate Change

Damaging invasive species that are expected to shift in range because of climate change.

Figure 8.15. Examples of invasive species include the following: (**a**) Hemlock woolly adelgid, an insect pest, is expected to spread northward with warmer winters and cause die-offs of eastern hemlock trees.[170] (**b**) Invasive carp are expected to benefit from warmer waters and expand into the Great Lakes, where they will compete with native fishes and present boating hazards through their habit of jumping out of the water.[171] (**c**) Eurasian watermilfoil chokes freshwater systems and outcompetes natives in warmer conditions.[172] (**d**) European green crabs, which benefit from warmer waters, harm economically important native shellfish fisheries.[173] Photo credits: (a) Kerry Wixted via Flickr [CC BY-NC 2.0]; (b) Steve Hillebrand, USFWS; (c) ©Stephen K. Hamilton, Cary Institute of Ecosystem Studies; (d) ©P. Sean McDonald, University of Washington.

Assisting Species Adaptation

Natural resource managers are implementing adaptation actions including increasing conservation efforts, reducing habitat fragmentation, protecting wildlife corridors, assisting species migration, and expanding protection activities.[174] For example, marine protected areas can reduce non-climate stressors like overfishing and facilitate recovery of populations following extreme events like heatwaves, which then benefits recreational and commercial fishing in surrounding areas (KM 28.2).[175] Many states now include climate impacts in state wildlife action plans; for example, Massachusetts has identified habitat patches allowing for movement of the threatened Blanding's turtle and is creating habitats that balance increased drought and other threats.[176,177,178]

Managing for connectivity can enhance species climate resilience, particularly for wide-ranging and migratory species.[179] Priorities include connecting climate refugia, areas of high diversity,[123,180] and current and future habitat types.[181] For example, resilience strategies for the saltmarsh sparrow (*Ammospiza caudacuta*), which has declined dramatically due to rising sea levels, include protection of areas expected to convert into future wetlands, use of runnels and other elevation manipulations, and high-marsh restoration.[182,183]

Assisted migration has been implemented for at-risk species such as the Laysan albatross, O'ahu tree snail, relict leopard frog, and wolf (Figure 8.16).[184] In the Chippewa National Forest in Minnesota, seeds of tree species native to red pine forests but collected 100–200 km to the south—and thus genetically distinct from local populations—are being planted to test assisted migration.[185]

Managing for Species Adaptation

Assisted migration can help species adapt to changing climate conditions.

Figure 8.16. One example is the translocation of wolves to Isle Royale National Park, Michigan. The loss of ice bridges in winter prevented new arrivals that would have maintained genetic viability of the population.[186] Photo credit: Jacob W. Frank, NPS.

Implications for Management

While protected areas can help species adapt to climate change, these areas are themselves vulnerable;[174,187,188,189] many US protected areas are expected to see major shifts in vegetation communities and other species.[190] Further, the existing US protected areas system has low overlap with projected climate refugia;[191] extending protection to include future habitat suitability for some species may double costs.[192] Given continued range shifts, areas with priority species that draw tourists (e.g., bird watchers) will need to refocus as some species become rarer or disappear,[193,194] impacting neighboring communities dependent on tourism revenue.

Conflicts (between humans and with wildlife) arising from climate-driven changes in distribution and availability of species and resources are occurring.[195,196] For example, some species are moving out of areas set up to conserve them, and range shifts of fish stocks (including across international boundaries) are causing challenges (KM 10.1).[197,198] Some adaptation policies (e.g., translocation of nonhuman species into human communities unwilling to coexist with them) may exacerbate conflicts (KM 17.2).[199] Adaptive management that prioritizes both climate change response planning and conflict management can reduce negative outcomes.[195,200,201]

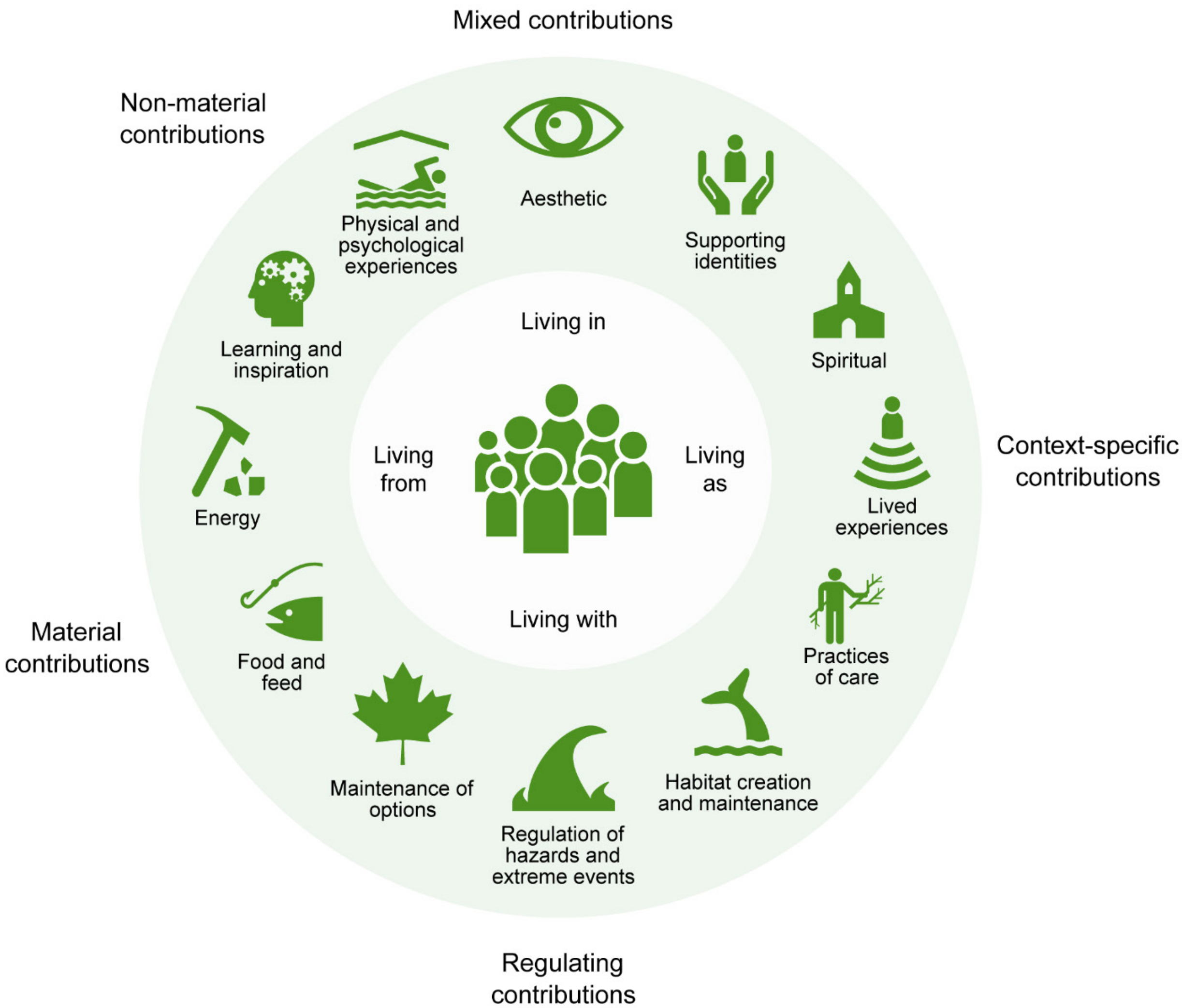
Key Message 8.3

Impacts to Ecosystem Services Create Risks and Opportunities

Climate change is having variable and increasing impacts on ecosystem services and benefits, from food production to clean water to carbon sequestration, with consequences for human well-being (*very likely*, *high confidence*). Changes in availability and quality of ecosystem services, combined with existing social inequities, have disproportionate impacts on certain communities (*very likely*, *high confidence*). Equity-driven nature-based solutions, designed to protect, manage, and restore ecosystems for human well-being, can provide climate adaptation and mitigation benefits (*likely*, *medium confidence*).

Ecosystem services provide substantial and often economically important contributions to communities, ranging from direct material benefits like food production and clean water to nonmaterial benefits like recreation (Figure 8.17). However, economic valuation alone does not reflect intrinsic or relational values that people hold toward nature;[202,203] for example, Tribal and Indigenous Peoples rely on ecosystems for supplies of culturally valuable food, materials for religious ceremonies, and relational links within communities and among generations (KM 16.1).[204,205]

Ecosystem Services and Their Benefits



Ecosystems provide a broad range of relational benefits, from the material to the spiritual.

Figure 8.17. Ecosystem services, also called "nature's contributions to people," are the benefits that humans receive or derive from ecosystems. These are both material (e.g., energy sources) and non-material (e.g., sense of place), and contribute to the regulation of ecosystem processes. The broad categories of benefits pictured are fluid and overlapping. People value nature in multiple ways, such as "living as" nature (e.g., Indigenous viewpoints that humans are part of the environment; Figure 16.3) or "living from" nature (e.g., people's dependency on key services). Adapted from O'Connor and Kenter 2019[206] [CC BY 4.0].

There are many adverse climate change effects on ecosystem services,[207,208] including reduced water availability for human and agricultural uses (KM 4.1), decreased productivity of crop species due to increased pest infestations (KM 11.1), and losses of hazard-mitigating ecosystems like wetlands and coastal shorelines that provide nursery and nesting habitat, recreation, and aesthetic pleasure (Table 8.2; KM 9.2). However, future trends on ecosystem use and benefits are not always clear. For example, rising temperatures can extend seasonal recreational opportunities, but if daily high temperatures exceed 27°–30°C (80.6°–86°F), recreation tends to decrease.[209,210]

Further, diminished benefits from ecosystem services can also occur based on other factors.[211,212] For example, discriminatory planning practices, housing segregation, and racism have created inequitable distributions of services, leading to communities of color experiencing reduced access to benefits like improved air quality or heat reduction (KM 12.2; Figure 12.6).[213,214,215] Lack of access often accompanies other environmental harms (e.g., greater exposure to allergens or risks of green gentrification, the displacement of local residents as environmental benefits improve).[216,217] Climate change is expected to exacerbate these impacts[207] and create further difficulties in addressing environmental racism, highlighting the need for clear management priorities and recognition of diverse values.[218,219]

Table 8.2. Examples of Climate Impacts on Ecosystem Services

Climate change affects the availability and quality of many ecosystem services, and many projected impacts on important ecosystem services will also have equity implications.

Ecosystem Service	Potential Climate Impacts	Equity Implications
Regulation of Natural Hazards	Coastal marsh retreat is projected due to sea level rise and increased storm activity.[220]	Flood risks are often inequitably distributed; for example, property damage risks can be disproportionately higher for Black communities.[221]
Physical and Psychological Experiences	Cold-weather recreational opportunities are projected to decline (e.g., fewer skiing days).[209,210,222]	Less green space access in low-income communities and communities of color already results in fewer opportunities for recreation.[223,224]
Water Quantity	Changes in precipitation, snowpack, soil moisture, and evapotranspiration are projected to alter surface and groundwater availability (KM 4.1; Figure A4.7).	Drought often has disparate impacts;[225] for example, Tribal reservations in the US Southwest with higher agricultural dependence will be particularly impacted.[226]
Regulation of Air Quality	Street trees provide considerable urban air quality benefits but are vulnerable to drought and heat.[227]	Existing tree canopy distribution is inequitable, accounting for greater air pollution[228,229,230] associated with legacies of redlining.[231]
Food Production (fisheries)	Aquatic systems are experiencing shifts in species ranges, phenologies, distributions, and productivities.[232]	Culturally important species, such as Chinook salmon for Pacific Northwest Tribes, are projected to dramatically decline in the future.[233]

Opportunities for Nature-Based Solutions

Ecosystem-based mitigation and adaptation opportunities are often called nature-based solutions (NBSs) or natural climate solutions (Figure 8.18).[234,235] NBSs support biodiversity and can provide other benefits when managed in collaboration with affected communities and use of local knowledge (KM 21.1). For example, coastal wetland restoration provides both mitigation and adaptation benefits by sequestering carbon and decreasing coastal flooding, wave action, and erosion[236] while improving water quality and increasing habitat biodiversity (KM 9.3; Focus on Blue Carbon).[237] NBS projects are often very cost-effective, spurring new financing options.[238,239]

Ecosystem-based adaptation is a type of NBS aimed at increasing community resilience to climate change through the use of ecosystems.[240,241] Examples include protecting and restoring floodplains to help reduce flood impacts[242] or helping farmers cope with drought through soil conservation measures.[243] There are high returns on investments to restore coastal ecosystems in particular, since US coral reefs provide estimated adaptation benefits of more than $1.8 billion annually (dollar year not provided).[244,245] These approaches can also have positive equity benefits when designed with local participation and buy-in through collaborative approaches (KM 31.4).[246,247,248,249,250,251]

Nature-Based Solutions

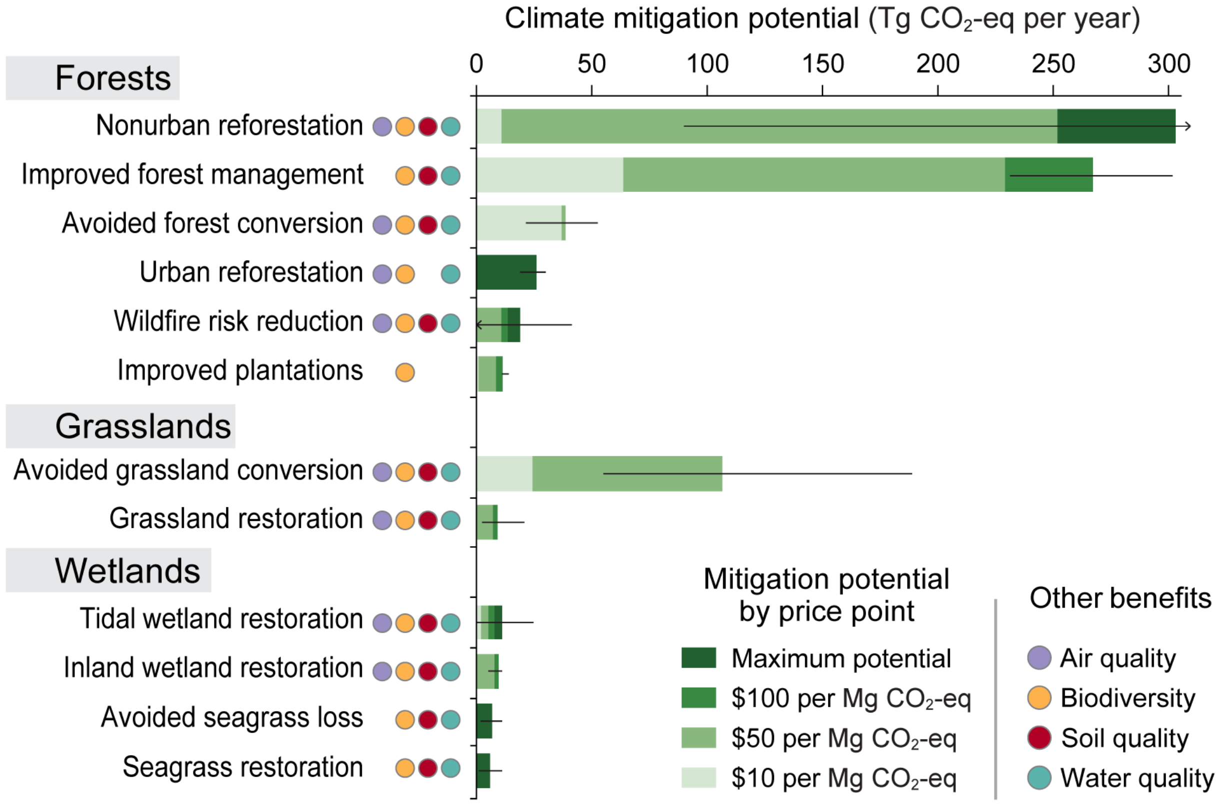
Nature-based solutions buffer the effects of climate change.

Figure 8.18. Nature-based solutions (NBS) are actions to protect, manage, and restore ecosystems to address societal challenges such as climate change. Examples in the US include (**a**) oyster restoration; (**b**) cover cropping; (**c**) stormwater management; and (**d**) urban agriculture. These not only help buffer the impacts of climate change, such as through physical barriers or improved local microclimates, but also provide additional benefits like food

and habitat provisioning.[252,253,254] Figure credit: Rutgers University and NPS. See figure metadata for additional contributors. Photo credits: (a) Linda Walters, NPS; (b) David Bosch, USDA; (c) Alisha Goldstein, EPA; (d) Bob Nichols, USDA.

Current and future opportunities for NBSs exist across the US, particularly for mitigation solutions focused on protecting and increasing carbon storage by natural ecosystems (Figures 6.6, 8.19; Focus on Blue Carbon).[255] Planning for future protected areas for both climate and biodiversity could emphasize areas that not only hold large amounts of carbon but also help species adapt,[256] recognizing the important role that many animal species play in carbon cycling.[257] However, NBSs themselves are also vulnerable to rising temperatures, sea level rise, and other climate impacts.[258]

Climate Mitigation Potential of Nature-Based Solutions in 2025



Nature-based solutions can support carbon storage while also providing other benefits.

Figure 8.19. Nature-based solutions (NBSs) can preserve or enhance carbon storage in soils and biomass across natural systems like forests, grasslands, and wetlands, as well as agricultural lands. Different approaches vary in their climate mitigation potential, shown here as teragrams of carbon dioxide equivalent (Tg CO_2-eq per year; length of bars) in the year 2025. Lighter green shades indicate the estimated portion of mitigation obtainable for less than $10, $50, or $100 per megagram of CO_2-eq (Mg CO_2-eq). The dark green "Maximum" category shows the highest technical carbon sequestration potential that is also consistent with meeting human needs for food and fiber. Black lines are error bars indicating either the 95% confidence interval or an uncertainty range, depending on the source of the estimate. The arrow indicates a range that may exceed the values shown on the chart. Other potential benefits of NBSs are also indicated for each category (colored dots). Figure addresses contiguous US only. Adapted from Fargione et al. 2018[259] [CC BY 4.0].

NBSs that involve restoring degraded ecosystems can improve resilience[260] and increase provision of ecosystem services.[261] Ideally, restoration is designed to recover a range of potential benefits.[262,263] However, multiple services cannot necessarily be maximized simultaneously, as focusing on one ecosystem service at the expense of other benefits leads to trade-offs.[264,265,266] Larger-scale restoration efforts are generally more successful when connected to local priorities,[267] including their use in addressing environmental inequities (Box 8.2).[268]

Box 8.2. Restoration and Ecosystem Management by Tribal Nations

Tribal forestry programs throughout the US provide exemplary models of Indigenous land management practices that showcase Tribes' ability to balance sustainable environmental stewardship, fulfilling the social, ecological and economic needs of their communities.[269] The "anchor forests" concept, in which Tribes are at the center of multiple landownerships and serve as the primary hub for providing forest management infrastructure, is one effective approach. Such initiatives maximize concepts of Tribal sovereignty and Indigenous Knowledge to restore forests at the pace and scale needed to mitigate and adapt to rapid climate change.[270] Furthermore, traditional and contemporary Indigenous management practices that support both cultural and spiritual relationships with nature and an equitable climate transition can serve as critical pathways to sustaining ecosystems (KMs 7.3, 16.1).[271] Incorporating local knowledge and Indigenous Peoples in the co-development of restoration activities can produce considerable benefits.[272]

Traceable Accounts

Process Description

The chapter lead author, coordinating lead author, and agency chapter lead authors discussed the Fourth National Climate Assessment (NCA4) ecosystems chapter and brainstormed topics that had emerged since then or were not well covered. The chapter lead author also pulled out key gaps identified from the US Global Change Research Program assessment review document and public comments. A tentative list was compiled of authors with expertise in ecosystems, biodiversity, and ecosystem services; marine, freshwater, and terrestrial systems covering NCA regions; and ecosystem types. The final author team comprised a mix of federal agency scientists and academic experts with varying experience in assessments and past NCAs. Key Messages were developed by the full author team through virtual meetings from fall 2021 through spring 2022, with additional inputs from a public engagement workshop held in January 2022, in which over 100 people participated virtually to suggest topics for review by the chapter. A Youth Dialogues public engagement workshop was held online in February 2022 in partnership with the Youth Environmental Alliance in Higher Education and Rutgers Climate Institute. Federal agency reviews in summer 2022 provided further suggestions for improvement, as did additional public comments and the National Academies review in spring 2023. At the April 2023 in-person meeting in Washington, DC, the author team collectively discussed the wording and confidence levels for the three Key Messages to ensure consensus around the statements.

Since NCA4, a plethora of research has been published describing how ecosystems are changing or are expected to change further in the face of climate change and other stressors, along with numerous specific species and ecosystem services impacts. The evidence base for this report is therefore heavily weighted to peer-reviewed journal articles published in the last five years.

Key Message 8.1

Climate Change Is Driving Rapid Ecosystem Transformations

Description of Evidence Base

Ecosystem Regime Shifts

Many examples of regime shifts resulting from transformative changes are already documented, and the evidence base is strong across multiple ecosystem types,[273] including forest transformations to grassland or woodland following increased wildfires; widespread die-off of pinyon pines from drought and bark beetle infestations; and shifts from healthy kelp forests to urchin barrens due to epizootic disease and marine heatwaves in nearshore marine environments.[144,274,275,276,277,278,279,280] Overall, regime shifts of temperate ecosystems toward more subtropical ones at their southern limits are expected in response to future decreases in the frequency and intensity of extreme cold events.[45] For example, mangrove forests in Florida and along the Gulf Coast are projected to expand northward into present-day salt marshes.[43]

Monitoring

Systematic biodiversity surveys, digitized museum records, and long-term automated data collection have all demonstrated the importance of multiple methods of monitoring of environmental changes through strong evidence bases.[281,282,283,284]

Major Uncertainties and Research Gaps

Complexity of Impacts on Ecosystems

The ability to predict ecological responses to changing climate conditions remains a key gap for most ecosystems because of complex interactions among species, the potential for adaptation (through both evolutionary responses and human activity), and the intersection of climate change with other drivers of change.[36,285,286] For example, warmer temperatures can lead not only to increased forest regeneration and tree growth but also to increased mortality of older trees through wildfires, insects, and disease, with the resulting net impacts highly uncertain.[287] Warmer winters are generally expected to benefit forest pests,[288] but complex interactions among pests, their hosts, and other disturbances can make the combined effects more muted than otherwise expected.[289,290,291] Recent research suggests that multiple disturbances can have counteracting effects, although patterns are not always clear, and sometimes intensified combined effects (synergies) also occur.[292,293]

Monitoring

There are a number of gaps in comprehensive, long-term ecological monitoring to detect changes and to predict the risks of future climate change.[48] Improved knowledge of biological response mechanisms that drive ecological changes[36] will enable better anticipation of ecosystem shifts, especially for systems dominated by long-lived species and where impacts emerge after a time lag;[294,295] this makes eliminating monitoring gaps (e.g., in Arctic and ocean regions) critical. Community monitoring programs are promising but can be biased (e.g., lack of uniform sampling) toward particular regions or species.[296]

Adaptive Management

While adaptive management is widely considered an effective approach for managing uncertainty through learning in order to conserve, manage, and restore ecosystems and species populations,[297] successful implementation is limited by the lack of effective monitoring mechanisms,[298] challenges in dealing with uncertainty, and lack of appropriate institutional mechanisms for its implementation, among other problems.[299,300,301,302] As a result, an adaptive governance approach is increasingly understood as a broader and more promising mechanism for addressing the social and institutional requirements of adaptive management while also facilitating social–ecological transformation.[300,303] However, the adaptive governance approach also has its own conceptual and implementation challenges that need to be addressed in order to enhance success, given insufficient evidence on effective implementation[298] and questions about its capacity to bring about transformational changes.[304] There is also potential for undesirable outcomes, such as inadequate consideration of power and social equity issues.[305,306,307,308] Moreover, there are gaps in research on enhancing the transition process toward adaptive management and governance and associated outcomes,[309] as well as lack of clarity on the synergies and trade-offs among determinants of the capacity for adaptation and transformation.[310,311]

Description of Confidence and Likelihood

A growing body of empirical field studies and monitoring programs shows that climate change, in concert with other stressors, is driving transformational changes across many ecosystems and that changes will accelerate with continued warming (*very likely*, *high confidence*). Given the growing impacts of ecosystem change, the serious implications for human well-being were also considered *very likely*, and the authors assessed *high confidence*, given the empirical studies across multiple ecosystems (i.e., not just projections) showing that a range of well-being impacts are already being experienced across economic, cultural, and social systems. As Chapter 2 has indicated, extreme events are increasing in frequency and/or severity, and these events are more frequently implicated in abrupt ecosystem changes; but because of limited studies examining the direct correlation of extreme events on abrupt ecosystem transformations, the authors assessed only *medium confidence*. The authors also note that adaptive governance frameworks, adaptive management, and monitoring all play a role in helping to cope with climate changes; but given the paucity of evidence of long-term impacts of adaptive governance, the authors assessed only *medium confidence*.

Key Message 8.2

Species Changes and Biodiversity Loss Are Accelerating

Description of Evidence Base

Range Shifts

Shifts in species ranges in response to changing climate occur across a wide range of species and are expected to accelerate.[312,313] The evidence base is strong across a wide range of marine, plant, invertebrate, reptile, bird, and mammal species; selected examples are shown in Figure 8.11, but many more exist. Further, there is strong evidence for the patterns of range shifts differing among types of species; for example, multiple studies have shown that marine species have expanded their ranges more readily than terrestrial species, with shifts in distributions occurring more quickly as well,[314,315] whereas terrestrial species tend to have greater behavioral adaptations and less physiological sensitivity to temperature changes.[316,317,318]

Phenological Changes

The evidence base of documented responses in the timing of life cycles to climate change is strong, ranging from earlier flowering dates in many parts of the country, to shifts in hibernation of mammals, to timing of egg laying of frogs.[319,320] Very rapid changes can be easily observed, for example, in short-lived plants that have high turnover rates and more rapid genetic adaptation,[321] lending strength to the evidence base.

Extinction Risks

Long-term studies (i.e., decades) are needed to discern the fingerprints of climate change on long-lived animals,[322] which can be challenging. But some impacts are in evidence; for example, sea level rise is expected to impact nesting site availability and quality for sea turtles, while warming temperatures can affect sex ratio of offspring.[323,324] Refugia have potential to mitigate some extinction risks for species able to take advantage of them, but the evidence base is fairly new. Further, emerging modeling studies have indicated that these areas, too, are at risk; for example, Ebersole et al. (2020)[127] found that under a 4°C (7.2°F) warming scenario, there was a >50% probability that refugia for freshwater fish species would decrease in area by 42%–77% by 2070.

Disease Risks

Disease risks are occurring as a result of many factors and across different hosts and pathogens; given the large number of potential risks, meta-analyses have been helpful in providing overviews of the evidence base. One comprehensive review of infectious diseases spread between humans and animals found that 58% of diseases worldwide have been exacerbated by climate change (e.g., warming, altered precipitation, and floods).[154] Only 16% of diseases were diminished by climate change. A global analysis of thousands of wildlife populations indicated that climate warming exacerbates wildlife disease throughout the temperate zone worldwide and is expected to increase wildlife disease in the United States.[325] A different global analysis of 6,801 ecological assemblages demonstrated that human-dominated ecosystems strongly favored animal species that host human disease pathogens while decreasing the presence of non-host animals,[326] a strong evidence base for the finding that stressed ecosystems tend to experience more disease risk.[153] Many empirical examples of ongoing disease outbreaks—e.g., fish kills and large-scale coral disease outbreaks following coral bleaching events—have increased in number and are evidence of perturbed aquatic systems where disease stresses are exacerbated by warming.[144,146] The well-documented catastrophic declines in amphibian populations caused by the invasive chytrid fungus *Batrachochytrium dendrobatidis* have also been well linked to warming conditions.[327]

Major Uncertainties and Research Gaps

Range Shifts

The speed and extent of some species range shifts remain uncertain. Climate envelope models use current relationships among species ranges and climatic characteristics to project how ranges may shift in the face of climate change,[328] yet they necessarily assume that climate is the main constraint on ranges and that species rapidly respond. In reality, species responses can be slowed and limited by dispersal ability, natural and human-created barriers, and species interactions.[329,330]

Moreover, climate change is expected to present organisms with novel environmental conditions, making predictions based on historical relationships problematic.[331] Specifically, improving such predictions would require a better understanding of the degree to which range shifts occur due to longer-term climatic changes versus periodic extreme weather events such as heatwaves brought on by those climatic changes.[86]

While climate refugia are increasingly discussed in the literature, they are themselves vulnerable to climate impacts, and there is uncertainty about their persistence and resilience.[126,127]

Phenological Changes

The individual and variable responses of species to climate change is expected to disrupt important biological interactions. Many risks posed by emerging mismatches among interacting species remain unclear,[332] as do needed management responses to reduce economic and social impacts.

Diseases and Invasives

Impacts of climate change on species health are complex and difficult to generalize across systems;[291] for example, the role of climate change among other drivers of the spread of tick-borne diseases, like changes in land use or human behavior, remains a topic of some debate.[152,156]

Studies showing that invasives could be limited in response to climate change are based mostly on studies of terrestrial species whose range shifts are often limited by oceans,[169] indicating that more research is needed on different types of species to improve projections.

Description of Confidence and Likelihood

There is *high confidence* that the interaction of climate change with other stressors will *very likely* lead to biodiversity loss, changes in species distribution and life cycles, and increasing impacts from invasives and diseases, given a very well-documented range of species changes across multiple ecosystem types, as well as clear economic and social consequences in many regions already experiencing these impacts. The evidence is strong, and the authors assessed *high confidence* that some species, particularly those that cannot easily relocate and those that are highly temperature sensitive, are facing heightened extinction risks, and that these are *very likely*, given that some species populations are already in serious decline at current levels of warming. Policy actions to help species adapt were assessed, and what they have in common is a clear identification of risks and prioritization of species and locations for protection. The evidence base for these policy actions is clear, and the authors have *high confidence* that such actions can expand and improve options for management.

Key Message 8.3

Impacts to Ecosystem Services Create Risks and Opportunities

Description of Evidence Base

Access to Ecosystem Services

There is strong evidence that communities of color experience greater air pollution inequity[228,229,230,231] compared to White communities and have reduced and/or less high-quality access to green space, trees, and other ecosystems that buffer these impacts. Limited access to resources and services also extends to those with limited income or wealth (also known as economic capacity), and these factors interact with race and other social hierarchies, including power, in complex ways.[333]

Climate Impacts on Ecosystem Services

There is strong evidence at the global level that warming and carbon dioxide fertilization effects have already altered some ecosystem services, such as coastal carbon storage and ecosystem biodiversity, as noted in the recent Intergovernmental Panel on Climate Change report.[2] For the US, while not all ecosystem services have been quantitatively assessed for climate impacts, those that have been show either currently observable declines (e.g., nearly 40% of pollinator-dependent crops in the US suffer from low pollinator abundance)[334] or projections of future decline (e.g., reduced outdoor recreation opportunities by 2050).[210]

Restoration

Evidence for the effectiveness of restoration at improving ecosystem service benefits is growing as more landscape-scale restoration is undertaken across multiple ecosystems.[263] Additionally, valuation of ecosystem services benefits has proven to be a strong driver of new restoration programs, as it helps identify potential ecosystems to manage or restore (e.g., how health benefits can be obtained from restoration of vegetated terrestrial systems).[262]

Major Uncertainties and Research Gaps

Measurement, Valuation, and Management of Ecosystem Services

There remain challenges in measuring, monitoring, and evaluating the impacts and effectiveness of many ecosystem services.[335] In the US, urban spaces continue to be under-researched, especially in communities of color, despite often being biodiverse environments;[336] and current research is usually limited to city-specific case studies of ecosystem services measurements and analyses, with less focus on comparative work.[248,337] Furthermore, many city planning documents do not include climate change adaptation practices regarding cultural services or environmental injustice in ways that translate to implementation[338] and instead focus on physical and natural resources, costs, or logistics.[247] Research that engages communities, residents, and small organizations in identifying and designing measurements, valuation, and management criteria is a persistent gap, given the continuing lack of resident participatory research and community science in identifying problems and implementing solutions. A few studies have connected multiple types of urban ecosystem services from a theoretical planning point of view,[248,337,339] but integrating justice into ecosystem service practices by prioritizing community needs, aligning methods of assessment and criteria to goals, and addressing environmental racism is a critical gap.[247]

Restoration

There are few examples of ecological restoration practices designed to be resilient to climate change,[340,341] with particular challenges around making decisions about what needs to be "restored"[342] and to what conditions or baseline, as well as how to minimize vulnerability to extreme climate events that may be unprecedented in recent history. There can be spatial disconnects between where restoration actions need to be implemented and where ecosystem service improvements will be observed,[343] and the economic cost of restoration efforts and stakeholder preferences for desired states can prevent recovery efforts.[344]

Nature-Based Solutions (NBSs)

NBSs could cause risks of undesirable outcomes if they entail ecosystem transformations or species introductions over large areas of land; thus, they require careful study prior to implementation to avoid exacerbation of environmental and social injustices.[345,346] There are increasing cases of poorly designed NBSs and rising concern over second-order effects, like green gentrification.[216,217] However, there are considerable research gaps regarding how to avoid these outcomes. Evidence suggests that more stakeholder engagement in carbon removal projects and policies could help maximize adaptation benefits,[347] but this is an area of ongoing research.

Description of Confidence and Likelihood

There is *high confidence* that climate is having variable and growing impacts on many ecosystem services, based on an expanding literature containing many regional examples. These changes are assessed as *very likely*, given the existing levels of warming in areas where impacts have already been observed. There is *high confidence* that these changes in availability and quality of ecosystem services, when combined with existing social inequities that are also well documented, will result in disproportionate impacts on some communities. These disproportionate impacts were assessed as *very likely*, given that impacts are already visible, particularly in urban areas. The authors assessed it to be *likely* that nature-based solutions designed to be equitable can provide multifunctional benefits for climate adaptation and mitigation, although there is only *medium confidence* that current examples of nature-based solutions are able to fully address mitigation and adaptation needs in an equitable manner, given a growing body of evidence that poorly designed or inequitable nature-based solutions do continue to be implemented in some places.

References

1. IPBES, 2019: *Summary for Policymakers of the Global Assessment Report on Biodiversity and Ecosystem Services of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services*. Díaz, S., J. Settele, E.S. Brondízio, H.T. Ngo, M. Guèze, J. Agard, A. Arneth, P. Balvanera, K.A. Brauman, S.H.M. Butchart, K.M.A. Chan, L.A. Garibaldi, K. Ichii, J. Liu, S.M. Subramanian, G.F. Midgley, P. Miloslavich, Z. Molnár, D. Obura, A. Pfaff, S. Polasky, A. Purvis, J. Razzaque, B. Reyers, R. Roy Chowdhury, Y.J. Shin, I.J. Visseren-Hamakers, K.J. Willis, and C.N. Zayas, Eds. IPBES Secretariat, Bonn, Germany, 56 pp. https://www.ipbes.net/sites/default/files/inline/files/ipbes_global_assessment_report_summary_for_policymakers.pdf

2. IPCC, 2022: Summary for policymakers. In: *Climate Change 2022: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Pörtner, H.-O., D.C. Roberts, M. Tignor, E.S. Poloczanska, K. Mintenbeck, A. Alegría, M. Craig, S. Langsdorf, S. Löschke, V. Möller, A. Okem, and B. Rama, Eds. Cambridge University Press, Cambridge, UK and New York, NY, USA, 3–33. https://doi.org/10.1017/9781009325844.001

3. Pecl, G.T., M.B. Araújo, J.D. Bell, J. Blanchard, T.C. Bonebrake, I.-C. Chen, T.D. Clark, R.K. Colwell, F. Danielsen, B. Evengård, L. Falconi, S. Ferrier, S. Frusher, R.A. Garcia, R.B. Griffis, A.J. Hobday, C. Janion-Scheepers, M.A. Jarzyna, S. Jennings, J. Lenoir, H.I. Linnetved, V.Y. Martin, P.C. McCormack, J. McDonald, N.J. Mitchell, T. Mustonen, J.M. Pandolfi, N. Pettorelli, E. Popova, S.A. Robinson, B.R. Scheffers, J.D. Shaw, C.J.B. Sorte, J.M. Strugnell, J.M. Sunday, M.-N. Tuanmu, A. Vergés, C. Villanueva, T. Wernberg, E. Wapstra, and S.E. Williams, 2017: Biodiversity redistribution under climate change: Impacts on ecosystems and human well-being. *Science*, **355** (6332), eaai9214. https://doi.org/10.1126/science.aai9214

4. Finney, C., 2014: *Black Faces, White Spaces: Reimagining the Relationship of African Americans to the Great Outdoors*. UNC Press, Chapel Hill, NC. https://uncpress.org/book/9781469614489/black-faces-white-spaces/

5. Whyte, K., 2020: Too late for Indigenous climate justice: Ecological and relational tipping points. *WIREs Climate Change*, **11** (1), e603. https://doi.org/10.1002/wcc.603

6. Weiskopf, S.R., M.A. Rubenstein, L.G. Crozier, S. Gaichas, R. Griffis, J.E. Halofsky, K.J. Hyde, T.L. Morelli, J.T. Morisette, R.C. Muñoz, A.J. Pershing, D.L. Petersone, R. Poudel, M.D. Staudinger, A.E. Sutton-Grier, L. Thompson, J. Vose, J.F. Weltzin, and K.P. Whyte, 2020: Climate change effects on biodiversity, ecosystems, ecosystem services, and natural resource management in the United States. *Science of The Total Environment*, **733**, 137782. https://doi.org/10.1016/j.scitotenv.2020.137782

7. Prober, S.M., V.A.J. Doerr, L.M. Broadhurst, K.J. Williams, and F. Dickson, 2019: Shifting the conservation paradigm: A synthesis of options for renovating nature under climate change. *Ecological Monographs*, **89** (1), e01333. https://doi.org/10.1002/ecm.1333

8. Lipton, D., M. Rubenstein, S.R. Weiskopf, S. Carter, J. Peterson, L. Crozier, M. Fogarty, S. Gaichas, K.J.W. Hyde, T.L. Morelli, J. Morisette, H. Moustahfid, R. Muñoz, R. Poudel, M.D. Staudinger, C. Stock, L. Thompson, R. Waples, and J.F. Weltzin, 2018: Ch. 7. Ecosystems, ecosystem services, and biodiversity. In: *Impacts, Risks, and Adaptation in the United States: Fourth National Climate Assessment, Volume II*. Reidmiller, D.R., C.W. Avery, D. Easterling, K. Kunkel, K.L.M. Lewis, T.K. Maycock, and B.C. Stewart, Eds. U.S. Global Change Research Program, Washington, DC, USA, 268–321. https://doi.org/10.7930/nca4.2018.ch7

9. Panetta, A.M., M.L. Stanton, and J. Harte, 2018: Climate warming drives local extinction: Evidence from observation and experimentation. *Science Advances*, **4** (2), 1819. https://doi.org/10.1126/sciadv.aaq1819

10. Román-Palacios, C. and J.J. Wiens, 2020: Recent responses to climate change reveal the drivers of species extinction and survival. *Proceedings of the National Academy of Sciences of the United States of America*, **117** (8), 4211–4217. https://doi.org/10.1073/pnas.1913007117

11. Parmesan, C., M.D. Morecroft, Y. Trisurat, R. Adrian, G.Z. Anshari, A. Arneth, Q. Gao, P. Gonzalez, R. Harris, J. Price, N. Stevens, and G.H. Talukdarr, 2022: Ch. 2. Terrestrial and freshwater ecosystems and their services. In: *Climate Change 2022: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Pörtner, H.-O., D.C. Roberts, M. Tignor, E.S. Poloczanska, K. Mintenbeck, A. Alegría, M. Craig, S. Langsdorf, S. Löschke, V. Möller, A. Okem, and B. Rama, Eds. Cambridge University Press, Cambridge, UK and New York, NY, USA, 197–377. https://doi.org/10.1017/9781009325844.004

12. Warren, R., J. Price, E. Graham, N. Forstenhaeusler, and J. VanDerWal, 2018: The projected effect on insects, vertebrates, and plants of limiting global warming to 1.5°C rather than 2°C. *Science*, **360** (6390), 791–795. https://doi.org/10.1126/science.aar3646

13. Doney, S.C., V.J. Fabry, R.A. Feely, and J.A. Kleypas, 2009: Ocean acidification: The other CO_2 problem. *Annual Review of Marine Science*, **1** (1), 169–192. https://doi.org/10.1146/annurev.marine.010908.163834

14. Bradford, J.B., J.L. Betancourt, B.J. Butterfield, S.M. Munson, and T.E. Wood, 2018: Anticipatory natural resource science and management for a changing future. *Frontiers in Ecology and the Environment*, **16** (5), 295–303. https://doi.org/10.1002/fee.1806

15. Malhi, Y., J. Franklin, N. Seddon, M. Solan, M.G. Turner, C.B. Field, and N. Knowlton, 2020: Climate change and ecosystems: Threats, opportunities and solutions. *Philosophical Transactions of the Royal Society B: Biological Sciences*, **375** (1794), 20190104. https://doi.org/10.1098/rstb.2019.0104

16. Reside, A.E., N. Butt, and V.M. Adams, 2018: Adapting systematic conservation planning for climate change. *Biodiversity and Conservation*, **27** (1), 1–29. https://doi.org/10.1007/s10531-017-1442-5

17. Harris, R.M.B., L.J. Beaumont, T.R. Vance, C.R. Tozer, T.A. Remenyi, S.E. Perkins-Kirkpatrick, P.J. Mitchell, A.B. Nicotra, S. McGregor, N.R. Andrew, M. Letnic, M.R. Kearney, T. Wernberg, L.B. Hutley, L.E. Chambers, M.S. Fletcher, M.R. Keatley, C.A. Woodward, G. Williamson, N.C. Duke, and D.M.J.S. Bowman, 2018: Biological responses to the press and pulse of climate trends and extreme events. *Nature Climate Change*, **8** (7), 579–587. https://doi.org/10.1038/s41558-018-0187-9

18. Zhou, S., B. Yu, and Y. Zhang, 2023: Global concurrent climate extremes exacerbated by anthropogenic climate change. *Science Advances*, **9** (10), 1638. https://doi.org/10.1126/sciadv.abo1638

19. Ibanez, T., W.J. Platt, P.J. Bellingham, G. Vieilledent, J. Franklin, P.H. Martin, C. Menkes, D.R. Pérez-Salicrup, J. Russell-Smith, and G. Keppel, 2022: Altered cyclone–fire interactions are changing ecosystems. *Trends in Plant Science*, **27** (12), 1218–1230. https://doi.org/10.1016/j.tplants.2022.08.005

20. Smith-Martin, C.M., R. Muscarella, R. Ankori-Karlinsky, S. Delzon, S.L. Farrar, M. Salva-Sauri, J. Thompson, J.K. Zimmerman, and M. Uriarte, 2022: Hurricanes increase tropical forest vulnerability to drought. *New Phytologist*, **235** (3), 1005–1017. https://doi.org/10.1111/nph.18175

21. Michalak, A.M., E.J. Anderson, D. Beletsky, S. Boland, N.S. Bosch, T.B. Bridgeman, J.D. Chaffin, K. Cho, R. Confesor, I. Daloğlu, J.V. DePinto, M.A. Evans, G.L. Fahnenstiel, L. He, J.C. Ho, L. Jenkins, T.H. Johengen, K.C. Kuo, E. LaPorte, X. Liu, M.R. McWilliams, M.R. Moore, D.J. Posselt, R.P. Richards, D. Scavia, A.L. Steiner, E. Verhamme, D.M. Wright, and M.A. Zagorski, 2013: Record-setting algal bloom in Lake Erie caused by agricultural and meteorological trends consistent with expected future conditions. *Proceedings of the National Academy of Sciences of the United States of America*, **110** (16), 6448–6452. https://doi.org/10.1073/pnas.1216006110

22. Guiterman, C.H., R.M. Gregg, L.A.E. Marshall, J.J. Beckmann, P.J. van Mantgem, D.A. Falk, J.E. Keeley, A.C. Caprio, J.D. Coop, P.J. Fornwalt, C. Haffey, R.K. Hagmann, S.T. Jackson, A.M. Lynch, E.Q. Margolis, C. Marks, M.D. Meyer, H. Safford, A.D. Syphard, A. Taylor, C. Wilcox, D. Carril, C.A.F. Enquist, D. Huffman, J. Iniguez, N.A. Molinari, C. Restaino, and J.T. Stevens, 2022: Vegetation type conversion in the US Southwest: Frontline observations and management responses. *Fire Ecology*, **18** (1), 6. https://doi.org/10.1186/s42408-022-00131-w

23. Belote, R.T., C. Carroll, S. Martinuzzi, J. Michalak, J.W. Williams, M.A. Williamson, and G.H. Aplet, 2018: Assessing agreement among alternative climate change projections to inform conservation recommendations in the contiguous United States. *Scientific Reports*, **8** (1), 9441. https://doi.org/10.1038/s41598-018-27721-6

24. Michalak, J.L., J.C. Withey, J.J. Lawler, and M.J. Case, 2017: Future climate vulnerability—Evaluating multiple lines of evidence. *Frontiers in Ecology and the Environment*, **15** (7), 367–376. https://doi.org/10.1002/fee.1516

25. Heinze, C., T. Blenckner, H. Martins, D. Rusiecka, R. Döscher, M. Gehlen, N. Gruber, E. Holland, Ø. Hov, F. Joos, J.B.R. Matthews, R. Rødven, and S. Wilson, 2021: The quiet crossing of ocean tipping points. *Proceedings of the National Academy of Sciences of the United States of America*, **118** (9), e2008478118. https://doi.org/10.1073/pnas.2008478118

26. Selkoe, K.A., T. Blenckner, M.R. Caldwell, L.B. Crowder, A.L. Erickson, T.E. Essington, J.A. Estes, R.M. Fujita, B.S. Halpern, M.E. Hunsicker, C.V. Kappel, R.P. Kelly, J.N. Kittinger, P.S. Levin, J.M. Lynham, M.E. Mach, R.G. Martone, L.A. Mease, A.K. Salomon, J.F. Samhouri, C. Scarborough, A.C. Stier, C. White, and J. Zedler, 2015: Principles for managing marine ecosystems prone to tipping points. *Ecosystem Health and Sustainability*, **1** (5), 1–18. https://doi.org/10.1890/ehs14-0024.1

27. Hillebrand, H., I. Donohue, W.S. Harpole, D. Hodapp, M. Kucera, A.M. Lewandowska, J. Merder, J.M. Montoya, and J.A. Freund, 2020: Thresholds for ecological responses to global change do not emerge from empirical data. *Nature Ecology & Evolution*, **4** (11), 1502–1509. https://doi.org/10.1038/s41559-020-1256-9

28. Langer, M., T.S. von Deimling, S. Westermann, R. Rolph, R. Rutte, S. Antonova, V. Rachold, M. Schultz, A. Oehme, and G. Grosse, 2023: Thawing permafrost poses environmental threat to thousands of sites with legacy industrial contamination. *Nature Communications*, **14** (1), 1721. https://doi.org/10.1038/s41467-023-37276-4

29. Miner, K.R., J. D'Andrilli, R. Mackelprang, A. Edwards, M.J. Malaska, M.P. Waldrop, and C.E. Miller, 2021: Emergent biogeochemical risks from Arctic permafrost degradation. *Nature Climate Change*, **11** (10), 809–819. https://doi.org/10.1038/s41558-021-01162-y

30. Schuur, E.A.G., B.W. Abbott, R. Commane, J. Ernakovich, E. Euskirchen, G. Hugelius, G. Grosse, M. Jones, C. Koven, V. Leshyk, D. Lawrence, M.M. Loranty, M. Mauritz, D. Olefeldt, S. Natali, H. Rodenhizer, V. Salmon, C. Schädel, J. Strauss, C. Treat, and M. Turetsky, 2022: Permafrost and climate change: Carbon cycle feedbacks from the warming Arctic. *Annual Review of Environment and Resources*, **47** (1), 343–371. https://doi.org/10.1146/annurev-environ-012220-011847

31. Ratajczak, Z., S.R. Carpenter, A.R. Ives, C.J. Kucharik, T. Ramiadantsoa, M.A. Stegner, J.W. Williams, J. Zhang, and M.G. Turner, 2018: Abrupt change in ecological systems: Inference and diagnosis. *Trends in Ecology & Evolution*, **33** (7), 513–526. https://doi.org/10.1016/j.tree.2018.04.013

32. Marshall, L.A. and D.A. Falk, 2020: Demographic trends in community functional tolerance reflect tree responses to climate and altered fire regimes. *Ecological Applications*, **30** (8), e02197. https://doi.org/10.1002/eap.2197

33. Hughes, T.P., J.T. Kerry, A.H. Baird, S.R. Connolly, T.J. Chase, A. Dietzel, T. Hill, A.S. Hoey, M.O. Hoogenboom, M. Jacobson, A. Kerswell, J.S. Madin, A. Mieog, A.S. Paley, M.S. Pratchett, G. Torda, and R.M. Woods, 2019: Global warming impairs stock–recruitment dynamics of corals. *Nature*, **568** (7752), 387–390. https://doi.org/10.1038/s41586-019-1081-y

34. Hughes, T.P., J.T. Kerry, A.H. Baird, S.R. Connolly, A. Dietzel, C.M. Eakin, S.F. Heron, A.S. Hoey, M.O. Hoogenboom, G. Liu, M.J. McWilliam, R.J. Pears, M.S. Pratchett, W.J. Skirving, J.S. Stella, and G. Torda, 2018: Global warming transforms coral reef assemblages. *Nature*, **556** (7702), 492–496. https://doi.org/10.1038/s41586-018-0041-2

35. Williams, J.W., A. Ordonez, and J.-C. Svenning, 2021: A unifying framework for studying and managing climate-driven rates of ecological change. *Nature Ecology & Evolution*, **5** (1), 17–26. https://doi.org/10.1038/s41559-020-01344-5

36. Turner, M.G., W.J. Calder, G.S. Cumming, T.P. Hughes, A. Jentsch, S.L. LaDeau, T.M. Lenton, B.N. Shuman, M.R. Turetsky, Z. Ratajczak, J.W. Williams, A.P. Williams, and S.R. Carpenter, 2020: Climate change, ecosystems and abrupt change: Science priorities. *Philosophical Transactions of the Royal Society B: Biological Sciences*, **375** (1794), 20190105. https://doi.org/10.1098/rstb.2019.0105

37. Svejcar, L.N., J.D. Kerby, T.J. Svejcar, B. Mackey, C.S. Boyd, O.W. Baughman, M.D. Madsen, and K.W. Davies, 2023: Plant recruitment in drylands varies by site, year, and seeding technique. *Restoration Ecology*, **31** (2), e13750. https://doi.org/10.1111/rec.13750

38. Foley, M.M., R.G. Martone, M.D. Fox, C.V. Kappel, L.A. Mease, A.L. Erickson, B.S. Halpern, K.A. Selkoe, P. Taylor, and C. Scarborough, 2015: Using ecological thresholds to inform resource management: Current options and future possibilities. *Frontiers in Marine Science*, **2**, 95. https://doi.org/10.3389/fmars.2015.00095

39. Johnstone, J.F., C.D. Allen, J.F. Franklin, L.E. Frelich, B.J. Harvey, P.E. Higuera, M.C. Mack, R.K. Meentemeyer, M.R. Metz, G.L.W. Perry, T. Schoennagel, and M.G. Turner, 2016: Changing disturbance regimes, ecological memory, and forest resilience. *Frontiers in Ecology and the Environment*, **14** (7), 369–378. https://doi.org/10.1002/fee.1311

40. Hutchison, C., D. Gravel, F. Guichard, and C. Potvin, 2018: Effect of diversity on growth, mortality, and loss of resilience to extreme climate events in a tropical planted forest experiment. *Scientific Reports*, **8** (1), 15443. https://doi.org/10.1038/s41598-018-33670-x

41. Isbell, F., D. Craven, J. Connolly, M. Loreau, B. Schmid, C. Beierkuhnlein, T.M. Bezemer, C. Bonin, H. Bruelheide, E. de Luca, A. Ebeling, J.N. Griffin, Q. Guo, Y. Hautier, A. Hector, A. Jentsch, J. Kreyling, V. Lanta, P. Manning, S.T. Meyer, A.S. Mori, S. Naeem, P.A. Niklaus, H.W. Polley, P.B. Reich, C. Roscher, E.W. Seabloom, M.D. Smith, M.P. Thakur, D. Tilman, B.F. Tracy, W.H. van der Putten, J. van Ruijven, A. Weigelt, W.W. Weisser, B. Wilsey, and N. Eisenhauer, 2015: Biodiversity increases the resistance of ecosystem productivity to climate extremes. *Nature*, **526** (7574), 574–577. https://doi.org/10.1038/nature15374

42. Farr, E.R., M.R. Johnson, M.W. Nelson, J.A. Hare, W.E. Morrison, M.D. Lettrich, B. Vogt, C. Meaney, U.A. Howson, P.J. Auster, F.A. Borsuk, D.C. Brady, M.J. Cashman, P. Colarusso, J.H. Grabowski, J.P. Hawkes, R. Mercaldo-Allen, D.B. Packer, and D.K. Stevenson, 2021: An assessment of marine, estuarine, and riverine habitat vulnerability to climate change in the Northeast U.S. *PLoS ONE*, **16** (12), e0260654. https://doi.org/10.1371/journal.pone.0260654

43. Osland, M.J., R.H. Day, and T.C. Michot, 2020: Frequency of extreme freeze events controls the distribution and structure of black mangroves (*Avicennia germinans*) near their northern range limit in coastal Louisiana. *Diversity and Distributions*, **26** (10), 1366–1382. https://doi.org/10.1111/ddi.13119

44. Osland, M.J., A.R. Hughes, A.R. Armitage, S.B. Scyphers, J. Cebrian, S.H. Swinea, C.C. Shepard, M.S. Allen, L.C. Feher, J.A. Nelson, C.L. O'Brien, Colt R. Sanspree, D.L. Smee, C.M. Snyder, A.P. Stetter, Philip W. Stevens, K.M. Swanson, L.H. Williams, Janell M. Brush, J. Marchionno, and R. Bardou, 2022: The impacts of mangrove range expansion on wetland ecosystem services in the southeastern United States: Current understanding, knowledge gaps, and emerging research needs. *Global Change Biology*, **28** (10), 3163–3187. https://doi.org/10.1111/gcb.16111

45. Osland, M.J., P.W. Stevens, M.M. Lamont, R.C. Brusca, K.M. Hart, J.H. Waddle, C.A. Langtimm, C.M. Williams, B.D. Keim, A.J. Terando, E.A. Reyier, K.E. Marshall, M.E. Loik, R.E. Boucek, A.B. Lewis, and J.A. Seminoff, 2021: Tropicalization of temperate ecosystems in North America: The northward range expansion of tropical organisms in response to warming winter temperatures. *Global Change Biology*, **27** (13), 3009–3034. https://doi.org/10.1111/gcb.15563

46. Ury, E.A., X. Yang, J.P. Wright, and E.S. Bernhardt, 2021: Rapid deforestation of a coastal landscape driven by sea-level rise and extreme events. *Ecological Applications*, **31** (5), e02339. https://doi.org/10.1002/eap.2339

47. Barnard, P.L., J.E. Dugan, H.M. Page, N.J. Wood, J.A.F. Hart, D.R. Cayan, L.H. Erikson, D.M. Hubbard, M.R. Myers, J.M. Melack, and S.F. Iacobellis, 2021: Multiple climate change-driven tipping points for coastal systems. *Scientific Reports*, **11** (1), 15560. https://doi.org/10.1038/s41598-021-94942-7

48. Malhi, Y., C. Girardin, D.B. Metcalfe, C.E. Doughty, L.E.O.C. Aragão, S.W. Rifai, I. Oliveras, A. Shenkin, J. Aguirre-Gutiérrez, C.A.L. Dahlsjö, T. Riutta, E. Berenguer, S. Moore, W.H. Huasco, N. Salinas, A.C.L. da Costa, L.P. Bentley, S. Adu-Bredu, T.R. Marthews, P. Meir, and O.L. Phillips, 2021: The Global Ecosystems Monitoring network: Monitoring ecosystem productivity and carbon cycling across the tropics. *Biological Conservation*, **253**, 108889. https://doi.org/10.1016/j.biocon.2020.108889

49. Scheffer, M., S.R. Carpenter, V. Dakos, and E.H. van Nes, 2015: Generic indicators of ecological resilience: Inferring the chance of a critical transition. *Annual Review of Ecology, Evolution, and Systematics*, **46** (1), 145–167. https://doi.org/10.1146/annurev-ecolsys-112414-054242

50. Jones, J.A. and C.T. Driscoll, 2022: Long-term ecological research on ecosystem responses to climate change. *BioScience*, **72** (9), 814–826. https://doi.org/10.1093/biosci/biac021

51. Unger, S., M. Rollins, A. Tietz, and H. Dumais, 2021: iNaturalist as an engaging tool for identifying organisms in outdoor activities. *Journal of Biological Education*, **55** (5), 537–547. https://doi.org/10.1080/00219266.2020.1739114

52. Crimmins, T., E. Denny, E. Posthumus, A. Rosemartin, R. Croll, M. Montano, and H. Panci, 2022: Science and management advancements made possible by the USA National Phenology network's nature's notebook platform. *BioScience*, **72** (9), 908–920. https://doi.org/10.1093/biosci/biac061

53. Danielsen, F., H. Eicken, M. Funder, N. Johnson, O. Lee, I. Theilade, D. Argyriou, and N.D. Burgess, 2022: Community monitoring of natural resource systems and the environment. *Annual Review of Environment and Resources*, **47** (1), 637–670. https://doi.org/10.1146/annurev-environ-012220-022325

54. Pearson, J., G. Jackson, and K.E. McNamara, 2023: Climate-driven losses to Indigenous and local knowledge and cultural heritage. *The Anthropocene Review*, **10** (2), 343–366. https://doi.org/10.1177/20530196211005482

55. McKinley, D.C., A.J. Miller-Rushing, H.L. Ballard, R. Bonney, H. Brown, S.C. Cook-Patton, D.M. Evans, R.A. French, J.K. Parrish, T.B. Phillips, S.F. Ryan, L.A. Shanley, J.L. Shirk, K.F. Stepenuck, J.F. Weltzin, A. Wiggins, O.D. Boyle, R.D. Briggs, S.F. Chapin, D.A. Hewitt, P.W. Preuss, and M.A. Soukup, 2017: Citizen science can improve conservation science, natural resource management, and environmental protection. *Biological Conservation*, **208**, 15–28. https://doi.org/10.1016/j.biocon.2016.05.015

56. Currie, D.J. and S. Venne, 2017: Climate change is not a major driver of shifts in the geographical distributions of North American birds. *Global Ecology and Biogeography*, **26** (3), 333–346. https://doi.org/10.1111/geb.12538

57. Valle, D., P. Albuquerque, Q. Zhao, A. Barberan, and R.J. Fletcher Jr., 2018: Extending the Latent Dirichlet Allocation model to presence/absence data: A case study on North American breeding birds and biogeographical shifts expected from climate change. *Global Change Biology*, **24** (11), 5560–5572. https://doi.org/10.1111/gcb.14412

58. Wang, J., D. Liu, P. Ciais, and J. Peñuelas, 2022: Decreasing rainfall frequency contributes to earlier leaf onset in northern ecosystems. *Nature Climate Change*, **12**, 386–392. https://doi.org/10.1038/s41558-022-01285-w

59. Nolan, C., J.T. Overpeck, J.R.M. Allen, P.M. Anderson, J.L. Betancourt, H.A. Binney, S. Brewer, M.B. Bush, B.M. Chase, R. Cheddadi, M. Djamali, J. Dodson, M.E. Edwards, W.D. Gosling, S. Haberle, S.C. Hotchkiss, B. Huntley, S.J. Ivory, A.P. Kershaw, S.-H. Kim, C. Latorre, M. Leydet, A.-M. Lézine, K.-B. Liu, Y. Liu, A.V. Lozhkin, M.S. McGlone, R.A. Marchant, A. Momohara, P.I. Moreno, S. Müller, B.L. Otto-Bliesner, C. Shen, J. Stevenson, H. Takahara, P.E. Tarasov, J. Tipton, A. Vincens, C. Weng, Q. Xu, Z. Zheng, and S.T. Jackson, 2018: Past and future global transformation of terrestrial ecosystems under climate change. *Science*, **361** (6405), 920–923. https://doi.org/10.1126/science.aan5360

60. Chambers, J.C., C.R. Allen, and S.A. Cushman, 2019: Operationalizing ecological resilience concepts for managing species and ecosystems at risk. *Frontiers in Ecology and Evolution*, **7**, 241. https://doi.org/10.3389/fevo.2019.00241

61. França, F.M., C.E. Benkwitt, G. Peralta, J.P.W. Robinson, N.A.J. Graham, J.M. Tylianakis, E. Berenguer, A.C. Lees, J. Ferreira, J. Louzada, and J. Barlow, 2020: Climatic and local stressor interactions threaten tropical forests and coral reefs. *Philosophical Transactions of the Royal Society B: Biological Sciences*, **375** (1794), 20190116. https://doi.org/10.1098/rstb.2019.0116

62. Schuurman, G.W., C.H. Hoffman, D.N. Cole, D.J. Lawrence, J.M. Morton, D.R. Magness, A.E. Cravens, S. Covington, R. O'Malley, and N.A. Fisichelli, 2020: Resist-Accept-Direct (RAD)—A Framework for the 21st-Century Natural Resource Manager. Natural Resource Report. NPS/NRSS/CCRP/NRR—2020/2213. U.S. Department of the Interior, National Park Service, Fort Collins, CO. https://doi.org/10.36967/nrr-2283597

63. Akamani, K., 2016: Adaptive water governance: Integrating the human dimensions into water resource governance. *Journal of Contemporary Water Research & Education*, **158** (1), 2–18. https://doi.org/10.1111/j.1936-704x.2016.03215.x

64. Pahl-Wostl, C., 2019: The role of governance modes and meta-governance in the transformation towards sustainable water governance. *Environmental Science & Policy*, **91**, 6–16. https://doi.org/10.1016/j.envsci.2018.10.008

65. Pahl-Wostl, C., C. Knieper, E. Lukat, F. Meergans, M. Schoderer, N. Schütze, D. Schweigatz, I. Dombrowsky, A. Lenschow, U. Stein, A. Thiel, J. Tröltzsch, and R. Vidaurre, 2020: Enhancing the capacity of water governance to deal with complex management challenges: A framework of analysis. *Environmental Science & Policy*, **107**, 23–35. https://doi.org/10.1016/j.envsci.2020.02.011

66. Akamani, K., 2021: An ecosystem-based approach to climate-smart agriculture with some considerations for social equity. *Agronomy*, **11** (8), 1564. https://doi.org/10.3390/agronomy11081564

67. Hörl, J., K. Keller, and R. Yousefpour, 2020: Reviewing the performance of adaptive forest management strategies with robustness analysis. *Forest Policy and Economics*, **119**, 102289. https://doi.org/10.1016/j.forpol.2020.102289

68. Akamani, K., 2020: Integrating deep ecology and adaptive governance for sustainable development: Implications for protected areas management. *Sustainability*, **12** (14), 5757. https://doi.org/10.3390/su12145757

69. Dietz, T., 2013: Bringing values and deliberation to science communication. *Proceedings of the National Academy of Sciences of the United States of America*, **110** (Supplement_3), 14081–14087. https://doi.org/10.1073/pnas.1212740110

70. Romsdahl, R., G. Blue, and A. Kirilenko, 2018: Action on climate change requires deliberative framing at local governance level. *Climatic Change*, **149** (3), 277–287. https://doi.org/10.1007/s10584-018-2240-0

71. Magness, D.R., L. Hoang, R.T. Belote, J. Brennan, W. Carr, F. Stuart Chapin, III, K. Clifford, W. Morrison, J.M. Morton, and H.R. Sofaer, 2022: Management foundations for navigating ecological transformation by resisting, accepting, or directing social–ecological change. *BioScience*, **72** (1), 30–44. https://doi.org/10.1093/biosci/biab083

72. Lynch, A.J., L.M. Thompson, J.M. Morton, E.A. Beever, M. Clifford, D. Limpinsel, R.T. Magill, D.R. Magness, T.A. Melvin, R.A. Newman, M.T. Porath, F.J. Rahel, J.H. Reynolds, G.W. Schuurman, S.A. Sethi, and J.L. Wilkening, 2022: RAD adaptive management for transforming ecosystems. *BioScience*, **72** (1), 45–56. https://doi.org/10.1093/biosci/biab091

73. Magness, D.R., E. Wagener, E. Yurcich, R. Mollnow, D. Granfors, and J.L. Wilkening, 2022: A multi-scale blueprint for building the decision context to implement climate change adaptation on national wildlife refuges in the United States. *Earth*, **3** (1), 136–156. https://doi.org/10.3390/earth3010011

74. West, J.M., C.A. Courtney, A.T. Hamilton, B.A. Parker, D.A. Gibbs, P. Bradley, and S.H. Julius, 2018: Adaptation design tool for climate-smart management of coral reefs and other natural resources. *Environmental Management*, **62** (4), 644–664. https://doi.org/10.1007/s00267-018-1065-y

75. West, J.M., C.A. Courtney, A.T. Hamilton, B.A. Parker, S.H. Julius, J. Hoffman, K.H. Koltes, and P. MacGowan, 2017: Climate-smart design for ecosystem management: A test application for coral reefs. *Environmental management*, **59** (1), 102–117. https://doi.org/10.1007/s00267-016-0774-3

76. Caro, T., Z. Rowe, J. Berger, P. Wholey, and A. Dobson, 2022: An inconvenient misconception: Climate change is not the principal driver of biodiversity loss. *Conservation Letters*, **15** (3), e12868. https://doi.org/10.1111/conl.12868

77. Jaureguiberry, P., N. Titeux, M. Wiemers, D.E. Bowler, L. Coscieme, A.S. Golden, C.A. Guerra, U. Jacob, Y. Takahashi, J. Settele, S. Díaz, Z. Molnár, and A. Purvis, 2022: The direct drivers of recent global anthropogenic biodiversity loss. *Science Advances*, **8** (45), 9982. https://doi.org/10.1126/sciadv.abm9982

78. Pansch, C., M. Scotti, F.R. Barboza, B. Al-Janabi, J. Brakel, E. Briski, B. Bucholz, M. Franz, M. Ito, F. Paiva, M. Saha, Y. Sawall, F. Weinberger, and M. Wahl, 2018: Heat waves and their significance for a temperate benthic community: A near-natural experimental approach. *Global Change Biology*, **24** (9), 4357–4367. https://doi.org/10.1111/gcb.14282

79. Peterson Williams, M.J., B. Robbins Gisclair, E. Cerny-Chipman, M. LeVine, and T. Peterson, 2022: The heat is on: Gulf of Alaska Pacific cod and climate-ready fisheries. *ICES Journal of Marine Science*, **79** (2), 573–583. https://doi.org/10.1093/icesjms/fsab032

80. Richards, R.A. and M. Hunter, 2021: Northern shrimp *Pandalus borealis* population collapse linked to climate-driven shifts in predator distribution. *PLoS ONE*, **16** (7), e0253914. https://doi.org/10.1371/journal.pone.0253914

81. Carlson, R.R., S.A. Foo, and G.P. Asner, 2019: Land use impacts on coral reef health: A ridge-to-reef perspective. *Frontiers in Marine Science*, **6**, 562. https://doi.org/10.3389/fmars.2019.00562

82. Evensen, N.R., Y.-M. Bozec, P.J. Edmunds, and P.J. Mumby, 2021: Scaling the effects of ocean acidification on coral growth and coral–coral competition on coral community recovery. *PeerJ*, **9**, e11608. https://doi.org/10.7717/peerj.11608

83. Johnson, M.D., J.J. Scott, M. Leray, N. Lucey, L.M.R. Bravo, W.L. Wied, and A.H. Altieri, 2021: Rapid ecosystem-scale consequences of acute deoxygenation on a Caribbean coral reef. *Nature Communications*, **12** (1), 4522. https://doi.org/10.1038/s41467-021-24777-3

84. Magel, J.M.T., J.H.R. Burns, R.D. Gates, and J.K. Baum, 2019: Effects of bleaching-associated mass coral mortality on reef structural complexity across a gradient of local disturbance. *Scientific Reports*, **9** (1), 2512. https://doi.org/10.1038/s41598-018-37713-1

85. Sampaio, E., C. Santos, I.C. Rosa, V. Ferreira, H.-O. Pörtner, C.M. Duarte, L.A. Levin, and R. Rosa, 2021: Impacts of hypoxic events surpass those of future ocean warming and acidification. *Nature Ecology & Evolution*, **5** (3), 311–321. https://doi.org/10.1038/s41559-020-01370-3

86. Smale, D.A., T. Wernberg, E.C.J. Oliver, M. Thomsen, B.P. Harvey, S.C. Straub, M.T. Burrows, L.V. Alexander, J.A. Benthuysen, M.G. Donat, M. Feng, A.J. Hobday, N.J. Holbrook, S.E. Perkins-Kirkpatrick, H.A. Scannell, A. Sen Gupta, B.L. Payne, and P.J. Moore, 2019: Marine heatwaves threaten global biodiversity and the provision of ecosystem services. *Nature Climate Change*, **9** (4), 306–312. https://doi.org/10.1038/s41558-019-0412-1

87. Kelly, L.T., K.M. Giljohann, A. Duane, N. Aquilué, S. Archibald, E. Batllori, A.F. Bennett, S.T. Buckland, Q. Canelles, M.F. Clarke, M.-J. Fortin, V. Hermoso, S. Herrando, R.E. Keane, F.K. Lake, M.A. McCarthy, A. Morán-Ordóñez, C.L. Parr, J.G. Pausas, T.D. Penman, A. Regos, L. Rumpff, J.L. Santos, A.L. Smith, A.D. Syphard, M.W. Tingley, and L. Brotons, 2020: Fire and biodiversity in the Anthropocene. *Science*, **370** (6519), 0355. https://doi.org/10.1126/science.abb0355

88. Jager, H.I., J.W. Long, R.L. Malison, B.P. Murphy, A. Rust, L.G.M. Silva, R. Sollmann, Z.L. Steel, M.D. Bowen, J.B. Dunham, J.L. Ebersole, and R.L. Flitcroft, 2021: Resilience of terrestrial and aquatic fauna to historical and future wildfire regimes in western North America. *Ecology and Evolution*, **11** (18), 12259–12284. https://doi.org/10.1002/ece3.8026

89. Jones, N.P., L. Kabay, K. Semon Lunz, and D.S. Gilliam, 2021: Temperature stress and disease drives the extirpation of the threatened pillar coral, *Dendrogyra cylindrus*, in southeast Florida. *Scientific Reports*, **11** (1), 14113. https://doi.org/10.1038/s41598-021-93111-0

90. Cohen, J.M., M.J. Lajeunesse, and J.R. Rohr, 2018: A global synthesis of animal phenological responses to climate change. *Nature Climate Change*, **8** (3), 224–228. https://doi.org/10.1038/s41558-018-0067-3

91. Franklin, K.A., M.A.C. Nicoll, S.J. Butler, K. Norris, N. Ratcliffe, S. Nakagawa, and J.A. Gill, 2022: Individual repeatability of avian migration phenology: A systematic review and meta-analysis. *Journal of Animal Ecology*, **91** (7), 1416–1430. https://doi.org/10.1111/1365-2656.13697

92. Inouye, D.W., 2022: Climate change and phenology. *WIREs Climate Change*, **13** (3), e764. https://doi.org/10.1002/wcc.764

93. Bai, H., D. Xiao, H. Zhang, F. Tao, and Y. Hu, 2019: Impact of warming climate, sowing date, and cultivar shift on rice phenology across China during 1981–2010. *International Journal of Biometeorology*, **63** (8), 1077–1089. https://doi.org/10.1007/s00484-019-01723-z

94. Liang, L., G.M. Henebry, L. Liu, X. Zhang, and L.-C. Hsu, 2021: Trends in land surface phenology across the conterminous United States (1982–2016) analyzed by NEON domains. *Ecological Applications*, **31** (5), e02323. https://doi.org/10.1002/eap.2323

95. Menzel, A., Y. Yuan, M. Matiu, T. Sparks, H. Scheifinger, R. Gehrig, and N. Estrella, 2020: Climate change fingerprints in recent European plant phenology. *Global Change Biology*, **26** (4), 2599–2612. https://doi.org/10.1111/gcb.15000

96. Song, Y., C.J. Zajic, T. Hwang, C.R. Hakkenberg, and K. Zhu, 2021: Widespread mismatch between phenology and climate in human-dominated landscapes. *AGU Advances*, **2** (4), e2021AV000431. https://doi.org/10.1029/2021av000431

97. Thornton, P.K., P.J. Ericksen, M. Herrero, and A.J. Challinor, 2014: Climate variability and vulnerability to climate change: A review. *Global Change Biology*, **20** (11), 3313–3328. https://doi.org/10.1111/gcb.12581

98. Anderegg, W.R.L., J.T. Abatzoglou, L.D.L. Anderegg, L. Bielory, P.L. Kinney, and L. Ziska, 2021: Anthropogenic climate change is worsening North American pollen seasons. *Proceedings of the National Academy of Sciences of the United States of America*, **118** (7), e2013284118. https://doi.org/10.1073/pnas.2013284118

99. Deutsch, C.A., J.J. Tewksbury, M. Tigchelaar, D.S. Battisti, S.C. Merrill, R.B. Huey, and R.L. Naylor, 2018: Increase in crop losses to insect pests in a warming climate. *Science*, **361** (6405), 916–919. https://doi.org/10.1126/science.aat3466

100. Schneider, L., M. Rebetez, and S. Rasmann, 2022: The effect of climate change on invasive crop pests across biomes. *Current Opinion in Insect Science*, **50**, 100895. https://doi.org/10.1016/j.cois.2022.100895

101. Li, D., B.J. Stucky, B. Baiser, and R. Guralnick, 2022: Urbanization delays plant leaf senescence and extends growing season length in cold but not in warm areas of the Northern Hemisphere. *Global Ecology and Biogeography*, **31** (2), 308–320. https://doi.org/10.1111/geb.13429

102. Li, D., B.J. Stucky, J. Deck, B. Baiser, and R.P. Guralnick, 2019: The effect of urbanization on plant phenology depends on regional temperature. *Nature Ecology & Evolution*, **3** (12), 1661–1667. https://doi.org/10.1038/s41559-019-1004-1

103. Kharouba, H.M., J. Ehrlén, A. Gelman, K. Bolmgren, J.M. Allen, S.E. Travers, and E.M. Wolkovich, 2018: Global shifts in the phenological synchrony of species interactions over recent decades. *Proceedings of the National Academy of Sciences of the United States of America*, **115** (20), 5211–5216. https://doi.org/10.1073/pnas.1714511115

104. Visser, M.E. and P. Gienapp, 2019: Evolutionary and demographic consequences of phenological mismatches. *Nature Ecology & Evolution*, **3** (6), 879–885. https://doi.org/10.1038/s41559-019-0880-8

105. Heberling, J.M., C. McDonough MacKenzie, J.D. Fridley, S. Kalisz, and R.B. Primack, 2019: Phenological mismatch with trees reduces wildflower carbon budgets. *Ecology Letters*, **22** (4), 616–623. https://doi.org/10.1111/ele.13224

106. Richardson, A.D., K. Hufkens, T. Milliman, D.M. Aubrecht, M.E. Furze, B. Seyednasrollah, M.B. Krassovski, J.M. Latimer, W.R. Nettles, R.R. Heiderman, J.M. Warren, and P.J. Hanson, 2018: Ecosystem warming extends vegetation activity but heightens vulnerability to cold temperatures. *Nature*, **560** (7718), 368–371. https://doi.org/10.1038/s41586-018-0399-1

107. Lambers, J.H.R., A.F. Cannistra, A. John, E. Lia, R.D. Manzanedo, M. Sethi, J. Sevigny, E.J. Theobald, and J.K. Waugh, 2021: Climate change impacts on natural icons: Do phenological shifts threaten the relationship between peak wildflowers and visitor satisfaction? *Climate Change Ecology*, **2**, 100008. https://doi.org/10.1016/j.ecochg.2021.100008

108. Ojea, E., S.E. Lester, and D. Salgueiro-Otero, 2020: Adaptation of fishing communities to climate-driven shifts in target species. *One Earth*, **2** (6), 544–556. https://doi.org/10.1016/j.oneear.2020.05.012

109. Fredston, A., M. Pinsky, R.L. Selden, C. Szuwalski, J.T. Thorson, S.D. Gaines, and B.S. Halpern, 2021: Range edges of North American marine species are tracking temperature over decades. *Global Change Biology*, **27** (13), 3145–3156. https://doi.org/10.1111/gcb.15614

110. MacLean, S.A. and S.R. Beissinger, 2017: Species' traits as predictors of range shifts under contemporary climate change: A review and meta-analysis. *Global Change Biology*, **23** (10), 4094–4105. https://doi.org/10.1111/gcb.13736

111. Pacifici, M., P. Visconti, S.H.M. Butchart, J.E.M. Watson, Francesca M. Cassola, and C. Rondinini, 2017: Species' traits influenced their response to recent climate change. *Nature Climate Change*, **7** (3), 205–208. https://doi.org/10.1038/nclimate3223

112. Lenoir, J., R. Bertrand, L. Comte, L. Bourgeaud, T. Hattab, J. Murienne, and G. Grenouillet, 2020: Species better track climate warming in the oceans than on land. *Nature Ecology & Evolution*, **4** (8), 1044–1059. https://doi.org/10.1038/s41559-020-1198-2

113. Freeman, B.G., J.A. Lee-Yaw, J.M. Sunday, and A.L. Hargreaves, 2018: Expanding, shifting and shrinking: The impact of global warming on species' elevational distributions. *Global Ecology and Biogeography*, **27** (11), 1268–1276. https://doi.org/10.1111/geb.12774

114. Graves, T.A., W.M. Janousek, S.M. Gaulke, A.C. Nicholas, D.A. Keinath, C.M. Bell, S. Cannings, R.G. Hatfield, J.M. Heron, J.B. Koch, H.L. Loffland, L.L. Richardson, A.T. Rohde, J. Rykken, J.P. Strange, L.M. Tronstad, and C.S. Sheffield, 2020: Western bumble bee: Declines in the continental United States and range-wide information gaps. *Ecosphere*, **11** (6), e03141. https://doi.org/10.1002/ecs2.3141

115. Lehmann, P., T. Ammunét, M. Barton, A. Battisti, S.D. Eigenbrode, J.U. Jepsen, G. Kalinkat, S. Neuvonen, P. Niemelä, J.S. Terblanche, B. Økland, and C. Björkman, 2020: Complex responses of global insect pests to climate warming. *Frontiers in Ecology and the Environment*, **18** (3), 141–150. https://doi.org/10.1002/fee.2160

116. Wagner, D.L., E.M. Grames, M.L. Forister, M.R. Berenbaum, and D. Stopak, 2021: Insect decline in the Anthropocene: Death by a thousand cuts. *Proceedings of the National Academy of Sciences of the United States of America*, **118** (2), e2023989118. https://doi.org/10.1073/pnas.2023989118

117. Choi, F., T. Gouhier, F. Lima, G. Rilov, R. Seabra, and B. Helmuth, 2019: Mapping physiology: Biophysical mechanisms define scales of climate change impacts. *Conservation Physiology*, **7** (1), 028. https://doi.org/10.1093/conphys/coz028

118. Forister, M.L., A.C. McCall, N.J. Sanders, J.A. Fordyce, J.H. Thorne, J. O'Brien, D.P. Waetjen, and A.M. Shapiro, 2010: Compounded effects of climate change and habitat alteration shift patterns of butterfly diversity. *Proceedings of the National Academy of Sciences of the United States of America*, **107** (5), 2088–2092. https://doi.org/10.1073/pnas.0909686107

119. Kroeker, K.J., E. Sanford, J.M. Rose, C.A. Blanchette, F. Chan, F.P. Chavez, B. Gaylord, B. Helmuth, T.M. Hill, G.E. Hofmann, M.A. McManus, B.A. Menge, K.J. Nielsen, P.T. Raimondi, A.D. Russell, and L. Washburn, 2016: Interacting environmental mosaics drive geographic variation in mussel performance and predation vulnerability. *Ecology Letters*, **19** (7), 771–779. https://doi.org/10.1111/ele.12613

120. McLaughlin, B.C., D.D. Ackerly, P.Z. Klos, J. Natali, T.E. Dawson, and S.E. Thompson, 2017: Hydrologic refugia, plants, and climate change. *Global Change Biology*, **23** (8), 2941–2961. https://doi.org/10.1111/gcb.13629

121. Morelli, T.L., C.W. Barrows, A.R. Ramirez, J.M. Cartwright, D.D. Ackerly, T.D. Eaves, J.L. Ebersole, M.A. Krawchuk, B.H. Letcher, M.F. Mahalovich, G.W. Meigs, J.L. Michalak, C.I. Millar, R.M. Quiñones, D. Stralberg, and J.H. Thorne, 2020: Climate-change refugia: Biodiversity in the slow lane. *Frontiers in Ecology and the Environment*, **18** (5), 228–234. https://doi.org/10.1002/fee.2189

122. Salois, S.L., T.C. Gouhier, B. Helmuth, F. Choi, R. Seabra, and F.P. Lima, 2022: Coastal upwelling generates cryptic temperature refugia. *Scientific Reports*, **12** (1), 19313. https://doi.org/10.1038/s41598-022-23717-5

123. Stralberg, D., C. Carroll, and S.E. Nielsen, 2020: Toward a climate-informed North American protected areas network: Incorporating climate-change refugia and corridors in conservation planning. *Conservation Letters*, **13** (4), e12712. https://doi.org/10.1111/conl.12712

124. Hannah, L., L. Flint, A.D. Syphard, M.A. Moritz, L.B. Buckley, and I.M. McCullough, 2014: Fine-grain modeling of species' response to climate change: Holdouts, stepping-stones, and microrefugia. *Trends in Ecology & Evolution*, **29** (7), 390–397. https://doi.org/10.1016/j.tree.2014.04.006

125. Peach, M.A., J.B. Cohen, J.L. Frair, B. Zuckerberg, P. Sullivan, W.F. Porter, and C. Lang, 2019: Value of protected areas to avian persistence across 20 years of climate and land-use change. *Conservation Biology*, **33** (2), 423–433. https://doi.org/10.1111/cobi.13205

126. Dixon, A.M., P.M. Forster, S.F. Heron, A.M.K. Stoner, and M. Beger, 2022: Future loss of local-scale thermal refugia in coral reef ecosystems. *PLoS Climate*, **1** (2), e0000004. https://doi.org/10.1371/journal.pclm.0000004

127. Ebersole, J.L., R.M. Quiñones, S. Clements, and B.H. Letcher, 2020: Managing climate refugia for freshwater fishes under an expanding human footprint. *Frontiers in Ecology and the Environment*, **18** (5), 271–280. https://doi.org/10.1002/fee.2206

128. Storlazzi, C.D., O.M. Cheriton, R. van Hooidonk, Z. Zhao, and R. Brainard, 2020: Internal tides can provide thermal refugia that will buffer some coral reefs from future global warming. *Scientific Reports*, **10** (1), 13435. https://doi.org/10.1038/s41598-020-70372-9

129. Tang, C.Q., T. Matsui, H. Ohashi, Y.-F. Dong, A. Momohara, S. Herrando-Moraira, S. Qian, Y. Yang, M. Ohsawa, H.T. Luu, P.J. Grote, P.V. Krestov, L. Ben, M. Werger, K. Robertson, C. Hobohm, C.-Y. Wang, M.-C. Peng, X. Chen, H.-C. Wang, W.-H. Su, R. Zhou, S. Li, L.-Y. He, K. Yan, M.-Y. Zhu, J. Hu, R.-H. Yang, W.-J. Li, M. Tomita, Z.-L. Wu, H.-Z. Yan, G.-F. Zhang, H. He, S.-R. Yi, H. Gong, K. Song, D. Song, X.-S. Li, Z.-Y. Zhang, P.-B. Han, L.-Q. Shen, D.-S. Huang, K. Luo, and J. López-Pujol, 2018: Identifying long-term stable refugia for relict plant species in East Asia. *Nature Communications*, **9** (1), 4488. https://doi.org/10.1038/s41467-018-06837-3

130. Morelli, T.L., C. Daly, S.Z. Dobrowski, D.M. Dulen, J.L. Ebersole, S.T. Jackson, J.D. Lundquist, C.I. Millar, S.P. Maher, W.B. Monahan, K.R. Nydick, K.T. Redmond, S.C. Sawyer, S. Stock, and S.R. Beissinger, 2016: Managing climate change refugia for climate adaptation. *PLoS ONE*, **11** (8), e0159909. https://doi.org/10.1371/journal.pone.0159909

131. Madliger, C.L., C.E. Franklin, O.P. Love, and S.J. Cooke, Eds., 2020: *Conservation Physiology: Applications for Wildlife Conservation and Management*. Oxford University Press. https://doi.org/10.1093/oso/9780198843610.001.0001

132. Royer-Tardif, S., L. Boisvert-Marsh, J. Godbout, N. Isabel, and I. Aubin, 2021: Finding common ground: Toward comparable indicators of adaptive capacity of tree species to a changing climate. *Ecology and Evolution*, **11** (19), 13081–13100. https://doi.org/10.1002/ece3.8024

133. Grose, S.O., L. Pendleton, A. Leathers, A. Cornish, and S. Waitai, 2020: Climate change will re-draw the map for marine megafauna and the people who depend on them. *Frontiers in Marine Science*, **7**, 547. https://doi.org/10.3389/fmars.2020.00547

134. Penn, J.L. and C. Deutsch, 2022: Avoiding ocean mass extinction from climate warming. *Science*, **376** (6592), 524–526. https://doi.org/10.1126/science.abe9039

135. Christiansen, F., S.M. Dawson, J.W. Durban, H. Fearnbach, C.A. Miller, L. Bejder, M. Uhart, M. Sironi, P. Corkeron, W. Rayment, E. Leunissen, E. Haria, R. Ward, H.A. Warick, I. Kerr, M.S. Lynn, H.M. Pettis, and M.J. Moore, 2020: Population comparison of right whale body condition reveals poor state of the North Atlantic right whale. *Marine Ecology Progress Series*, **640**, 1–16. https://doi.org/10.3354/meps13299

136. Pimiento, C., F. Leprieur, D. Silvestro, J.S. Lefcheck, C. Albouy, D.B. Rasher, M. Davis, J.-C. Svenning, and J.N. Griffin, 2020: Functional diversity of marine megafauna in the Anthropocene. *Science Advances*, **6** (16), 7650. https://doi.org/10.1126/sciadv.aay7650

137. Pershing, A.J. and K. Stamieszkin, 2020: The North Atlantic ecosystem, from plankton to whales. *Annual Review of Marine Science*, **12**, 339–359. https://doi.org/10.1146/annurev-marine-010419-010752

138. Sorochan, K.A., S. Plourde, M.F. Baumgartner, and C.L. Johnson, 2021: Availability, supply, and aggregation of prey (*Calanus* spp.) in foraging areas of the North Atlantic right whale (*Eubalaena glacialis*). *ICES Journal of Marine Science*, **78** (10), 3498–3520. https://doi.org/10.1093/icesjms/fsab200

139. Record, N.R., J.A. Runge, D.E. Pendleton, W.M. Balch, K.T.A. Davies, A.J. Pershing, C.L. Johnson, K. Stamieszkin, R. Ji, Z. Feng, S.D. Kraus, R.D. Kenney, C.A. Hudak, C.A. Mayo, C. Chen, J.E. Salisbury, and C.R.S. Thompson, 2019: Rapid climate-driven circulation changes threaten conservation of endangered North Atlantic right whales. *Oceanography*, **32** (2), 162–169. https://doi.org/10.5670/oceanog.2019.201

140. Stewart, J.D., J.W. Durban, A.R. Knowlton, M.S. Lynn, H. Fearnbach, J. Barbaro, W.L. Perryman, C.A. Miller, and M.J. Moore, 2021: Decreasing body lengths in North Atlantic right whales. *Current Biology*, **31** (14), 3174–3179. https://doi.org/10.1016/j.cub.2021.04.067

141. Bullen, C.D., A.A. Campos, E.J. Gregr, I. McKechnie, and K.M.A. Chan, 2021: The ghost of a giant—Six hypotheses for how an extinct megaherbivore structured kelp forests across the North Pacific Rim. *Global Ecology and Biogeography*, **30** (10), 2101–2118. https://doi.org/10.1111/geb.13370

142. Buttke, D., M. Wild, R. Monello, G. Schuurman, M. Hahn, and K. Jackson, 2021: Managing wildlife disease under climate change. *EcoHealth*, **18** (4), 406–410. https://doi.org/10.1007/s10393-021-01542-y

143. Hale, V.L., P.M. Dennis, D.S. McBride, J.M. Nolting, C. Madden, D. Huey, M. Ehrlich, J. Grieser, J. Winston, D. Lombardi, S. Gibson, L. Saif, M.L. Killian, K. Lantz, R.M. Tell, M. Torchetti, S. Robbe-Austerman, M.I. Nelson, S.A. Faith, and A.S. Bowman, 2022: SARS-CoV-2 infection in free-ranging white-tailed deer. *Nature*, **602** (7897), 481–486. https://doi.org/10.1038/s41586-021-04353-x

144. Harvell, C.D., D. Montecino-Latorre, J.M. Caldwell, J.M. Burt, K. Bosley, A. Keller, S.F. Heron, A.K. Salomon, L. Lee, O. Pontier, C. Pattengill-Semmens, and J.K. Gaydos, 2019: Disease epidemic and a marine heat wave are associated with the continental-scale collapse of a pivotal predator (*Pycnopodia helianthoides*). *Science Advances*, **5** (1), 7042. https://doi.org/10.1126/sciadv.aau7042

145. Harvell, D., 2019: *Ocean Outbreak: Confronting the Rising Tide of Marine Disease*. University of California Press, 232 pp. https://www.ucpress.edu/book/9780520382985/ocean-outbreak

146. Till, A., A.L. Rypel, A. Bray, and S.B. Fey, 2019: Fish die-offs are concurrent with thermal extremes in north temperate lakes. *Nature Climate Change*, **9**, 637–641. https://doi.org/10.1038/s41558-019-0520-y

147. Weiskopf, S.R., O.E. Ledee, and L.M. Thompson, 2019: Climate change effects on deer and moose in the Midwest. *The Journal of Wildlife Management*, **83** (4), 769–781. https://doi.org/10.1002/jwmg.21649

148. Cohen, J.M., M.D. Venesky, E.L. Sauer, D.J. Civitello, T.A. McMahon, E.A. Roznik, and J.R. Rohr, 2017: The thermal mismatch hypothesis explains host susceptibility to an emerging infectious disease. *Ecology Letters*, **20** (2), 184–193. https://doi.org/10.1111/ele.12720

149. Chaloner, T.M., S.J. Gurr, and D.P. Bebber, 2021: Plant pathogen infection risk tracks global crop yields under climate change. *Nature Climate Change*, **11** (8), 710–715. https://doi.org/10.1038/s41558-021-01104-8

150. Juroszek, P., P. Racca, S. Link, J. Farhumand, and B. Kleinhenz, 2020: Overview on the review articles published during the past 30 years relating to the potential climate change effects on plant pathogens and crop disease risks. *Plant Pathology*, **69** (2), 179–193. https://doi.org/10.1111/ppa.13119

151. Carlson, C.J., G.F. Albery, C. Merow, C.H. Trisos, C.M. Zipfel, E.A. Eskew, K.J. Olival, N. Ross, and S. Bansal, 2022: Climate change increases cross-species viral transmission risk. *Nature*, **607** (7919), 555–562. https://doi.org/10.1038/s41586-022-04788-w

152. Gilbert, L., 2021: The impacts of climate change on ticks and tick-borne disease risk. *Annual Review of Entomology*, **66** (1), 373–388. https://doi.org/10.1146/annurev-ento-052720-094533

153. Keesing, F. and R.S. Ostfeld, 2021: Impacts of biodiversity and biodiversity loss on zoonotic diseases. *Proceedings of the National Academy of Sciences of the United States of America*, **118** (17), e2023540118. https://doi.org/10.1073/pnas.2023540118

154. Mora, C., T. McKenzie, I.M. Gaw, J.M. Dean, H. von Hammerstein, T.A. Knudson, R.O. Setter, C.Z. Smith, K.M. Webster, J.A. Patz, and E.C. Franklin, 2022: Over half of known human pathogenic diseases can be aggravated by climate change. *Nature Climate Change*, **12** (9), 869–875. https://doi.org/10.1038/s41558-022-01426-1

155. Islam, M.R., U. Bulut, T.P. Feria-Arroyo, M.G. Tyshenko, and T. Oraby, 2022: Modeling the impact of climate change on cervid chronic wasting disease in semi-arid south Texas. *Frontiers in Epidemiology*, **2**, 889280. https://doi.org/10.3389/fepid.2022.889280

156. Ogden, N.H., C. Ben Beard, H.S. Ginsberg, and J.I. Tsao, 2021: Possible effects of climate change on ixodid ticks and the pathogens they transmit: Predictions and observations. *Journal of Medical Entomology*, **58** (4), 1536–1545. https://doi.org/10.1093/jme/tjaa220

157. Sonenshine, D.E., 2018: Range expansion of tick disease vectors in North America: Implications for spread of tick-borne disease. *International Journal of Environmental Research and Public Health*, **15** (3), 478. https://doi.org/10.3390/ijerph15030478

158. Escobar, L.E., J. Escobar-Dodero, and N.B.D. Phelps, 2018: Infectious disease in fish: Global risk of viral hemorrhagic septicemia virus. *Reviews in Fish Biology and Fisheries*, **28** (3), 637–655. https://doi.org/10.1007/s11160-018-9524-3

159. Taylor, R.A., S.J. Ryan, C.A. Lippi, D.G. Hall, H.A. Narouei-Khandan, J.R. Rohr, and L.R. Johnson, 2019: Predicting the fundamental thermal niche of crop pests and diseases in a changing world: A case study on citrus greening. *Journal of Applied Ecology*, **56** (8), 2057–2068. https://doi.org/10.1111/1365-2664.13455

160. Singerman, A. and M.E. Rogers, 2020: The economic challenges of dealing with citrus greening: The case of Florida. *Journal of Integrated Pest Management*, **11** (1), 3. https://doi.org/10.1093/jipm/pmz037

161. Fortini, L.B., L.R. Kaiser, L.M. Keith, J. Price, R.F. Hughes, J.D. Jacobi, and J.B. Friday, 2019: The evolving threat of Rapid ʻŌhiʻa Death (ROD) to Hawaiʻi's native ecosystems and rare plant species. *Forest Ecology and Management*, **448**, 376–385. https://doi.org/10.1016/j.foreco.2019.06.025

162. Severud, W.J., M. Petz Giguere, T. Walters, T.J. Garwood, K. Teager, K.M. Marchetto, L. Gustavo R. Oliveira-Santos, S.A. Moore, and T.M. Wolf, 2023: Terrestrial gastropod species-specific responses to forest management: Implications for *Parelaphostrongylus tenuis* transmission to moose. *Forest Ecology and Management*, **529**, 120717. https://doi.org/10.1016/j.foreco.2022.120717

163. Walton, C.J., N.K. Hayes, and D.S. Gilliam, 2018: Impacts of a regional, multi-year, multi-species coral disease outbreak in southeast Florida. *Frontiers in Marine Science*, **5**, 323. https://doi.org/10.3389/fmars.2018.00323

164. Gervais, J.A., R. Kovach, A. Sepulveda, R. Al-Chokhachy, J. Joseph Giersch, and C.C. Muhlfeld, 2020: Climate-induced expansions of invasive species in the Pacific Northwest, North America: A synthesis of observations and projections. *Biological Invasions*, **22** (7), 2163–2183. https://doi.org/10.1007/s10530-020-02244-2

165. Seebens, H., S. Bacher, T.M. Blackburn, C. Capinha, W. Dawson, S. Dullinger, P. Genovesi, P.E. Hulme, M. van Kleunen, I. Kühn, J.M. Jeschke, B. Lenzner, A.M. Liebhold, Z. Pattison, J. Pergl, P. Pyšek, M. Winter, and F. Essl, 2021: Projecting the continental accumulation of alien species through to 2050. *Global Change Biology*, **27** (5), 970–982. https://doi.org/10.1111/gcb.15333

166. Hickman, J.E. and M.T. Lerdau, 2013: Biogeochemical impacts of the northward expansion of kudzu under climate change: The importance of ecological context. *Ecosphere*, **4** (10), art121. https://doi.org/10.1890/es13-00142.1

167. Stephens, K.L., M.E. Dantzler-Kyer, M.A. Patten, and L. Souza, 2019: Differential responses to global change of aquatic and terrestrial invasive species: Evidences from a meta-analysis. *Ecosphere*, **10** (4), e02680. https://doi.org/10.1002/ecs2.2680

168. Vilizzi, L., G.H. Copp, J.E. Hill, B. Adamovich, L. Aislabie, et al., 2021: A global-scale screening of non-native aquatic organisms to identify potentially invasive species under current and future climate conditions. *Science of The Total Environment*, **788**, 147868. https://doi.org/10.1016/j.scitotenv.2021.147868

169. Bellard, C., J.M. Jeschke, B. Leroy, and G.M. Mace, 2018: Insights from modeling studies on how climate change affects invasive alien species geography. *Ecology and Evolution*, **8** (11), 5688–5700. https://doi.org/10.1002/ece3.4098

170. Ellison, A.M., D.A. Orwig, M.C. Fitzpatrick, and E.L. Preisser, 2018: The past, present, and future of the hemlock woolly adelgid (*Adelges tsugae*) and its ecological interactions with eastern hemlock (*Tsuga canadensis*) forests. *Insects*, **9** (4), 172. https://doi.org/10.3390/insects9040172

171. Alsip, P.J., H. Zhang, M.D. Rowe, E. Rutherford, D.M. Mason, C. Riseng, and Z. Su, 2020: Modeling the interactive effects of nutrient loads, meteorology, and invasive mussels on suitable habitat for Bighead and Silver Carp in Lake Michigan. *Biological Invasions*, **22** (9), 2763–2785. https://doi.org/10.1007/s10530-020-02296-4

172. Patrick, D.A., N. Boudreau, Z. Bozic, G.S. Carpenter, D.M. Langdon, S.R. LeMay, S.M. Martin, R.M. Mourse, S.L. Prince, and K.M. Quinn, 2012: Effects of climate change on late-season growth and survival of native and non-native species of watermilfoil (*Myriophyllum* spp.): Implications for invasive potential and ecosystem change. *Aquatic Botany*, **103**, 83–88. https://doi.org/10.1016/j.aquabot.2012.06.008

173. Yamada, S.B., J.L. Fisher, and P.M. Kosro, 2021: Relationship between ocean ecosystem indicators and year class strength of the invasive European green crab (*Carcinus maenas*). *Progress in Oceanography*, **196**, 102618. https://doi.org/10.1016/j.pocean.2021.102618

174. Hoffmann, S., 2022: Challenges and opportunities of area-based conservation in reaching biodiversity and sustainability goals. *Biodiversity and Conservation*, **31** (2), 325–352. https://doi.org/10.1007/s10531-021-02340-2

175. Kroeker, K.J., M.H. Carr, P.T. Raimondi, J.E. Caselle, L. Washburn, S.R. Palumbi, J.A. Barth, F. Chan, B.A. Menge, K. Milligan, M. Novak, and J.W. White, 2019: Planning for change: Assessing the potential role of marine protected areas and fisheries management approaches for resilience management in a changing ocean. *Oceanography*, **32** (3), 116–125. https://doi.org/10.5670/oceanog.2019.318

176. MassWildlife, 2015: Massachusetts State Wildlife Action Plan 2015. Massachusetts Division of Fisheries and Wildlife, Westborough, MA. https://www.mass.gov/service-details/state-wildlife-action-plan-swap

177. Staudinger, M.D., T.L. Morelli, and A.M. Bryan, 2015: Integrating Climate Change into Northeast and Midwest State Wildlife Action Plans. Northeast Climate Science Center, Amherst, MA, 201 pp. https://necasc.umass.edu/projects/integrating-climate-change-state-wildlife-action-plans

178. Zimmerer, R., T.L. Morelli, M. Ocana, and J. O'Leary, 2018: The Climate Project Screening Tool Report for the Massachusetts Division of Fisheries and Wildlife's Northeast District. MassWildlife. https://www.mass.gov/doc/northeast-district-climate-project-screening-tool-report/download

179. Carroll, C. and R.F. Noss, 2021: Rewilding in the face of climate change. *Conservation Biology*, **35** (1), 155–167. https://doi.org/10.1111/cobi.13531

180. Taylor, L., S.P. Saunders, J.X. Wu, B.L. Bateman, J. Grand, W.V. DeLuca, and C.B. Wilsey, 2022: Choice of prioritization method impacts recommendations for climate-informed bird conservation in the United States. *Ecography*, **2022** (12), e06401. https://doi.org/10.1111/ecog.06401

181. Keeley, A.T.H., D.D. Ackerly, D.R. Cameron, N.E. Heller, P.R. Huber, C.A. Schloss, J.H. Thorne, and A.M. Merenlender, 2018: New concepts, models, and assessments of climate-wise connectivity. *Environmental Research Letters*, **13** (7), 073002. https://doi.org/10.1088/1748-9326/aacb85

182. Besterman, A.F., R.W. Jakuba, W. Ferguson, D. Brennan, J.E. Costa, and L.A. Deegan, 2022: Buying time with runnels: A climate adaptation tool for salt marshes. *Estuaries and Coasts*, **45** (6), 1491–1501. https://doi.org/10.1007/s12237-021-01028-8

183. Wigand, C., T. Ardito, C. Chaffee, W. Ferguson, S. Paton, K. Raposa, C. Vandemoer, and E. Watson, 2017: A climate change adaptation strategy for management of coastal marsh systems. *Estuaries and Coasts*, **40** (3), 682–693. https://doi.org/10.1007/s12237-015-0003-y

184. Butt, N., A.L.M. Chauvenet, V.M. Adams, M. Beger, R.V. Gallagher, D.F. Shanahan, M. Ward, J.E.M. Watson, and H.P. Possingham, 2021: Importance of species translocations under rapid climate change. *Conservation Biology*, **35** (3), 775–783. https://doi.org/10.1111/cobi.13643

185. Palik, B.J., P.W. Clark, A.W. D'Amato, C. Swanston, and L. Nagel, 2022: Operationalizing forest-assisted migration in the context of climate change adaptation: Examples from the eastern USA. *Ecosphere*, **13** (10), e4260. https://doi.org/10.1002/ecs2.4260

186. Orning, E.K., M.C. Romanski, S. Moore, Y. Chenaux-Ibrahim, J. Hart, and J.L. Belant, 2020: Emigration and first-year movements of initial Wolf translocations to Isle Royale. *Northeastern Naturalist*, **27** (4), 701–708. https://doi.org/10.1656/045.027.0410

187. Gonzalez, P., F. Wang, M. Notaro, D.J. Vimont, and J.W. Williams, 2018: Disproportionate magnitude of climate change in United States national parks. *Environmental Research Letters*, **13** (10), 104001. https://doi.org/10.1088/1748-9326/aade09

188. Hoffmann, S., S.D.H. Irl, and C. Beierkuhnlein, 2019: Predicted climate shifts within terrestrial protected areas worldwide. *Nature Communications*, **10** (1), 4787. https://doi.org/10.1038/s41467-019-12603-w

189. Wilson, K.L., D.P. Tittensor, B. Worm, and H.K. Lotze, 2020: Incorporating climate change adaptation into marine protected area planning. *Global Change Biology*, **26** (6), 3251–3267. https://doi.org/10.1111/gcb.15094

190. Holsinger, L., S.A. Parks, M.-A. Parisien, C. Miller, E. Batllori, and M.A. Moritz, 2019: Climate change likely to reshape vegetation in North America's largest protected areas. *Conservation Science and Practice*, **1** (7), e50. https://doi.org/10.1111/csp2.50

191. Suraci, J.P., L.S. Farwell, C.E. Littlefield, P.T. Freeman, L.J. Zachmann, V.A. Landau, J.J. Anderson, and B.G. Dickson, 2023: Achieving conservation targets by jointly addressing climate change and biodiversity loss. *Ecosphere*, **14** (4), e4490. https://doi.org/10.1002/ecs2.4490

192. Lawler, J.J., D.S. Rinnan, J.L. Michalak, J.C. Withey, C.R. Randels, and H.P. Possingham, 2020: Planning for climate change through additions to a national protected area network: Implications for cost and configuration. *Philosophical Transactions of the Royal Society B: Biological Sciences*, **375** (1794), 20190117. https://doi.org/10.1098/rstb.2019.0117

193. Wu, J.X., B.L. Bateman, P.J. Heglund, L. Taylor, A.J. Allstadt, D. Granfors, H. Westerkam, N.L. Michel, and C.B. Wilsey, 2022: U.S. National Wildlife Refuge System likely to see regional and seasonal species turnover in bird assemblages under a 2°C warming scenario. *Ornithological Applications*, **124** (3), 016. https://doi.org/10.1093/ornithapp/duac016

194. Wu, J.X., C.B. Wilsey, L. Taylor, and G.W. Schuurman, 2018: Projected avifaunal responses to climate change across the U.S. National Park System. *PLoS ONE*, **13** (3), e0190557. https://doi.org/10.1371/journal.pone.0190557

195. Froese, R. and J. Schilling, 2019: The nexus of climate change, land use, and conflicts. *Current Climate Change Reports*, **5** (1), 24–35. https://doi.org/10.1007/s40641-019-00122-1

196. Koubi, V., 2019: Climate change and conflict. *Annual Review of Political Science*, **22** (1), 343–360. https://doi.org/10.1146/annurev-polisci-050317-070830

197. Dubik, B.A., E.C. Clark, T. Young, S.B.J. Zigler, M.M. Provost, M.L. Pinsky, and K. St. Martin, 2019: Governing fisheries in the face of change: Social responses to long-term geographic shifts in a U.S. fishery. *Marine Policy*, **99**, 243–251. https://doi.org/10.1016/j.marpol.2018.10.032

198. Palacios-Abrantes, J., T.L. Frölicher, G. Reygondeau, U.R. Sumaila, A. Tagliabue, Colette C.C. Wabnitz, and William W.L. Cheung, 2022: Timing and magnitude of climate-driven range shifts in transboundary fish stocks challenge their management. *Global Change Biology*, **28** (7), 2312–2326. https://doi.org/10.1111/gcb.16058

199. Berger-Tal, O., D.T. Blumstein, and R.R. Swaisgood, 2020: Conservation translocations: A review of common difficulties and promising directions. *Animal Conservation*, **23** (2), 121–131. https://doi.org/10.1111/acv.12534

200. Mach, K.J., C.M. Kraan, W.N. Adger, H. Buhaug, M. Burke, J.D. Fearon, C.B. Field, C.S. Hendrix, J.-F. Maystadt, J. O'Loughlin, P. Roessler, J. Scheffran, K.A. Schultz, and N. von Uexkull, 2019: Climate as a risk factor for armed conflict. *Nature*, **571** (7764), 193–197. https://doi.org/10.1038/s41586-019-1300-6

201. Pinsky, M.L., L.A. Rogers, J.W. Morley, and T.L. Frölicher, 2020: Ocean planning for species on the move provides substantial benefits and requires few trade-offs. *Science Advances*, **6** (50), 8428. https://doi.org/10.1126/sciadv.abb8428

202. Himes, A. and B. Muraca, 2018: Relational values: The key to pluralistic valuation of ecosystem services. *Current Opinion in Environmental Sustainability*, **35**, 1–7. https://doi.org/10.1016/j.cosust.2018.09.005

203. Michaelis, A.K., W.C. Walton, D.W. Webster, and L.J. Shaffer, 2021: Cultural ecosystem services enabled through work with shellfish. *Marine Policy*, **132**, 104689. https://doi.org/10.1016/j.marpol.2021.104689

204. Dam Lam, R., A. Gasparatos, S. Chakraborty, H. Rivera, and T. Stanley, 2019: Multiple values and knowledge integration in indigenous coastal and marine social-ecological systems research: A systematic review. *Ecosystem Services*, **37**, 100910. https://doi.org/10.1016/j.ecoser.2019.100910

205. Mockta, T.K., P.Z. Fulé, A. Sánchez Meador, T. Padilla, and Y.-S. Kim, 2018: Sustainability of culturally important teepee poles on Mescalero Apache Tribal Lands: Characteristics and climate change effects. *Forest Ecology and Management*, **430**, 250–258. https://doi.org/10.1016/j.foreco.2018.08.017

206. O'Connor, S. and J.O. Kenter, 2019: Making intrinsic values work: Integrating intrinsic values of the more-than-human world through the Life Framework of Values. *Sustainability Science*, **14** (5), 1247–1265. https://doi.org/10.1007/s11625-019-00715-7

207. Runting, R.K., B.A. Bryan, L.E. Dee, F.J.F. Maseyk, L. Mandle, P. Hamel, K.A. Wilson, K. Yetka, H.P. Possingham, and J.R. Rhodes, 2017: Incorporating climate change into ecosystem service assessments and decisions: A review. *Global Change Biology*, **23** (1), 28–41. https://doi.org/10.1111/gcb.13457

208. Warziniack, T., M. Lawson, and S. Karen Dante-Wood, 2018: Ch. 10. Effects of climate change on ecosystem services in the Northern Rockies. In: *Climate Change and Rocky Mountain Ecosystems*. Halofsky, J.E. and D.L. Peterson, Eds. Springer, Cham, Switzerland, 189–208. https://doi.org/10.1007/978-3-319-56928-4_10

209. Brice, E.M., B.A. Miller, H. Zhang, K. Goldstein, S.N. Zimmer, G.J. Grosklos, P. Belmont, C.G. Flint, J.E. Givens, P.B. Adler, M.W. Brunson, and J.W. Smith, 2020: Impacts of climate change on multiple use management of Bureau of Land Management land in the Intermountain West, USA. *Ecosphere*, **11** (11), e03286. https://doi.org/10.1002/ecs2.3286

210. Wilkins, E.J., Y. Chikamoto, A.B. Miller, and J.W. Smith, 2021: Climate change and the demand for recreational ecosystem services on public lands in the continental United States. *Global Environmental Change*, **70**, 102365. https://doi.org/10.1016/j.gloenvcha.2021.102365

211. Martin, D.M., J.A. Specht, M.R. Canick, K.L. Leo, and K. Freeman, 2022: Using decision analysis to integrate habitat and community values for coastal resilience planning. *Estuaries and Coasts*, **45** (2), 331–344. https://doi.org/10.1007/s12237-021-00970-x

212. Meerow, S., 2019: A green infrastructure spatial planning model for evaluating ecosystem service tradeoffs and synergies across three coastal megacities. *Environmental Research Letters*, **14** (12), 125011. https://doi.org/10.1088/1748-9326/ab502c

213. Alves Carvalho Nascimento, L. and V. Shandas, 2021: Integrating diverse perspectives for managing neighborhood trees and urban ecosystem services in Portland, OR (US). *Land*, **10** (1), 48. https://doi.org/10.3390/land10010048

214. Herreros-Cantis, P. and T. McPhearson, 2021: Mapping supply of and demand for ecosystem services to assess environmental justice in New York City. *Ecological Applications*, **31** (6), e02390. https://doi.org/10.1002/eap.2390

215. Richards, D.R., R.N. Belcher, L.R. Carrasco, P.J. Edwards, S. Fatichi, P. Hamel, M. Masoudi, M.J. McDonnell, N. Peleg, and M.C. Stanley, 2022: Global variation in contributions to human well-being from urban vegetation ecosystem services. *One Earth*, **5** (5), 522–533. https://doi.org/10.1016/j.oneear.2022.04.006

216. Anguelovski, I., J.J. Connolly, M. Garcia-Lamarca, H. Cole, and H. Pearsall, 2019: New scholarly pathways on green gentrification: What does the urban 'green turn' mean and where is it going? *Progress in Human Geography*, **43** (6), 1064–1086. https://doi.org/10.1177/0309132518803799

217. Rigolon, A. and J. Németh, 2018: "We're not in the business of housing:" Environmental gentrification and the nonprofitization of green infrastructure projects. *Cities*, **81**, 71–80. https://doi.org/10.1016/j.cities.2018.03.016

218. Hendricks, M.D. and S. Van Zandt, 2021: Unequal protection revisited: Planning for environmental justice, hazard vulnerability, and critical infrastructure in communities of color. *Environmental Justice*, **14** (2), 87–97. https://doi.org/10.1089/env.2020.0054

219. Schell, C.J., K. Dyson, T.L. Fuentes, S.D. Roches, N.C. Harris, D.S. Miller, C.A. Woelfle-Erskine, and M.R. Lambert, 2020: The ecological and evolutionary consequences of systemic racism in urban environments. *Science*, **369** (6510), 4497. https://doi.org/10.1126/science.aay4497

220. EPA, 2022: EPA's Report on the Environment (ROE). U.S. Environmental Protection Agency. https://www.epa.gov/report-environment

221. Sanders, B.F., J.E. Schubert, D.T. Kahl, K.J. Mach, D. Brady, A. AghaKouchak, F. Forman, R.A. Matthew, N. Ulibarri, and S.J. Davis, 2023: Large and inequitable flood risks in Los Angeles, California. *Nature Sustainability*, **6** (1), 47–57. https://doi.org/10.1038/s41893-022-00977-7

222. Ma, S., C.A. Craig, and S. Feng, 2021: Camping climate resources: The camping climate index in the United States. *Current Issues in Tourism*, **24** (18), 2523–2531. https://doi.org/10.1080/13683500.2020.1846503

223. Nesbitt, L., M.J. Meitner, C. Girling, S.R.J. Sheppard, and Y. Lu, 2019: Who has access to urban vegetation? A spatial analysis of distributional green equity in 10 US cities. *Landscape and Urban Planning*, **181**, 51–79. https://doi.org/10.1016/j.landurbplan.2018.08.007

224. Spotswood, E.N., M. Benjamin, L. Stoneburner, M.M. Wheeler, E.E. Beller, D. Balk, T. McPhearson, M. Kuo, and R.I. McDonald, 2021: Nature inequity and higher COVID-19 case rates in less-green neighbourhoods in the United States. *Nature Sustainability*, **4** (12), 1092–1098. https://doi.org/10.1038/s41893-021-00781-9

225. Stewart, I.T., J. Rogers, and A. Graham, 2020: Water security under severe drought and climate change: Disparate impacts of the recent severe drought on environmental flows and water supplies in central California. *Journal of Hydrology X*, **7**, 100054. https://doi.org/10.1016/j.hydroa.2020.100054

226. Drugova, T., K.R. Curtis, and M.-K. Kim, 2022: The impacts of drought on Southwest tribal economies. JAWRA *Journal of the American Water Resources Association*, **58** (5), 639–653. https://doi.org/10.1111/1752-1688.13018

227. McBride, J.R. and I. Laćan, 2018: The impact of climate-change induced temperature increases on the suitability of street tree species in California (USA) cities. *Urban Forestry & Urban Greening*, **34**, 348–356. https://doi.org/10.1016/j.ufug.2018.07.020

228. Daouda, M., L. Henneman, J. Goldsmith, M.-A. Kioumourtzoglou, and A. Casey Joan, 2022: Racial/ethnic disparities in nationwide $PM_{2.5}$ concentrations: Perils of assuming a linear relationship. *Environmental Health Perspectives*, **130** (7), 077701. https://doi.org/10.1289/ehp11048

229. Tessum, C.W., J.S. Apte, A.L. Goodkind, N.Z. Muller, K.A. Mullins, D.A. Paolella, S. Polasky, N.P. Springer, S.K. Thakrar, J.D. Marshall, and J.D. Hill, 2019: Inequity in consumption of goods and services adds to racial–ethnic disparities in air pollution exposure. *Proceedings of the National Academy of Sciences of the United States of America*, **116** (13), 6001–6006. https://doi.org/10.1073/pnas.1818859116

230. Tessum, C.W., D.A. Paolella, S.E. Chambliss, J.S. Apte, J.D. Hill, and J.D. Marshall, 2021: $PM_{2.5}$ polluters disproportionately and systemically affect people of color in the United States. *Science Advances*, **7** (18), 4491. https://doi.org/10.1126/sciadv.abf4491

231. Lane, H.M., R. Morello-Frosch, J.D. Marshall, and J.S. Apte, 2022: Historical redlining is associated with present-day air pollution disparities in U.S. cities. *Environmental Science & Technology Letters*, **9** (4), 345–350. https://doi.org/10.1021/acs.estlett.1c01012

232. Staudinger, M.D., A.J. Lynch, S.K. Gaichas, M.G. Fox, D. Gibson-Reinemer, J.A. Langan, A.K. Teffer, S.J. Thackeray, and I.J. Winfield, 2021: How does climate change affect emergent properties of aquatic ecosystems? *Fisheries*, **46** (9), 423–441. https://doi.org/10.1002/fsh.10606

233. Crozier, L.G., B.J. Burke, B.E. Chasco, D.L. Widener, and R.W. Zabel, 2021: Climate change threatens Chinook salmon throughout their life cycle. *Communications Biology*, **4** (1), 222. https://doi.org/10.1038/s42003-021-01734-w

234. Cohen-Shacham, E., A. Andrade, J. Dalton, N. Dudley, M. Jones, C. Kumar, S. Maginnis, S. Maynard, C.R. Nelson, F.G. Renaud, R. Welling, and G. Walters, 2019: Core principles for successfully implementing and upscaling Nature-based Solutions. *Environmental Science & Policy*, **98**, 20–29. https://doi.org/10.1016/j.envsci.2019.04.014

235. Griscom, B.W., J. Adams, P.W. Ellis, R.A. Houghton, G. Lomax, D.A. Miteva, W.H. Schlesinger, D. Shoch, J.V. Siikamäki, P. Smith, P. Woodbury, C. Zganjar, A. Blackman, J. Campari, R.T. Conant, C. Delgado, P. Elias, T. Gopalakrishna, M.R. Hamsik, M. Herrero, J. Kiesecker, E. Landis, L. Laestadius, S.M. Leavitt, S. Minnemeyer, S. Polasky, P. Potapov, F.E. Putz, J. Sanderman, M. Silvius, E. Wollenberg, and J. Fargione, 2017: Natural climate solutions. *Proceedings of the National Academy of Sciences of the United States of America*, **114** (44), 11645–11650. https://doi.org/10.1073/pnas.1710465114

236. Roelvink, F.E., C.D. Storlazzi, A.R. van Dongeren, and S.G. Pearson, 2021: Coral reef restorations can be optimized to reduce coastal flooding hazards. *Frontiers in Marine Science*, **8**, 653945. https://doi.org/10.3389/fmars.2021.653945

237. Morecroft, M.D., S. Duffield, M. Harley, J.W. Pearce-Higgins, N. Stevens, O. Watts, and J. Whitaker, 2019: Measuring the success of climate change adaptation and mitigation in terrestrial ecosystems. *Science*, **366** (6471), 9256. https://doi.org/10.1126/science.aaw9256

238. Guerry, A.D., J. Silver, J. Beagle, K. Wyatt, K. Arkema, J. Lowe, P. Hamel, R. Griffin, S. Wolny, E. Plane, M. Griswold, H. Papendick, and J. Sharma, 2022: Protection and restoration of coastal habitats yield multiple benefits for urban residents as sea levels rise. *npj Urban Sustainability*, **2** (1), 13. https://doi.org/10.1038/s42949-022-00056-y

239. Schelske, O., J.R. Bohn, and C. Fitzgerald, 2021: Ch. 19. Insuring natural ecosystems as an innovative conservation funding mechanism: A case study on coral reefs. In: *Handbook of Disaster Risk Reduction for Resilience: New Frameworks for Building Resilience to Disasters*. Eslamian, S. and F. Eslamian, Eds. Springer, Cham, Switzerland, 435–452. https://doi.org/10.1007/978-3-030-61278-8_19

240. Akamani, K. and T.E. Hall, 2019: Scale and co-management outcomes: Assessing the impact of collaborative forest management on community and household resilience in Ghana. *Heliyon*, **5** (1), e01125. https://doi.org/10.1016/j.heliyon.2019.e01125

241. Jones, H.P., B. Nickel, T. Srebotnjak, W. Turner, M. Gonzalez-Roglich, E. Zavaleta, and D.G. Hole, 2020: Global hotspots for coastal ecosystem-based adaptation. *PLoS ONE*, **15** (5), e0233005. https://doi.org/10.1371/journal.pone.0233005

242. Peck, A.J., S.L. Adams, A. Armstrong, A.K. Bartlett, M.L. Bortman, A.B. Branco, M.L. Brown, J.L. Donohue, M.o. Kodis, M.J. McCann, and E. Smith, 2022: A new framework for flood adaptation: Introducing the Flood Adaptation Hierarchy. *Ecology and Society*, **27** (4). https://doi.org/10.5751/es-13544-270405

243. Donatti, C.I., C.A. Harvey, D. Hole, S.N. Panfil, and H. Schurman, 2020: Indicators to measure the climate change adaptation outcomes of ecosystem-based adaptation. *Climatic Change*, **158** (3), 413–433. https://doi.org/10.1007/s10584-019-02565-9

244. Beck, M.W., N. Heck, S. Narayan, P. Menéndez, B.G. Reguero, S. Bitterwolf, S. Torres-Ortega, G.-M. Lange, K. Pfliegner, V. Pietsch McNulty, and I.J. Losada, 2022: Return on investment for mangrove and reef flood protection. *Ecosystem Services*, **56**, 101440. https://doi.org/10.1016/j.ecoser.2022.101440

245. Reguero, B.G., C.D. Storlazzi, A.E. Gibbs, J.B. Shope, A.D. Cole, K.A. Cumming, and M.W. Beck, 2021: The value of US coral reefs for flood risk reduction. *Nature Sustainability*, **4** (8), 688–698. https://doi.org/10.1038/s41893-021-00706-6

246. Ferreira, V., A.P. Barreira, L. Loures, D. Antunes, and T. Panagopoulos, 2020: Stakeholders' engagement on nature-based solutions: A systematic literature review. *Sustainability*, **12** (2), 640. https://doi.org/10.3390/su12020640

247. Hoover, F.-A., S. Meerow, Z.J. Grabowski, and T. McPhearson, 2021: Environmental justice implications of siting criteria in urban green infrastructure planning. *Journal of Environmental Policy & Planning*, **23** (5), 665–682. https://doi.org/10.1080/1523908x.2021.1945916

248. Jordan, P., F.-A. Hoover, and M.E. Hopton, 2022: Leveraging ancillary benefits from urban greenspace—A case study of St. Louis, Missouri. *Urban Water Journal*, **19** (3), 314–323. https://doi.org/10.1080/1573062x.2021.2001544

249. Jurjonas, M. and E. Seekamp, 2020: 'A commons before the sea:' Climate justice considerations for coastal zone management. *Climate and Development*, **12** (3), 199–203. https://doi.org/10.1080/17565529.2019.1611533

250. Shi, L., 2020: Beyond flood risk reduction: How can green infrastructure advance both social justice and regional impact? *Socio-Ecological Practice Research*, **2** (4), 311–320. https://doi.org/10.1007/s42532-020-00065-0

251. Vasseur, L., 2021: How ecosystem-based adaptation to climate change can help coastal communities through a participatory approach. *Sustainability*, **13** (4), 2344. https://doi.org/10.3390/su13042344

252. Croeser, T., G. Garrard, R. Sharma, A. Ossola, and S. Bekessy, 2021: Choosing the right nature-based solutions to meet diverse urban challenges. *Urban Forestry & Urban Greening*, **65**, 127337. https://doi.org/10.1016/j.ufug.2021.127337

253. Howie, A.H. and M.J. Bishop, 2021: Contemporary oyster reef restoration: Responding to a changing world. *Frontiers in Ecology and Evolution*, **9**, 689915. https://doi.org/10.3389/fevo.2021.689915

254. Kaye, J.P. and M. Quemada, 2017: Using cover crops to mitigate and adapt to climate change. A review. *Agronomy for Sustainable Development*, **37** (1), 1–17. https://doi.org/10.1007/s13593-016-0410-x

255. Law, B.E., L.T. Berner, P.C. Buotte, D.J. Mildrexler, and W.J. Ripple, 2021: Strategic Forest Reserves can protect biodiversity in the western United States and mitigate climate change. *Communications Earth & Environment*, **2** (1), 254. https://doi.org/10.1038/s43247-021-00326-0

256. Carroll, C. and J.C. Ray, 2021: Maximizing the effectiveness of national commitments to protected area expansion for conserving biodiversity and ecosystem carbon under climate change. *Global Change Biology*, **27** (15), 3395–3414. https://doi.org/10.1111/gcb.15645

257. Malhi, Y., T. Lander, E. le Roux, N. Stevens, M. Macias-Fauria, L. Wedding, C. Girardin, J.Å. Kristensen, C.J. Sandom, T.D. Evans, J.-C. Svenning, and S. Canney, 2022: The role of large wild animals in climate change mitigation and adaptation. *Current Biology*, **32** (4), R181–R196. https://doi.org/10.1016/j.cub.2022.01.041

258. Seddon, N., A. Chausson, P. Berry, C.A.J. Girardin, A. Smith, and B. Turner, 2020: Understanding the value and limits of nature-based solutions to climate change and other global challenges. *Philosophical Transactions of the Royal Society B: Biological Sciences*, **375** (1794), 20190120. https://doi.org/10.1098/rstb.2019.0120

259. Fargione, J.E., S. Bassett, T. Boucher, S.D. Bridgham, R.T. Conant, S.C. Cook-patton, P.W. Ellis, A. Falcucci, J.W. Fourqurean, T. Gopalakrishna, H. Gu, B. Henderson, M.D. Hurteau, K.D. Kroeger, T. Kroeger, T.J. Lark, S.M. Leavitt, G. Lomax, R.I. McDonald, J.P. Megonigal, D.A. Miteva, C.J. Richardson, J. Sanderman, D. Shoch, S.A. Spawn, J.W. Veldman, C.A. WIlliams, P.B. Woodbury, C. Zganjar, M. Baranski, R.A. Houghton, E. Landis, E. McGlynn, W.H. Schlesinger, J.V. Siikamakiariana, E. Sutton-Grierand, and B.W. Griscom, 2018: Natural climate solutions for the United States. *Science Advances*, **4** (11), 1869. https://doi.org/10.1126/sciadv.aat1869

260. Shaver, E.C., E. McLeod, M.Y. Hein, S.R. Palumbi, K. Quigley, T. Vardi, P.J. Mumby, D. Smith, P. Montoya-Maya, E.M. Muller, A.T. Banaszak, I.M. McLeod, and D. Wachenfeld, 2022: A roadmap to integrating resilience into the practice of coral reef restoration. *Global Change Biology*, **28** (16), 4751–4764. https://doi.org/10.1111/gcb.16212

261. Taillardat, P., B.S. Thompson, M. Garneau, K. Trottier, and D.A. Friess, 2020: Climate change mitigation potential of wetlands and the cost-effectiveness of their restoration. *Interface Focus*, **10** (5), 20190129. https://doi.org/10.1098/rsfs.2019.0129

262. Kashuba, R., C. Menzie, and L. Martin, 2021: Risk of cardiovascular disease is driven by different combinations of environmental, medical and behavioral factors: Building a conceptual model for cumulative risk assessment. *Human and Ecological Risk Assessment: An International Journal*, **27** (7), 1902–1925. https://doi.org/10.1080/10807039.2021.1925083

263. McDonald, T., G.D. Gann, J. Jonson, and K.W. Dixon, 2016: International Standards for the Practice of Ecological Restoration—Including Principles and Key Concepts. Society for Ecological Restoration, Washington, DC. https://seraustralasia.com/wheel/image/SER_International_Standards.pdf

264. Carruthers, T.J.B., E.P. Kiskaddon, M.M. Baustian, K.M. Darnell, L.C. Moss, C.L. Perry, and C. Stagg, 2022: Tradeoffs in habitat value to maximize natural resource benefits from coastal restoration in a rapidly eroding wetland: Is monitoring land area sufficient? *Restoration Ecology*, **30** (4), e13564. https://doi.org/10.1111/rec.13564

265. Lavorel, S., B. Locatelli, M.J. Colloff, and E. Bruley, 2020: Co-producing ecosystem services for adapting to climate change. *Philosophical Transactions of the Royal Society B: Biological Sciences*, **375** (1794), 20190119. https://doi.org/10.1098/rstb.2019.0119

266. Li, R., H. Zheng, P. O'Connor, H. Xu, Y. Li, F. Lu, B.E. Robinson, Z. Ouyang, Y. Hai, and G.C. Daily, 2021: Time and space catch up with restoration programs that ignore ecosystem service trade-offs. *Science Advances*, **7** (14), 8650. https://doi.org/10.1126/sciadv.abf8650

267. Rossi, R., C. Bisland, L. Sharpe, E. Trentacoste, B. Williams, and S. Yee, 2022: Identifying and aligning ecosystem services and beneficiaries associated with best management practices in Chesapeake Bay watershed. *Environmental Management*, **69** (2), 384–409. https://doi.org/10.1007/s00267-021-01561-z

268. Smardon, R., S. Moran, and A.K. Baptiste, 2018: *Revitalizing Urban Waterway Communities: Streams of Environmental Justice*. Routledge, London, UK and New York, USA, 228 pp. https://www.routledge.com/revitalizing-urban-waterway-communities-streams-of-environmental-justice/smardon-moran-baptiste/p/book/9780367605896

269. Dockry, M.J. and S.J. Hoagland, 2017: A special issue of the *Journal of Forestry*—Tribal forest management: Innovations for sustainable forest management. *Journal of Forestry*, **115** (5), 339–340. https://doi.org/10.5849/jof-2017-040

270. Jacobson, M.A., R. Hajjar, E.J. Davis, and S. Hoagland, 2021: Learning from tribal leadership and the anchor forest concept for implementing cross-boundary forest management. *Journal of Forestry*, **119** (6), 605–617. https://doi.org/10.1093/jofore/fvab031

271. Long, J.W., R.W. Goode, and F.K. Lake, 2020: Recentering ecological restoration with tribal perspectives. *Fremontia*, **48** (1), 14–19. https://www.fs.usda.gov/research/treesearch/61600

272. Reyes-García, V., Á. Fernández-Llamazares, P. McElwee, Z. Molnár, K. Öllerer, S.J. Wilson, and E.S. Brondizio, 2019: The contributions of Indigenous Peoples and local communities to ecological restoration. *Restoration Ecology*, **27** (1), 3–8. https://doi.org/10.1111/rec.12894

273. Biggs, R., G. D. Peterson, and J. C. Rocha, 2018: The regime shifts database: A framework for analyzing regime shifts in social-ecological systems. *Ecology and Society*, **23** (3), 9. https://doi.org/10.5751/es-10264-230309

274. Breshears, D.D., C.J.W. Carroll, M.D. Redmond, A.P. Wion, C.D. Allen, N.S. Cobb, N. Meneses, J.P. Field, L.A. Wilson, D.J. Law, L.M. McCabe, and O. Newell-Bauer, 2018: A dirty dozen ways to die: Metrics and modifiers of mortality driven by drought and warming for a tree species. *Frontiers in Forests and Global Change*, **1**, 4. https://doi.org/10.3389/ffgc.2018.00004

275. Canadell, J.G. and R.B. Jackson, Eds., 2021: *Ecosystem Collapse and Climate Change*. Springer, Cham, Switzerland, 366 pp. https://doi.org/10.1007/978-3-030-71330-0

276. Davis, K.T., S.Z. Dobrowski, P.E. Higuera, Z.A. Holden, T.T. Veblen, M.T. Rother, S.A. Parks, A. Sala, and M.P. Maneta, 2019: Wildfires and climate change push low-elevation forests across a critical climate threshold for tree regeneration. *Proceedings of the National Academy of Sciences of the United States of America*, **116** (13), 6193–6198. https://doi.org/10.1073/pnas.1815107116

277. Stevens-Rumann, C.S., K.B. Kemp, P.E. Higuera, B.J. Harvey, M.T. Rother, D.C. Donato, P. Morgan, and T.T. Veblen, 2018: Evidence for declining forest resilience to wildfires under climate change. *Ecology Letters*, **21** (2), 243–252. https://doi.org/10.1111/ele.12889

278. Guiterman, C.H., E.Q. Margolis, C.D. Allen, D.A. Falk, and T.W. Swetnam, 2018: Long-term persistence and fire resilience of oak shrubfields in dry conifer forests of northern New Mexico. *Ecosystems*, **21** (5), 943–959. https://www.jstor.org/stable/48719582

279. O'Connor, C.D., D.A. Falk, and G.M. Garfin, 2020: Projected climate-fire interactions drive forest to shrubland transition on an Arizona Sky Island. *Frontiers in Environmental Science*, **8**, 137. https://doi.org/10.3389/fenvs.2020.00137

280. van Mantgem, P.J., D.A. Falk, E.C. Williams, A.J. Das, and N.L. Stephenson, 2020: The influence of pre-fire growth patterns on post-fire tree mortality for common conifers in western US parks. *International Journal of Wildland Fire*, **29** (6), 513–518. https://doi.org/10.1071/wf19020

281. Allen, J.M. and B.A. Bradley, 2016: Out of the weeds? Reduced plant invasion risk with climate change in the continental United States. *Biological Conservation*, **203**, 306–312. https://doi.org/10.1016/j.biocon.2016.09.015

282. Crall, A.W., G.J. Newman, C.S. Jarnevich, T.J. Stohlgren, D.M. Waller, and J. Graham, 2010: Improving and integrating data on invasive species collected by citizen scientists. *Biological Invasions*, **12** (10), 3419–3428. https://doi.org/10.1007/s10530-010-9740-9

283. Lázaro-Lobo, A., R.D. Lucardi, C. Ramirez-Reyes, and G.N. Ervin, 2021: Region-wide assessment of fine-scale associations between invasive plants and forest regeneration. *Forest Ecology and Management*, **483**, 118930. https://doi.org/10.1016/j.foreco.2021.118930

284. Prevéy, J., M. Vellend, N. Rüger, R.D. Hollister, A.D. Bjorkman, I.H. Myers-Smith, S.C. Elmendorf, K. Clark, E.J. Cooper, B. Elberling, A.M. Fosaa, G.H.R. Henry, T.T. Høye, I.S. Jónsdóttir, K. Klanderud, E. Lévesque, M. Mauritz, U. Molau, S.M. Natali, S.F. Oberbauer, Z.A. Panchen, E. Post, S.B. Rumpf, N.M. Schmidt, E.A.G. Schuur, P.R. Semenchuk, T. Troxler, J.M. Welker, and C. Rixen, 2017: Greater temperature sensitivity of plant phenology at colder sites: Implications for convergence across northern latitudes. *Global Change Biology*, **23** (7), 2660–2671. https://doi.org/10.1111/gcb.13619

285. Boyd, P.W., S. Collins, S. Dupont, K. Fabricius, J.-P. Gattuso, J. Havenhand, D.A. Hutchins, U. Riebesell, M.S. Rintoul, M. Vichi, H. Biswas, A. Ciotti, K. Gao, M. Gehlen, C.L. Hurd, H. Kurihara, C.M. McGraw, J.M. Navarro, G.E. Nilsson, U. Passow, and H.-O. Pörtner, 2018: Experimental strategies to assess the biological ramifications of multiple drivers of global ocean change—A review. *Global Change Biology*, **24** (6), 2239–2261. https://doi.org/10.1111/gcb.14102

286. Turley, C. and J.-P. Gattuso, 2012: Future biological and ecosystem impacts of ocean acidification and their socioeconomic-policy implications. *Current Opinion in Environmental Sustainability*, **4** (3), 278–286. https://doi.org/10.1016/j.cosust.2012.05.007

287. Agne, M.C., P.A. Beedlow, D.C. Shaw, D.R. Woodruff, E.H. Lee, S.P. Cline, and R.L. Comeleo, 2018: Interactions of predominant insects and diseases with climate change in Douglas-fir forests of western Oregon and Washington, U.S.A. *Forest Ecology and Management*, **409**, 317–332. https://doi.org/10.1016/j.foreco.2017.11.004

288. Seidl, R., D. Thom, M. Kautz, D. Martin-Benito, M. Peltoniemi, G. Vacchiano, J. Wild, D. Ascoli, M. Petr, J. Honkaniemi, M.J. Lexer, V. Trotsiuk, P. Mairota, M. Svoboda, M. Fabrika, T.A. Nagel, and C.P.O. Reyer, 2017: Forest disturbances under climate change. *Nature Climate Change*, **7** (6), 395–402. https://doi.org/10.1038/nclimate3303

289. Finch, D.M., J.L. Butler, J.B. Runyon, C.J. Fettig, F.F. Kilkenny, S. Jose, S.J. Frankel, S.A. Cushman, R.C. Cobb, J.S. Dukes, J.A. Hicke, and S.K. Amelon, 2021: Ch. 4. Effects of climate change on invasive species. In: *Invasive Species in Forests and Rangelands of the United States: A Comprehensive Science Synthesis for the United States Forest Sector*. Poland, T.M., T. Patel-Weynand, D.M. Finch, C.F. Miniat, D.C. Hayes, and V.M. Lopez, Eds. Springer, Cham, Switzerland, 57–83. https://doi.org/10.1007/978-3-030-45367-1_4

290. Gandhi, K. and R. Hofstetter, Eds., 2021: *Bark Beetle Management, Ecology, and Climate Change*. Academic Press. https://doi.org/10.1016/c2019-0-04282-3

291. Jactel, H., J. Koricheva, and B. Castagneyrol, 2019: Responses of forest insect pests to climate change: Not so simple. *Current Opinion in Insect Science*, **35**, 103–108. https://doi.org/10.1016/j.cois.2019.07.010

292. Lopez, B.E., J.M. Allen, J.S. Dukes, J. Lenoir, M. Vilà, D.M. Blumenthal, E.M. Beaury, E.J. Fusco, B.B. Laginhas, T.L. Morelli, M.W. O'Neill, C.J.B. Sorte, A. Maceda-Veiga, R. Whitlock, and B.A. Bradley, 2022: Global environmental changes more frequently offset than intensify detrimental effects of biological invasions. *Proceedings of the National Academy of Sciences of the United States of America*, **119** (22), e2117389119. https://doi.org/10.1073/pnas.2117389119

293. Lucash, M.S., R.M. Scheller, B.R. Sturtevant, E.J. Gustafson, A.M. Kretchun, and J.R. Foster, 2018: More than the sum of its parts: How disturbance interactions shape forest dynamics under climate change. *Ecosphere*, **9** (6), e02293. https://doi.org/10.1002/ecs2.2293

294. Hastings, A., K.C. Abbott, K. Cuddington, T. Francis, G. Gellner, Y.-C. Lai, A. Morozov, S. Petrovskii, K. Scranton, and M.L. Zeeman, 2018: Transient phenomena in ecology. *Science*, **361** (6406), 6412. https://doi.org/10.1126/science.aat6412

295. Hughes, T.P., C. Linares, V. Dakos, I.A. van de Leemput, and E.H. van Nes, 2013: Living dangerously on borrowed time during slow, unrecognized regime shifts. *Trends in Ecology & Evolution*, **28** (3), 149–155. https://doi.org/10.1016/j.tree.2012.08.022

296. Tang, B., J.S. Clark, and A.E. Gelfand, 2021: Modeling spatially biased citizen science effort through the eBird database. *Environmental and Ecological Statistics*, **28** (3), 609–630. https://doi.org/10.1007/s10651-021-00508-1

297. Olsson, P., V. Galaz, and W.J. Boonstra, 2014: Sustainability transformations: A resilience perspective. *Ecology and Society*, **19** (4). https://doi.org/10.5751/es-06799-190401

298. Walker, B., S.R. Carpenter, C. Folke, L. Gunderson, G.D. Peterson, M. Scheffer, M. Schoon, and F.R. Westley, 2020: Navigating the chaos of an unfolding global cycle. *Ecology and Society*, **25** (4). https://doi.org/10.5751/es-12072-250423

299. Allen, C.R. and L.H. Gunderson, 2011: Pathology and failure in the design and implementation of adaptive management. *Journal of Environmental Management*, **92** (5), 1379–1384. https://doi.org/10.1016/j.jenvman.2010.10.063

300. Kochskämper, E., T.M. Koontz, and J. Newig, 2021: Systematic learning in water governance: Insights from five local adaptive management projects for water quality innovation. *Ecology and Society*, **26** (1). https://doi.org/10.5751/es-12080-260122

301. Peat, M., K. Moon, F. Dyer, W. Johnson, and S.J. Nichols, 2017: Creating institutional flexibility for adaptive water management: Insights from two management agencies. *Journal of Environmental Management*, **202**, 188–197. https://doi.org/10.1016/j.jenvman.2017.06.059

302. West, S., R. Beilin, and H. Wagenaar, 2019: Introducing a practice perspective on monitoring for adaptive management. *People and Nature*, **1** (3), 387–405. https://doi.org/10.1002/pan3.10033

303. Walker, B.H., 2012: A commentary on "Resilience and water governance: Adaptive governance in the Columbia River Basin". *Ecology and Society*, **17** (4). https://doi.org/10.5751/es-05422-170429

304. Eshuis, J. and L. Gerrits, 2021: The limited transformational power of adaptive governance: A study of institutionalization and materialization of adaptive governance. *Public Management Review*, **23** (2), 276–296. https://doi.org/10.1080/14719037.2019.1679232

305. Burch, S., A. Gupta, C.Y.A. Inoue, A. Kalfagianni, Å. Persson, A.K. Gerlak, A. Ishii, J. Patterson, J. Pickering, M. Scobie, J. Van der Heijden, J. Vervoort, C. Adler, M. Bloomfield, R. Djalante, J. Dryzek, V. Galaz, C. Gordon, R. Harmon, S. Jinnah, R.E. Kim, L. Olsson, J. Van Leeuwen, V. Ramasar, P. Wapner, and R. Zondervan, 2019: New directions in earth system governance research. *Earth System Governance*, **1**, 100006. https://doi.org/10.1016/j.esg.2019.100006

306. Dewulf, A., T. Karpouzoglou, J. Warner, A. Wesselink, F. Mao, J. Vos, P. Tamas, A.E. Groot, A. Heijmans, F. Ahmed, L. Hoang, S. Vij, and W. Buytaert, 2019: The power to define resilience in social–hydrological systems: Toward a power-sensitive resilience framework. *WIREs Water*, **6** (6), e1377. https://doi.org/10.1002/wat2.1377

307. Koontz, T.M., D. Gupta, P. Mudliar, and P. Ranjan, 2015: Adaptive institutions in social-ecological systems governance: A synthesis framework. *Environmental Science & Policy*, **53**, 139–151. https://doi.org/10.1016/j.envsci.2015.01.003

308. Morrison, T.H., W.N. Adger, K. Brown, M.C. Lemos, D. Huitema, J. Phelps, L. Evans, P. Cohen, A.M. Song, R. Turner, T. Quinn, and T.P. Hughes, 2019: The black box of power in polycentric environmental governance. *Global Environmental Change*, **57**, 101934. https://doi.org/10.1016/j.gloenvcha.2019.101934

309. Fedele, G., C.I. Donatti, C.A. Harvey, L. Hannah, and D.G. Hole, 2019: Transformative adaptation to climate change for sustainable social-ecological systems. *Environmental Science & Policy*, **101**, 116–125. https://doi.org/10.1016/j.envsci.2019.07.001

310. Barnes, M.L., P. Wang, J.E. Cinner, N.A.J. Graham, A.M. Guerrero, L. Jasny, J. Lau, S.R. Sutcliffe, and J. Zamborain-Mason, 2020: Social determinants of adaptive and transformative responses to climate change. *Nature Climate Change*, **10** (9), 823–828. https://doi.org/10.1038/s41558-020-0871-4

311. Wilson, R.S., A. Herziger, M. Hamilton, and J.S. Brooks, 2020: From incremental to transformative adaptation in individual responses to climate-exacerbated hazards. *Nature Climate Change*, **10** (3), 200–208. https://doi.org/10.1038/s41558-020-0691-6

312. Anderegg, W.R.L., L.D.L. Anderegg, K.L. Kerr, and A.T. Trugman, 2019: Widespread drought-induced tree mortality at dry range edges indicates that climate stress exceeds species' compensating mechanisms. *Global Change Biology*, **25** (11), 3793–3802. https://doi.org/10.1111/gcb.14771

313. Ralston, J., W.V. DeLuca, R.E. Feldman, and D.I. King, 2017: Population trends influence species ability to track climate change. *Global Change Biology*, **23** (4), 1390–1399. https://doi.org/10.1111/gcb.13478

314. Pinsky, M.L., R.L. Selden, and Z.J. Kitchel, 2020: Climate-driven shifts in marine species ranges: Scaling from organisms to communities. *Annual Review of Marine Science*, **12** (1), 153–179. https://doi.org/10.1146/annurev-marine-010419-010916

315. Poloczanska, E.S., C.J. Brown, W.J. Sydeman, W. Kiessling, D.S. Schoeman, P.J. Moore, K. Brander, J.F. Bruno, L.B. Buckley, M.T. Burrows, C.M. Duarte, B.S. Halpern, J. Holding, C.V. Kappel, M.I. O'Connor, J.M. Pandolfi, C. Parmesan, F. Schwing, S.A. Thompson, and A.J. Richardson, 2013: Global imprint of climate change on marine life. *Nature Climate Change*, **3** (10), 919–925. https://doi.org/10.1038/nclimate1958

316. Kinlan, B.P. and S.D. Gaines, 2003: Propagule dispersal in marine and terrestrial environments: A community perspective. *Ecology*, **84** (8), 2007–2020. https://doi.org/10.1890/01-0622

317. Pinsky, M.L., A.M. Eikeset, D.J. McCauley, J.L. Payne, and J.M. Sunday, 2019: Greater vulnerability to warming of marine versus terrestrial ectotherms. *Nature*, **569** (7754), 108–111. https://doi.org/10.1038/s41586-019-1132-4

318. Robinson, L.M., J. Elith, A.J. Hobday, R.G. Pearson, B.E. Kendall, H.P. Possingham, and A.J. Richardson, 2011: Pushing the limits in marine species distribution modelling: Lessons from the land present challenges and opportunities. *Global Ecology and Biogeography*, **20** (6), 789–802. https://doi.org/10.1111/j.1466-8238.2010.00636.x

319. Arietta, A.Z.A., L.K. Freidenburg, M.C. Urban, S.B. Rodrigues, A. Rubinstein, and D.K. Skelly, 2020: Phenological delay despite warming in wood frog *Rana sylvatica* reproductive timing: A 20-year study. *Ecography*, **43** (12), 1791–1800. https://doi.org/10.1111/ecog.05297

320. Johnson, H.E., D.L. Lewis, T.L. Verzuh, C.F. Wallace, R.M. Much, L.K. Willmarth, and S.W. Breck, 2018: Human development and climate affect hibernation in a large carnivore with implications for human–carnivore conflicts. *Journal of Applied Ecology*, **55** (2), 663–672. https://doi.org/10.1111/1365-2664.13021

321. Büntgen, U., A. Piermattei, P.J. Krusic, J. Esper, T. Sparks, and A. Crivellaro, 2022: Plants in the UK flower a month earlier under recent warming. *Proceedings of the Royal Society B: Biological Sciences*, **289** (1968), 20212456. https://doi.org/10.1098/rspb.2021.2456

322. Orgeret, F., A. Thiebault, K.M. Kovacs, C. Lydersen, M.A. Hindell, S.A. Thompson, W.J. Sydeman, and P.A. Pistorius, 2022: Climate change impacts on seabirds and marine mammals: The importance of study duration, thermal tolerance and generation time. *Ecology Letters*, **25** (1), 218–239. https://doi.org/10.1111/ele.13920

323. Maurer, A.S., K. Gross, and S.P. Stapleton, 2022: Beached Sargassum alters sand thermal environments: Implications for incubating sea turtle eggs. *Journal of Experimental Marine Biology and Ecology*, **546**, 151650. https://doi.org/10.1016/j.jembe.2021.151650

324. Ware, M., S.A. Ceriani, J.W. Long, and M.M.P.B. Fuentes, 2021: Exposure of loggerhead sea turtle nests to waves in the Florida Panhandle. *Remote Sensing*, **13** (14), 2654. https://doi.org/10.3390/rs13142654

325. Cohen, J.M., E.L. Sauer, O. Santiago, S. Spencer, and J.R. Rohr, 2020: Divergent impacts of warming weather on wildlife disease risk across climates. *Science*, **370** (6519), eabb1702. https://doi.org/10.1126/science.abb1702

326. Gibb, R., D.W. Redding, K.Q. Chin, C.A. Donnelly, T.M. Blackburn, T. Newbold, and K.E. Jones, 2020: Zoonotic host diversity increases in human-dominated ecosystems. *Nature*, **584** (7821), 398–402. https://doi.org/10.1038/s41586-020-2562-8

327. Fisher, M.C. and T.W.J. Garner, 2020: Chytrid fungi and global amphibian declines. *Nature Reviews Microbiology*, **18** (6), 332–343. https://doi.org/10.1038/s41579-020-0335-x

328. Elith, J. and J.R. Leathwick, 2009: Species distribution models: Ecological explanation and prediction across space and time. *Annual Review of Ecology, Evolution, and Systematics*, **40** (1), 677–697. https://doi.org/10.1146/annurev.ecolsys.110308.120159

329. Midgley, G.F., W. Thuiller, and S.I. Higgins, 2007: Ch. 11. Plant species migration as a key uncertainty in predicting future impacts of climate change on ecosystems: Progress and challenges. In: *Terrestrial Ecosystems in a Changing World*. Canadell, J.G., D.E. Pataki, and L.F. Pitelka, Eds. Springer Berlin Heidelberg, Berlin, Heidelberg, 129–137. https://doi.org/10.1007/978-3-540-32730-1_11

330. Moullec, F., N. Barrier, S. Drira, F. Guilhaumon, T. Hattab, M.A. Peck, and Y.-J. Shin, 2022: Using species distribution models only may underestimate climate change impacts on future marine biodiversity. *Ecological Modelling*, **464**, 109826. https://doi.org/10.1016/j.ecolmodel.2021.109826

331. Hoveka, L.N., M. van der Bank, and T.J. Davies, 2022: Winners and losers in a changing climate: How will protected areas conserve red list species under climate change? *Diversity and Distributions*, **28** (4), 782–792. https://doi.org/10.1111/ddi.13488

332. Samplonius, J.M., A. Atkinson, C. Hassall, K. Keogan, S.J. Thackeray, J.J. Assmann, M.D. Burgess, J. Johansson, K.H. Macphie, J.W. Pearce-Higgins, E.G. Simmonds, Ø. Varpe, J.C. Weir, D.Z. Childs, E.F. Cole, F. Daunt, T. Hart, O.T. Lewis, N. Pettorelli, B.C. Sheldon, and A.B. Phillimore, 2021: Strengthening the evidence base for temperature-mediated phenological asynchrony and its impacts. *Nature Ecology & Evolution*, **5** (2), 155–164. https://doi.org/10.1038/s41559-020-01357-0

333. Thomas, K., R.D. Hardy, H. Lazrus, M. Mendez, B. Orlove, I. Rivera-Collazo, J.T. Roberts, M. Rockman, B.P. Warner, and R. Winthrop, 2019: Explaining differential vulnerability to climate change: A social science review. *WIREs Climate Change*, **10** (2), e565. https://doi.org/10.1002/wcc.565

334. Winkler, K.J., M.C. Dade, and J.T. Rieb, 2021: Mismatches in the ecosystem services literature—A review of spatial, temporal, and functional-conceptual mismatches. *Current Landscape Ecology Reports*, **6** (2), 23–34. https://doi.org/10.1007/s40823-021-00063-2

335. Heris, M., K.J. Bagstad, C. Rhodes, A. Troy, A. Middel, K.G. Hopkins, and J. Matuszak, 2021: Piloting urban ecosystem accounting for the United States. *Ecosystem Services*, **48**, 101226. https://doi.org/10.1016/j.ecoser.2020.101226

336. Aronson, M.F., C.A. Lepczyk, K.L. Evans, M.A. Goddard, S.B. Lerman, J.S. MacIvor, C.H. Nilon, and T. Vargo, 2017: Biodiversity in the city: Key challenges for urban green space management. *Frontiers in Ecology and the Environment*, **15** (4), 189–196. https://doi.org/10.1002/fee.1480

337. Meerow, S. and J.P. Newell, 2017: Spatial planning for multifunctional green infrastructure: Growing resilience in Detroit. *Landscape and Urban Planning*, **159**, 62–75. https://doi.org/10.1016/j.landurbplan.2016.10.005

338. Grabowski, Z.J., T. McPhearson, A.M. Matsler, P. Groffman, and S.T.A. Pickett, 2022: What is green infrastructure? A study of definitions in US city planning. *Frontiers in Ecology and the Environment*, **20** (3), 152–160. https://doi.org/10.1002/fee.2445

339. Hoover, F.-A. and M.E. Hopton, 2019: Developing a framework for stormwater management: Leveraging ancillary benefits from urban greenspace. *Urban Ecosystems*, **22** (6), 1139–1148. https://doi.org/10.1007/s11252-019-00890-6

340. Shriver, R.K., C.M. Andrews, D.S. Pilliod, R.S. Arkle, J.L. Welty, M.J. Germino, M.C. Duniway, D.A. Pyke, and J.B. Bradford, 2018: Adapting management to a changing world: Warm temperatures, dry soil, and interannual variability limit restoration success of a dominant woody shrub in temperate drylands. *Global Change Biology*, **24** (10), 4972–4982. https://doi.org/10.1111/gcb.14374

341. Simonson, W.D., E. Miller, A. Jones, S. García-Rangel, H. Thornton, and C. McOwen, 2021: Enhancing climate change resilience of ecological restoration—A framework for action. *Perspectives in Ecology and Conservation*, **19** (3), 300–310. https://doi.org/10.1016/j.pecon.2021.05.002

342. Hobbs, R.J., 2016: Degraded or just different? Perceptions and value judgements in restoration decisions. *Restoration Ecology*, **24** (2), 153–158. https://doi.org/10.1111/rec.12336

343. Opperman, J.J. and G.E. Galloway, 2022: Nature-based solutions for managing rising flood risk and delivering multiple benefits. *One Earth*, **5** (5), 461–465. https://doi.org/10.1016/j.oneear.2022.04.012

344. Lynham, J., B.S. Halpern, T. Blenckner, T. Essington, J. Estes, M. Hunsicker, C. Kappel, A.K. Salomon, C. Scarborough, K.A. Selkoe, and A. Stier, 2017: Costly stakeholder participation creates inertia in marine ecosystems. *Marine Policy*, **76**, 122–129. https://doi.org/10.1016/j.marpol.2016.11.011

345. Aidoo, F.S., 2021: Architectures of mis/managed retreat: Black land loss to green housing gains. *Journal of Environmental Studies and Sciences*, **11** (3), 451–464. https://doi.org/10.1007/s13412-021-00684-3

346. Heck, S., 2021: Greening the color line: Historicizing water infrastructure redevelopment and environmental justice in the St. Louis metropolitan region. *Journal of Environmental Policy & Planning*, **23** (5), 565–580. https://doi.org/10.1080/1523908x.2021.1888702

347. Buck, H.J., J. Furhman, D.R. Morrow, D.L. Sanchez, and F.M. Wang, 2020: Adaptation and carbon removal. *One Earth*, **3** (4), 425–435. https://doi.org/10.1016/j.oneear.2020.09.008