Fifth National Climate Assessment: Chapter 7

Forests

Chapter 7. Forests

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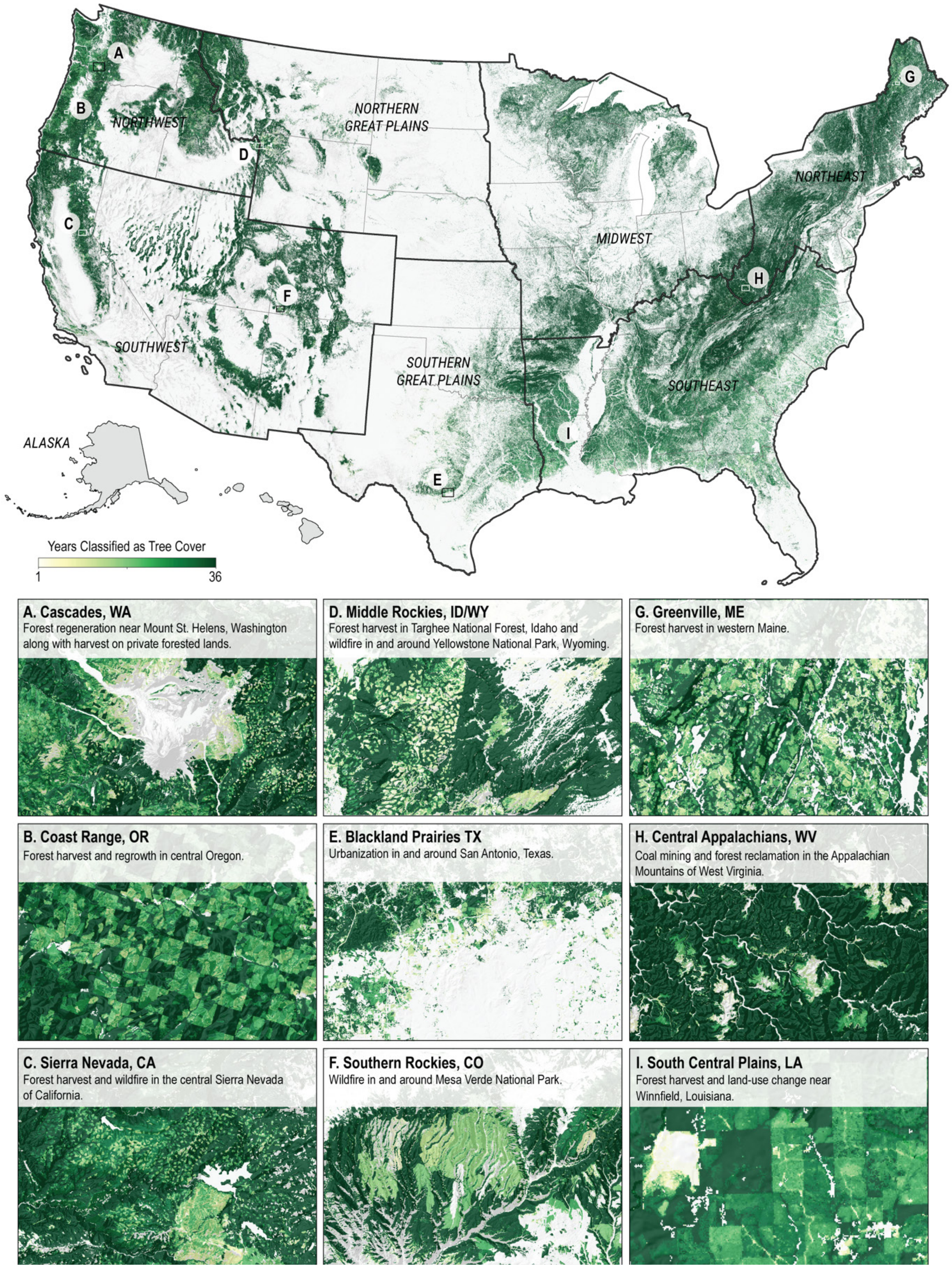
Introduction

Forest ecosystems provide ecological, economic, and social goods and services (hereafter ecosystem services) to natural systems and humankind. These include air purification; regulating water quantity and quality; provisioning fish and wildlife habitat, food, medicine, shelter, wood, and other forest products; provisioning aesthetics, outdoor recreation, and spiritual renewal; and regulating climate through carbon transfers and other processes.[1] The livelihoods, health, nutrition, and cultural practices and traditions of many Indigenous and Tribal Peoples depend on forest ecosystems (Ch. 16). Social and economic drivers influence how and when forests are managed to maintain or restore ecosystem services critical to human health and welfare.

Forests represent more than one-third (766 million acres) of the land base in the US, with an additional 125 million acres of trees outside of forests in woodlands and developed areas. The amount of forest and tree cover has remained relatively stable over the last 100 years despite substantial land-use change into and out of forest and tree cover, especially in recent decades (Figures 7.1, 6.2).[2] Forest land area and tree cover have declined slightly in the contiguous US in the last two decades due mostly to cropland expansion and urbanization (Figure 6.4),[3,4] including expansion of the wildland–urban interface (WUI).[5] Forests contributed more than 4% of total US manufacturing gross domestic product in 2020 (nearly $336 billion in 2022 dollars), and the forest products industry is among the top 10 manufacturing sector employers in the US.[6]

Tree Cover Dynamics

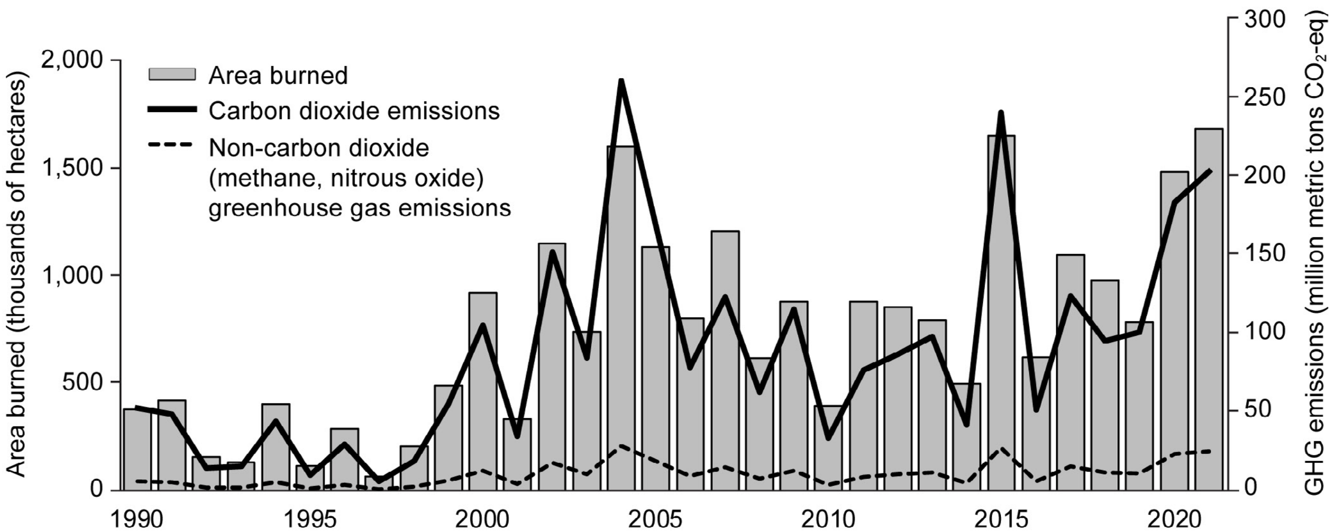


The persistence of tree cover in the United States varies due to many driving forces.

Figure 7.1. This figure shows the number of years each 30 m by 30 m pixel was classified as forest cover during 1985–2020. Insets (**A–I**) show that patterns of forest cover vary considerably across regions, often due to differences in the factors causing forest change. Patterns in tree cover change in the US are driven, in large part, by climate-related disturbances, land use, and land-use change. Data were unavailable for Alaska, Hawai'i and the Affiliated US Pacific Islands, and the US Caribbean. Figure credit: USGS.

The vulnerability of US forests to climate change and climate-related disturbances varies (relative to natural variability) due to differences in biophysical conditions and local and regional variations in climate (Chs. 2, 3). For example, although 21st-century temperatures (2001–2020) have increased almost everywhere in the US (relative to 1951–1970), this warming has not occurred uniformly across the US (KM 3.4; Figure 3.11). Due to these differences, the capacity of some US forests to provide ecosystem services is increasingly affected by climate change and climate-related disturbances (KMs 7.1, 7.2).[7] For example, the amount of forest burned and greenhouse gas (GHG) emissions from fires have increased substantially since 1990, mostly in the West, with three of the five worst wildfire years (based on area burned and GHG emissions) occurring since 2015 (Figure 7.2).[3] Proactive adaptation will assist the provisioning of ecosystem services from forests. Examples of adaptation in US forests have proliferated since 2017 (KM 7.3; Ch. 31) on federal, state, local, Tribal, and private lands (e.g., Moser et al. 2019;[8] USDA 2022,[9] 2021[10]). The effects of climate change on forests in specific regions of the US are discussed in several of the regional chapters (e.g., Chs. 21–24, 27–29).

Estimated Annual Greenhouse Gas (GHG) Emissions from Wildfires and Prescribed Fires



The amount of forest area burned and associated greenhouse gas emissions have increased in recent decades in the United States.

Figure 7.2. Estimated forest area burned and greenhouse gas emissions (carbon dioxide, methane, and nitrous oxide) from wildfires and prescribed fires in the contiguous US and Alaska have increased since the late 1990s. Climate change is affecting the likelihood and scale of wildfires in US forests. In some cases, wildfires (particularly in the western US) have slowed or stopped recovery of forests from previous disturbances, reducing their capacity to sequester and store carbon. Adapted from Domke et al. 2023.[3]

Key Message 7.1

Forests Are Increasingly Affected by Climate Change and Disturbances

Climate change is increasing the frequency, scale, and severity of some disturbances that drive forest change and affect ecosystem services (*high confidence*). Continued warming and regional changes in precipitation are expected to amplify interactions among disturbance agents (*likely*, *high confidence*) and further alter forest ecosystem structure and function (*likely*, *high confidence*).

Climate change affects disturbances such as wildfires, insects, diseases, and land uses, as well as the interactions among these disturbances, all of which shape forest ecosystems through changes in growth, mortality, regeneration, and recruitment of vegetation over space and time (Figure 6.1 in Vose et al. 2018[11]). Disturbances altered by climate change pose risks to current and future forest health (i.e., the extent to which ecosystem processes are functioning within their natural range of historical variation) and will affect forest conditions across landscapes for years to centuries. Weather events such as droughts, hurricanes, windstorms, and floods may exacerbate disturbance effects, especially in extreme cases (Figure 7.3; Chs. 8, 9). The exposure and sensitivity of forests to climate change and climate-related disturbances vary with disturbance, forest condition, management history, and the rate and magnitude of change.

Coastal Ghost Forest

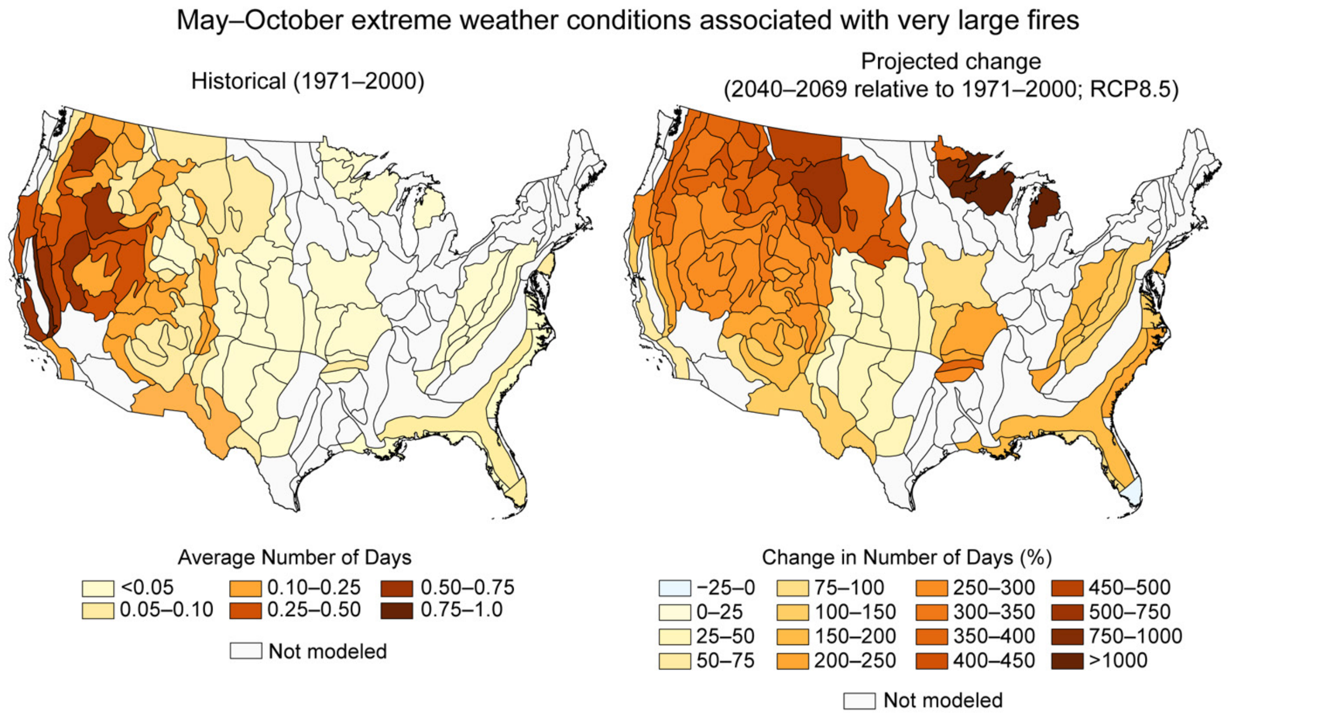
Coastal ghost forests result when trees are killed by sea level rise and saltwater intrusion.

Figure 7.3. The photo shows a coastal ghost forest (foreground) near Blackwater National Wildlife Refuge, Maryland. As sea levels rise in response to climate change, the replacement of coastal forests with tidal wetlands will affect many ecosystem services, including storm surge buffering capacity. Photo credit: ©Matthew L. Kirwan, Virginia Institute of Marine Science.

Climate change is affecting the likelihood and scale of wildfires in US forests. For example, the amount of forest burned by wildfires in the West has increased relative to the mid- to late 20th century[12,13] due, in part, to warming increasing vapor pressure deficits and rates of evapotranspiration (KM 4.1),[12,14] as well as decreases in precipitation (KM 4.1).[15] Fire activity is projected to increase with further warming and reductions in precipitation,[14,16] although increases depend on regional fuel types and may eventually decrease in some forests due to reductions in fuel loads.[17] The area burned by high-severity wildfires (e.g., stand-replacing fires) has increased in the West since 1985 by about eightfold,[18] partly due to warmer, drier conditions (Figure 7.4; KM 2.1). Where abundant fuels are available, western US forests have experienced an increase in the proportion of area burned at high severity, especially in the Southwest (KM 28.5).[18] Increased fire severity is expected to become more widespread in US forests in the future.[19] Atypical re-burns and levels of fuel flammability that were historically rare are expected to become more common (Focus on Western Wildfires).

Determining the effects of climate change on wildfires is more difficult in regions outside the West, for example, in areas where prescribed fire use has changed substantially over time (Southeast), where wildfire was historically rare (Northeast), and where forests represent a small portion of the landscape (agricultural regions in the central US). Furthermore, fire intensity (energy released during wildfire) and severity depend on fuel availability and flammability, which are directly affected by management (including wildfire suppression) and land use,[20] as well as climate-driven changes in weather. However, altered meteorological conditions (e.g., relative humidity and wind speed), especially extreme conditions promoting wildfire spread, have become more prevalent in recent decades[21] and are attributed, in part, to climate change (KM 2.2).[22] Changes in human demography in the WUI and increases in the ratio of human to natural fire ignitions[23] have combined with climate change to alter historical expectations of fire initiation and spread. One study found that a long-term trend in nighttime vapor pressure deficit, not simulated in climate models, explained recent fire managers' observations that the rates of spread of fires in the West slowed less at night.[24]

Very Large Fires



Conditions conducive to very large fires are projected to increase.

Figure 7.4. The left panel shows historical (1971–2000) values for the annual number of days in May through October with extreme weather conditions conducive to very large fires (VLFs; more than 12,000 acres). The right panel shows the percent change in the number of days for a projected future (2040–2069) climate under a very high scenario (RCP8.5). Changes are summarized by Bailey ecosections, which are areas of similar vegetation and climate defined by Bailey (2016).[25] The number of days with conditions associated with VLFs more than doubles in many ecosections, with more than a fourfold increase for parts of the Northwest, fivefold for the northern Rockies, and over sevenfold for the Upper Midwest. Projected conditions are an average of a 17-GCM (global climate model) ensemble selected for data availability. Areas with no color indicate lack of data (sufficient data are unavailable or where wildfires were historically rare). Data were unavailable for Alaska, Hawai'i and the Affiliated US Pacific Islands, and the US Caribbean. Figure credit: USGS.

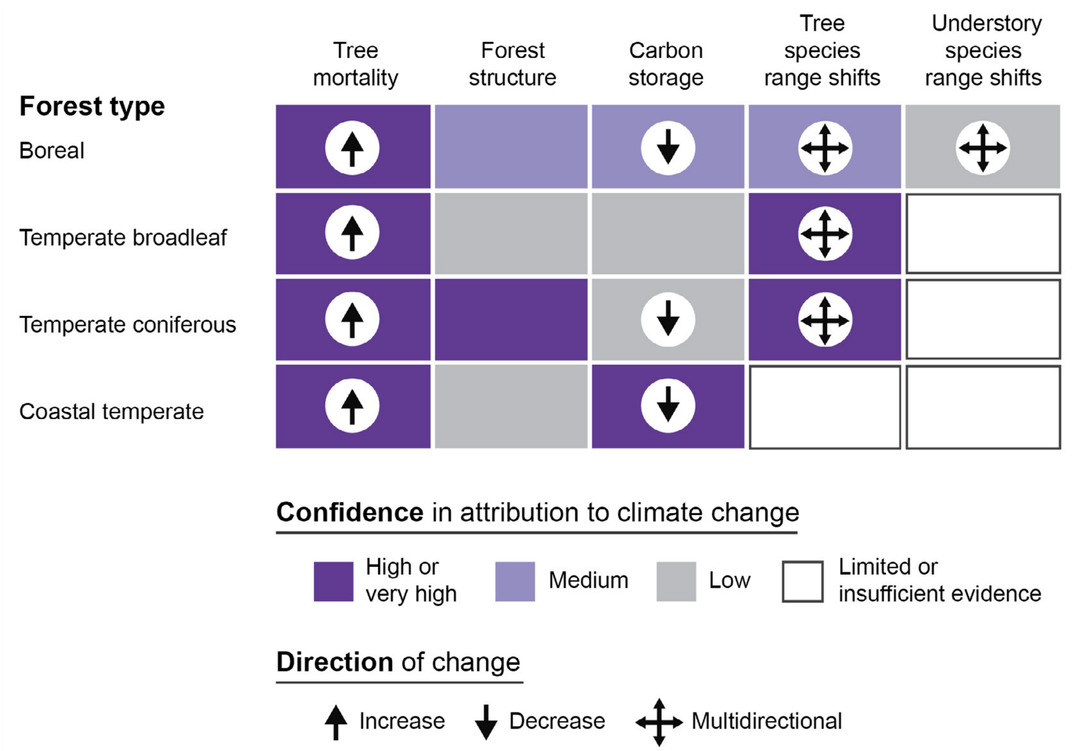
In addition to wildfire, native and invasive (non-native) insects, diseases, and plants are important forest disturbances with climatic and non-climatic factors influencing their extent and effects. Tree mortality from bark beetles in the West has increased in the late 20th and early 21st centuries due, in part, to climate change (Box 7.1).[26,27,28,29] The effects of climate change on other forest insects and diseases are less certain. For example, white pine blister rust (a disease caused by the non-native fungus *Cronartium ribicola*) is expected to decrease where conditions become warmer and drier (Southwest) but increase where conditions become warmer and wetter (high-elevation subalpine forests).[30] Warming, altered precipitation patterns, extreme events, and disturbances all influence invasion pathways and may facilitate the establishment and spread of invasive species (KM 8.2).[31] In Hawai‘i, climate change and the spread of invasive grasses have increased the frequency and extent of wildfires.[32] In the Southeast, warming temperatures have allowed cold-sensitive invasive species like kudzu to move farther north,[33] affecting forest structure and composition. Kudzu and other woody vines are stimulated by increased carbon dioxide (CO_2)[34] and in some cases outcompete trees and other plants.[35] Even in the absence of other disturbances, warming and drought are important drivers of tree mortality in the US and globally.[36]

Sea level rise, another climate-related disturbance, affects the distribution, structure, and composition of forests (KM 9.2). Saltwater intrusion has reduced the health, diversity, and productivity of some coastal forests in the East (Figure 7.3).[37] Sea level is projected to result in the loss of existing mangrove forests in many places in future decades.[38,39,40] However, warming during winter has facilitated northward migration of mangroves in the Southeast (Figure 7.7).[41]

Forest structure, function, and diversity are affected across a broad range of spatial scales (Figure 7.5). Variation in environmental conditions, historical and contemporary disturbances, management history, and land use have modified many forests, making them more vulnerable to droughts, wildfires, and other disturbances.[42] These disturbances accelerate tree mortality; alter tree and other plant species distributions, age and size distributions, and regeneration success; and can lead to conversion to non-forest ecosystems (e.g., Falk et al. 2022;[43] Stanke et al. 2021[44]).

Ecological transformations and shifts in forest habitats are occurring because of climate change (KM 8.1).[45] In some low-elevation forests in the West, tree regeneration over the last 20 years has been limited by unfavorable climate. High wildfire severity and low seed availability has further reduced postfire regeneration in some locations.[46,47] Eastern tree species migration is associated with increased seed production but is limited to some extent by the occurrence and distribution of large urban areas in the East.

Effects of Climate Change on Forests



Climate change and climate-related disturbances are affecting forests in the United States.

Figure 7.5. The figure shows recently documented effects, specific to individual forest types, that have been attributed to climate change and climate-related disturbances. Effects include increased tree mortality across all types with high confidence, changes in forest structure with variable confidence, less carbon storage across three of the four forest types, and variable shifts in plant species composition. Confidence levels reflect the uncertainty in attributions based on available literature. Arrows indicate the direction of change where suitable data exist. In the case of temperate forests, structure is changing but not in a unidirectional way. Boreal forest reflects changes only in Alaska. Assessments in the figure are based on recent relevant literature, and citations can be found in the metadata. Adapted with permission from Figure SPM.2 in IPCC 2022.[48]

Although the effects of climate change on tree species have been well studied, effects on understory plants are poorly understood.[49] In Wisconsin, shifts in understory plant species lag regional climate changes, but less so for species with broader site occupancies and larger seed masses.[50] In Oregon's Siskiyou Mountains, average temperature increases of about 3.6°F since 1948 have caused differing effects on plant communities. Low-elevation herb communities are now consistent with a hotter, drier climate and resemble plant communities in more southerly topographic positions. At higher elevations, herbs of northern biogeographic affinity have increased.[51]

Some management activities and land-use changes, especially rapid expansion of the WUI,[5] have reduced the adaptive capacity of forests to variations in climate and climate-related disturbances.[52,53,54] The WUI is more prevalent in the East but is expanding at a faster rate in the West.[5] In the East, forests in the WUI retain larger trees and aboveground biomass than less developed forests, but with less structural diversity (i.e., WUI forests have fewer saplings, seedlings, and dead trees). This raises concerns about diminished ecological function, reduced diversity of wildlife habitat, and vulnerability to warming.[55] In the West, wildfire exclusion in dry forests historically adapted to frequent wildfire has altered forest structure and composition, resulting in higher surface and canopy fuel loads and increased vulnerability to high-severity wildfire.[56,57]

Box 7.1. Bark Beetles and Climate Change

Bark beetles spend most of their lives within a host tree, feeding and reproducing beneath the bark. Climate change has increased the impacts of some bark beetles due to 1) warming, which in some cases has increased life cycles and decreased overwintering mortality of beetles within the host tree; and 2) drought, as drought-stressed hosts have compromised defenses and offer little resistance to colonization by bark beetles.[26,27,58] Warming during summer increases the probability of a spruce beetle completing its life cycle in one year compared to two years,[59] which has increased spruce beetle populations in some areas (Figure 7.6). In California, warming and drought incited mortality of more than 100 million trees during 2014–2017, most attributed to western pine beetles (Figure 7.6) colonizing ponderosa pines.[60,61] About 30% of the tree mortality in California was attributed to warming accelerating the life cycle of western pine beetle, with the remainder attributed to increases in host susceptibility due to drought stress.[29] The biomass of ponderosa pines in California may not return to levels that occurred prior to the drought due to future warming, droughts, and western pine beetle outbreaks.[62]

Warming has allowed mountain pine beetles to erupt at elevations and latitudes where winters historically were cold enough to kill most mountain pine beetle brood within the host tree.[26] In New York and New England, a recent climate-driven range expansion of southern pine beetle resulted in a new bark beetle-host interaction in pitch pine forests.[63] In Alaska, an ongoing spruce beetle outbreak has affected more than 1.6 million acres since 2016 and expanded into the Alaska Range,[27] threatening spruce forests in interior Alaska, where spruce beetle populations were historically regulated by cold winter temperatures.[64]

Bark beetle outbreaks are often detrimental to the provision of ecosystem services,[65] and can affect other disturbances and their effects on ecosystem services. For example, in some forests, mountain pine beetle outbreaks have increased the severity of wildfires[66] and the abundance of invasive weeds.[67] Silvicultural interventions such as thinning to reduce tree densities can be used to increase the resistance and resilience of some forests to bark beetles (KM 7.3), a relationship attributed to decreases in tree competition and associated increases in tree vigor, among other factors.[27]

Spruce and Pine Beetle Outbreaks

Outbreaks of spruce and pine beetles, partly attributable to climate change, are killing trees in the West.

Figure 7.6. These photos show a spruce beetle outbreak on the Bridger–Teton National Forest in Wyoming (**left**) and a western pine beetle outbreak on the Sierra National Forest in California (**right**). Discolored trees were colonized and killed by bark beetles. Warming and drought have increased the impacts of some bark beetles in US forests, affecting many ecosystem services. Photo credits: Christopher J. Fettig, USDA Forest Service.

Key Message 7.2

Climate Change Affects Ecosystem Services Provided by Forests

Climate change threatens the ecosystem services forests provide that enrich human lives and sustain life more broadly. Increasing temperatures, changing precipitation patterns, and altered disturbances are affecting the capacity of forest ecosystems to sequester and store carbon (*high confidence*), provide clean water and clean air (*high confidence*), produce timber and non-timber products (*high confidence*), and provide recreation (*medium confidence*), among other benefits. Future climate effects will interact with societal changes to determine the capacity of forests to provide ecosystem services (*likely, high confidence*).

Some effects of climate change and climate-related disturbances on ecosystem services and their associated economic benefits are gradual, driven by annual or seasonal warming, altered precipitation patterns, or sea level rise. Others are more rapid, driven by extreme events such as droughts, hurricanes, or heatwaves. Co-occurrence and/or interactions among disturbances (compound disturbances) can amplify the effects of individual disturbances on ecosystem services (Box 7.1; Figure 7.7; KM 2.3).[68,69]

Climate change is projected to affect forest growth domestically and internationally, wood and paper markets (e.g., Tian et al. 2016[70]), and the amount of carbon stored in harvested wood products (Box 7.2; KM 12.2; e.g., Johnston and Radeloff 2019[71]). However, the strength of these effects is uncertain due to disturbances, such as droughts, wildfires, insects, and diseases, that limit forest growth.[72] Forest management actions taken in response to climate change can also affect timber product outputs, carbon, and associated ecosystem services (e.g., Creutzburg et al. 2017[73]). Sea level rise also directly and indirectly affects timber output and carbon storage through loss of coastal forests to saltwater intrusion and housing losses and rebuilding, with a projected 800,000 new residential units needed in the US by 2050 to accommodate relocations due to sea level rise under a very high scenario (RCP8.5).[74]

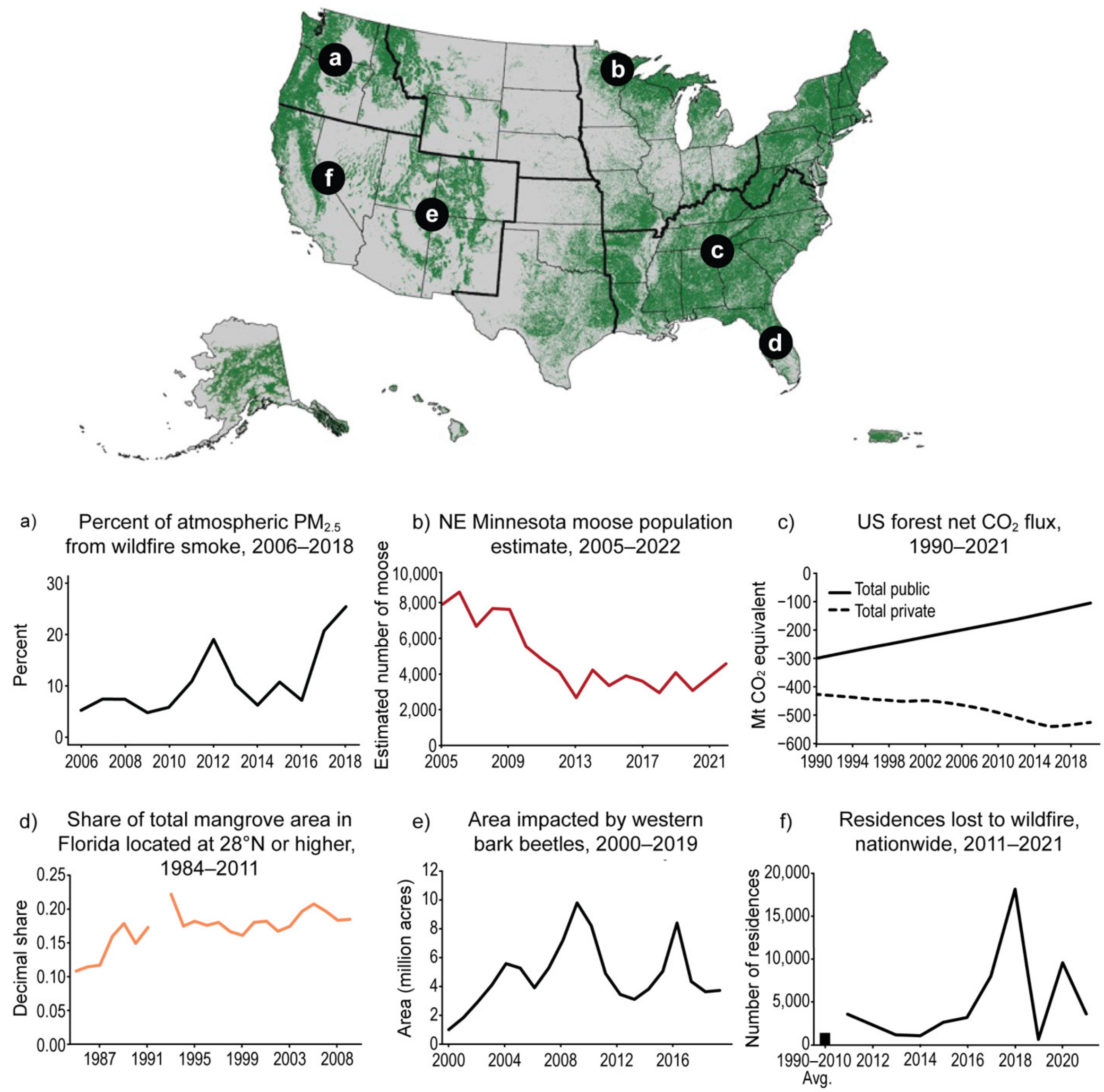
Climate change is altering the ranges and abundances of some plants and fungi used for food, medicine, and other purposes. Reduced snow depth, for example, can increase plant injury and mortality through increased exposure of tissues to frosts,[75,76,77] as well as reduced microbial biomass and activity.[78,79] Many plants and fungi have precise ecological requirements and narrow geographic ranges, leaving them vulnerable to climate change.[80] Some species are at their range limits, unable to adapt to rapidly changing conditions.[81] Effects differ by plant and fungal species, relating to their sensitivity and adaptive capacity.

Climate change affects heritage values, cultural identity, and spiritual connections associated with forests, exacerbating environmental injustices affecting Indigenous and Tribal food sovereignty, health, cultural practices, and knowledge transmission (Chs. 16, 20).[82] Examples of culturally significant species affected by climate change include salmon, brook trout, oaks, pinyon pine, and whitebark pine (Box 7.3).[83,84,85,86,87] In 2023, whitebark pine was listed as a threatened species by the US Fish and Wildlife Service, with white pine blister rust, mountain pine beetle, altered wildfire patterns, and climate change identified as major threats to its existence.[88] Climate-related changes highlight fluctuating consistency, timing, and availability of culturally significant foods, fibers, and medicines.[89,90,91]

Climate change decreases some forest-based recreational activities and increases others. For example, warming and reduced snowpack have had negative effects on winter sports (e.g., cross-country skiing, snowshoeing, and snowmobiling) and positive effects on warm-weather activities, with mixed effects on water-based activities.[92] Participation in fishing and motorized water activities is projected to increase in the North, while motorized water activities are projected to decrease in parts of the West.[93]

Increases in the amount of forest burned by wildfires are creating negative human health effects and growing economic losses.[94] Increases in wildfire smoke are increasing respiratory and cardiovascular-associated hospitalizations (KM 14.2; Focus on Western Wildfires)[95] and out-of-hospital cases of cardiac arrest.[96] Chemicals mobilized into the environment from wildfire-ignited structures and infrastructure can differ from those emitted from burning forest fuels, potentially increasing human health concerns (KM 14.2).[97,98]

Forest Ecosystem Services



Climate change has affected the provisioning of forest ecosystem goods and services in the United States.

Figure 7.7. (**a**) Increases in fine particulate matter air pollutants ($PM_{2.5}$) caused by wildfires degrade air quality and increase human health risks (data for Alaska, Hawai'i, Puerto Rico, US Virgin Islands, and US-Affiliated Pacific Islands are not available). (**b**) Reduction in moose hunting opportunities stems from climate-related increases in parasites; declines in hunting opportunities have also been noted in the western US.[99] (**c**) Increased tree mortality is shrinking carbon sequestration in public forests (Mt is millions of metric tons). (**d**) Northward migration of mangroves is displacing saltwater marshes, altering coastal storm protection and affecting recreation (data for 1992 are not available). (**e**) Increased tree mortality by western bark beetles lowers home values through reduced environmental amenities.[100] (**f**) Housing losses due to wildfires increased by fivefold in the 2010s compared to the average from 1990 to 2010, with substantial interannual variability; data exclude losses from US-Affiliated Pacific

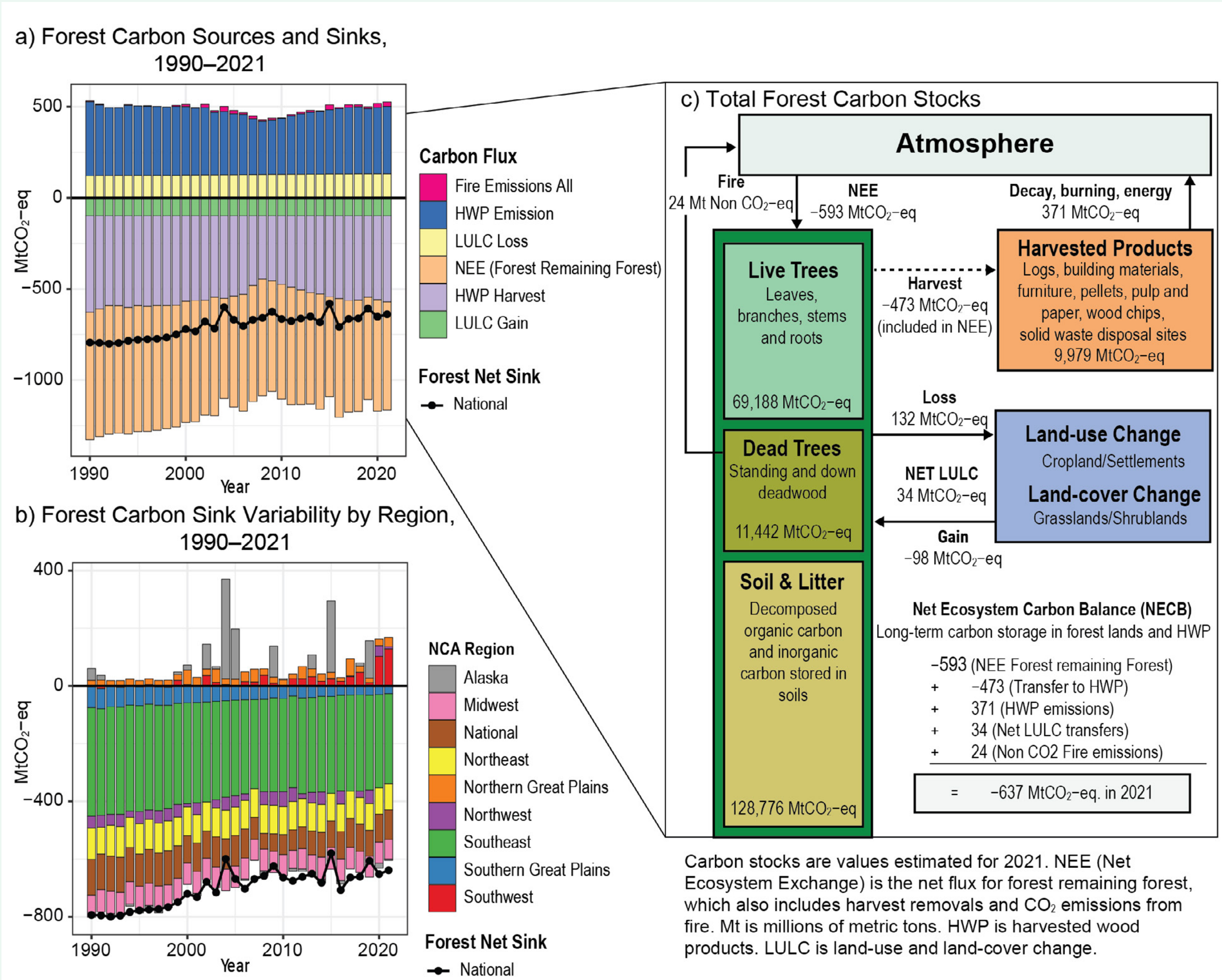
Islands. Notes: Map excludes depictions of forest area for the US Virgin Islands and US-Affiliated Pacific Islands due to the large scale of the map. US Virgin Islands forest area is 46,967 acres.[101] Forest areas for US-Affiliated Pacific Islands are as follows: Federated States of Micronesia (143,466 acres), Marshall Islands (23,252 acres), Northern Mariana Islands (75,407 acres), Palau (90,685 acres), American Sāmoa (43,631 acres), and Guam (63,833 acres); US Affiliated Pacific Island summary data are from sources cited in Lugo et al. 2022.[102] Figure credits: (top) USDA Forest Service; (a) adapted with permission from Burke et al. 2021;[103] (b) USDA Forest Service; (c) adapted from Domke et al. 2023;[3] (d) USDA Forest Service; (e) adapted from Fettig et al. 2022;[27] (f) USDA Forest Service.

Extreme events have been linked to declines in populations of amphibians, birds, fish, invertebrates, mammals, plants, and reptiles (KM 8.2).[104] Recent insect population declines have been attributed, in part, to climate change, with wide-reaching consequences.[105,106] Climate change is increasing the intensity of hurricanes in the East and their associated rainfall,[107,108] although projected changes in the frequency of hurricanes due to warming are uncertain (Chs. 2, 3; e.g., Sobel et al. 2021[109]). Increased intensities of hurricanes could affect the structure and function of forests and wildlife habitat (e.g., Brown et al. 2011[110]). Mobile species or species capable of rapid population growth (e.g., invasives) generally benefit from extreme events and abrupt disturbances.[104]

Box 7.2. Forests and Carbon

Carbon is continuously cycled between the Earth and atmosphere. Forests help regulate climate, as live plants remove carbon dioxide (CO_2) from the atmosphere through photosynthesis, facilitating maintenance and growth, and release some of that carbon through respiration. Forest ecosystems are the largest terrestrial carbon sink on Earth.[111] In the US, the amount of carbon stored in forests (primarily in soils and trees), as well as in harvested wood products that are either in use (e.g., paper, plywood) or in solid waste disposal sites (e.g., landfills), is equivalent to nearly three decades of fossil fuel emissions. On average, between 2017 and 2021, forest ecosystem carbon uptake has offset the equivalent of more than 13% of economy-wide CO_2 emissions each year.[3] In recent decades, the rate of forest carbon sequestration has slowly declined, in part due to increasing frequency and severity of climate-related disturbances, leading to interannual variability in the forest carbon sink and abrupt (e.g., wildfire) and/or gradual (e.g., insect outbreak) transfers of carbon to the atmosphere, dead organic matter pools (dead wood, litter), and soils (Figure 7.8; KM 6.1).[112,113] In some cases, climate-related disturbances have slowed or stopped recovery of forests, reducing their capacity to store carbon (Figure 7.8b),[62,114,115,116] and these trends are projected to continue under multiple climate, land-use, and socioeconomic scenarios. Human activities such as forest management (e.g., timber harvesting, prescribed fire, and other silvicultural interventions) are also major drivers of forest ecosystem carbon dynamics. Harvesting, for example, results in the transfer of some carbon stored in live and dead trees to the atmosphere as well as to harvested wood products and may alter the capacity of forest ecosystems to store new carbon.[112,117] Land-use changes, including cropland expansion and urbanization, have also contributed to the decline in carbon sequestration and/or storage.[115,118] Yet managing forest ecosystems, including forest soils,[119] for the purposes of carbon sequestration and/or storage, along with many other ecosystem services, remains a relatively cost-effective strategy for mitigating climate change (KM 6.3; Ch. 32).[112,120,121,122]

Forest Carbon Sink



The forest carbon sink has declined in recent decades in the United States, with substantial interannual variability.

Figure 7.8. The figure shows (**a**) the interannual variability in forest carbon sources and sinks during the period 1990–2021; (**b**) the interannual variability in the forest carbon sink in the US by National Climate Assessment region during 1990–2021; and (**c**) the total forest carbon stocks by ecosystem pool (boxes) and mean annual transfers among the atmosphere and forest ecosystem pools, harvested wood products, and land conversions (arrows) in 2021. Negative estimates indicate net carbon uptake (i.e., a net removal of carbon from the atmosphere or transfer between ecosystem pools or land categories). Forest ecosystems are the largest carbon sink in the US. There is substantial interannual variability in greenhouse gas emissions and removals from forest land that is driven, in large part, by climate-related disturbances, land use, and land-use change. Figure credit: USDA Forest Service and USGS.

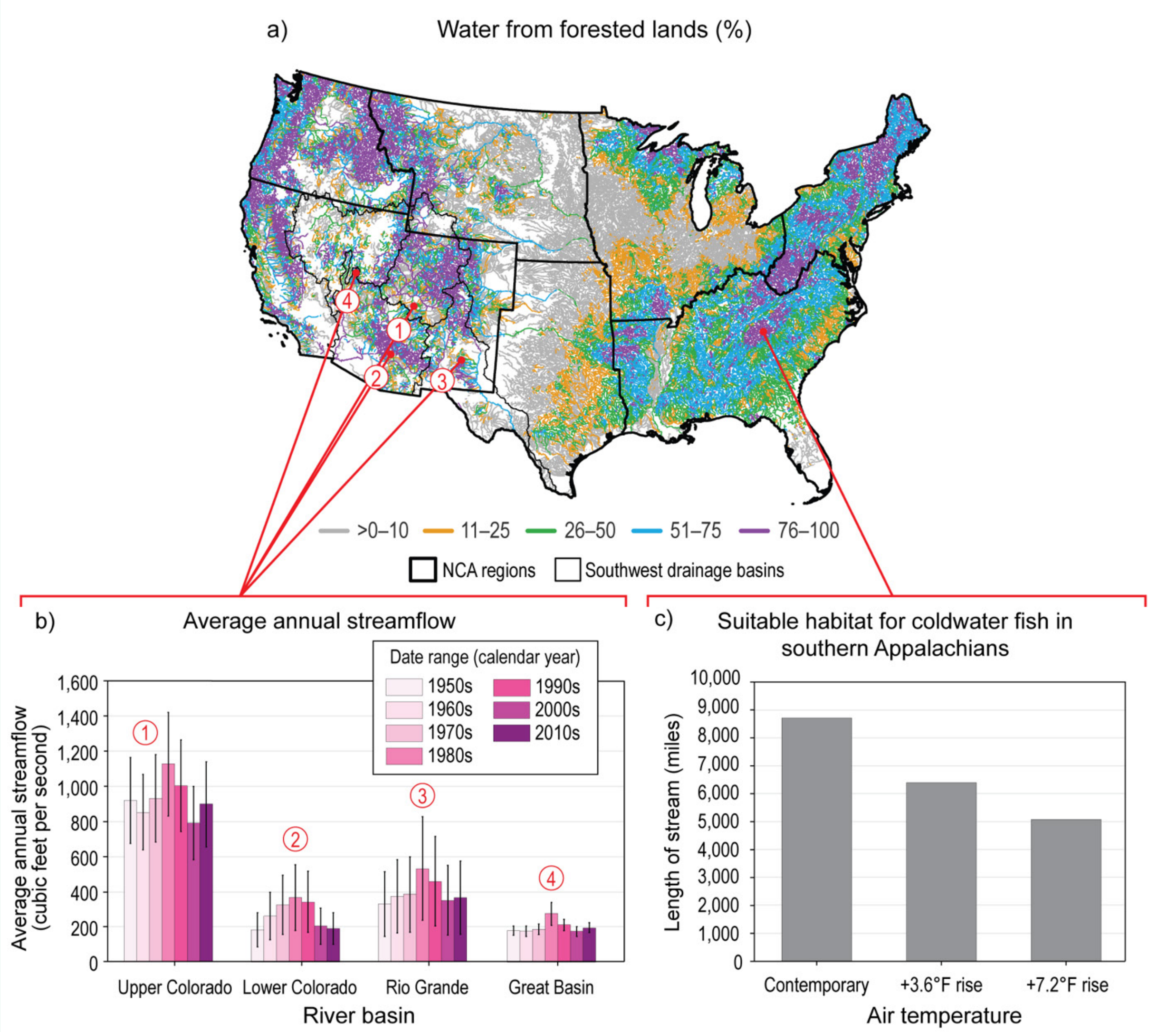
Box 7.3. Climate Change Effects on Forest Water Resources

Forests are a critical source of water in the US (Figure 7.9a),[123,124] and climate change and climate-related disturbances are directly and indirectly affecting the availability and quality of water from forests. Warming across the West has resulted in reduced snowpack and earlier snowmelt and spring runoff, decreasing downstream water availability (KM 4.1).[125] In the Southwest, higher temperatures and reduced precipitation have decreased streamflow in recent decades (Figure 7.9b).[126] Shifts in precipitation and declining snowpacks are decreasing the magnitude and/or frequency of flooding in some areas but increasing them in others (Figure A4.8).[127,128] Models indicate that climate change will affect flood events as some watersheds transition from snow-dominated precipitation, or mixed rain and snow, to rain-dominated precipitation.[129,130] Wildfires and other disturbances (e.g., bark beetle outbreaks) can also result in changes in the availability and quality of water from forests.[131,132] Following wildfires, tree mortality decreases evapotranspiration, thereby increasing water runoff and supply.[133] However, wildfire also increases the runoff of sediments, metals, and other chemicals into water bodies for several years or more after a fire,[134] with higher rates of drinking-water standard violations occurring in burned versus unburned watersheds.[135]

Climate change impacts on water quantity and quality in turn affect aquatic life. Warming, drought, and declines in snowpack increase stream temperatures,[136] decreasing coldwater fish habitat (Figure 7.9c).[137,138,139] Shifts in precipitation from snow to rain are projected in much of southern Alaska.[140] Anticipated effects include changes in streamflow timing and magnitude, with negative effects on salmon production and salmon habitat.[141]

Adaptation measures can reduce some of the effects of climate change on water resources. Management practices, such as reintroducing American beaver, have increased water storage in some landscapes[142] but have had mixed effects on water quality for salmon in the Northwest.[143] Maximizing riparian forest buffers reduces erosion and sedimentation, provides habitat for wildlife, and is projected to delay or reduce stream warming through enhanced shading.[144] Thinning and surface-fuel reduction can lessen the risk of high-severity wildfires in fire-prone buffers and adjacent forests in the West,[145,146] with the potential to reduce fire severity and consequently the effects of wildfire on water resources.[132]

Climate Effects on Forest Water Resources



Climate change and climate-related disturbances are affecting the availability and quality of water from forests in the United States.

Figure 7.9. Panel (**a**) shows the percent of surface water originating on forest lands across the contiguous US, illustrating that forests are a critical source of water. Panel (**b**) shows decadal average variations in average annual streamflow (measured in cubic feet per second [ft^3/s]) from Hydrologic Unit Code 8 (HUC8) watersheds with greater than 50% forest cover, no impoundments above the streamflow gauges, at least four gauges per basin, and complete records back to 1950 in the Great Basin (number of HUC8 gauges = 6), Upper Colorado (16), Lower Colorado (5), and Rio Grande (4). Data generally show annual streamflow has been comparatively lower in more recent years compared to earlier decades. Panel (**c**) shows projected changes in suitable coldwater fish habitat in the Southeast under 3.6°F and 7.2°F warming air temperature over contemporary (2012) air temperature. Projections suggest suitable coldwater fish habitat will decline in the future as air temperatures increase. Figure credits: (a) adapted from Liu et al. 2022;[124] (b, c) USDA Forest Service.

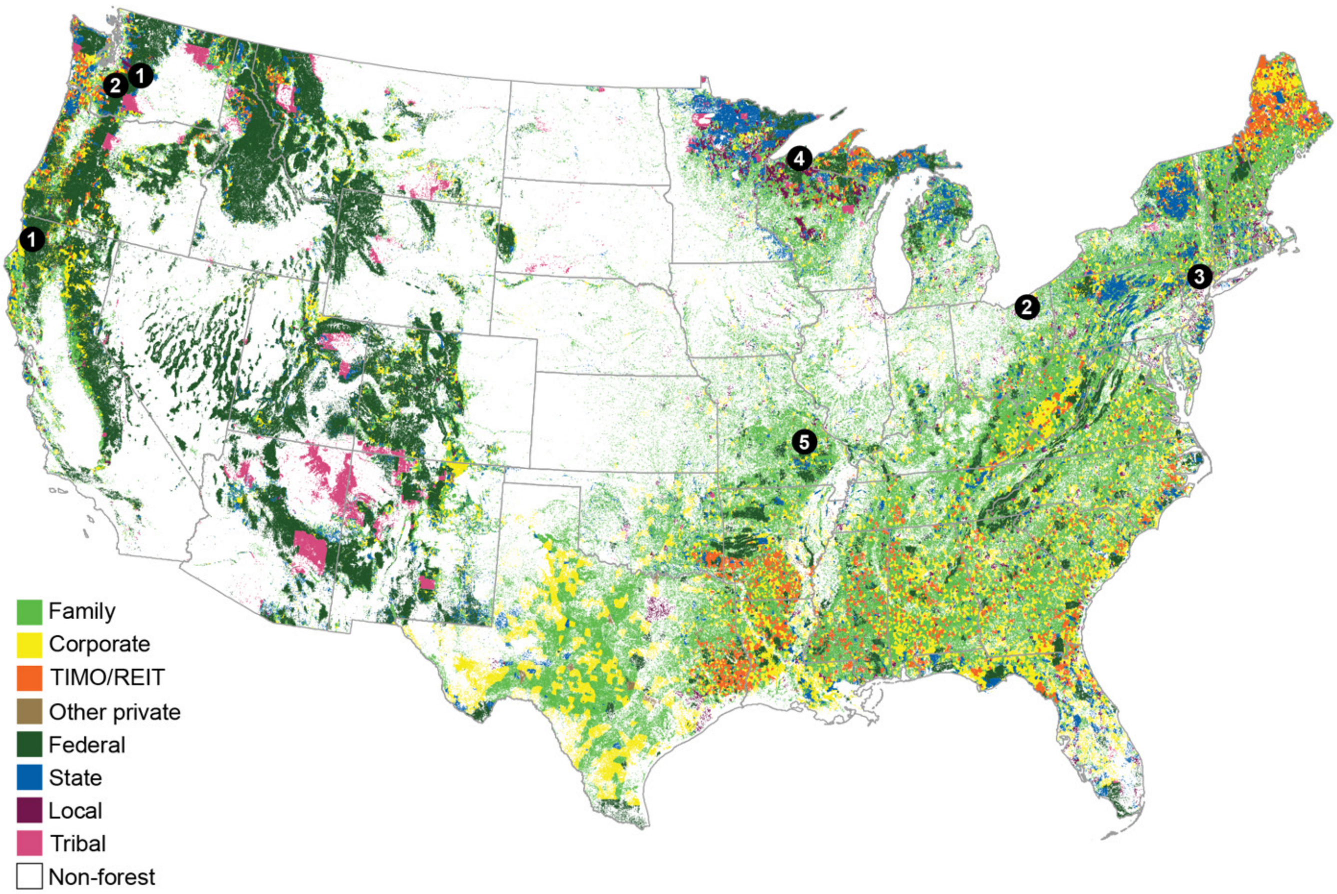
Key Message 7.3

Adaptation Actions Are Necessary for Maintaining Resilient Forest Ecosystems

Climate change creates challenges for natural resource managers charged with preserving the function, health, and productivity of forest ecosystems (*high confidence*). Forest landowners, managers, and policymakers working at local, state, Tribal, and federal levels are preparing for climate change through the development and implementation of vulnerability assessments and adaptation plans (*medium confidence*). Proactive adaptation of management strategies that create, maintain, and restore resilient forest ecosystems are critical to maintaining equitable provisioning of ecosystem services (*medium confidence*).

Proactive adaptation of forest management can help maintain the continued provisioning of ecosystem services from forests (e.g., Peterson and Halofsky 2018;[147] Voggesser et al. 2013[87]). Since 2017, the development of assessments, frameworks, and tools to guide adaptation in forests has accelerated. Climate change vulnerability assessments and adaptation plans for federal (e.g., Halofsky et al. 2016;[148] Timberlake and Schultz 2019[149]), state (Figure 31.1; e.g., Ontl et al. 2018;[150] PADEP 2021[151]), private,[152] and Tribal lands[91,153] have proliferated. Similarly, many guides and frameworks for adaptation have been introduced (e.g., Adaptation Partners 2023;[154] Schuurman et al. 2020[155]). Examples of implementation of adaptation practices in forests are now much more widespread (Figure 7.10; Table 7.1).

Climate Adaptation and Forest Ownership



Adaptation actions occur across many types of forest ownership and management in the United States.

Figure 7.10. Forests in the eastern US are mostly privately owned, whereas the majority of forests in the western US are federally managed. Climate change adaptation actions have been implemented in diverse forest ownership settings. The numbers on the map correspond to locations of adaptation examples listed in Table 7.1 (example 6 is not depicted as it focuses on Puerto Rico, which is not shown on the map). TIMO = timber investment management organization; REIT = real estate investment trust. These data are not available for Alaska, Hawai'i, the US Caribbean, or the US-Affiliated Pacific Islands. Adapted from Sass et al. 2020.[156]

Table 7.1. Examples of Climate Change Adaptation Actions in Forest Ecosystems

Map Location	Climate Change Effect	Adaptation Response	References and Resources
1	Longer wildfire season and increased area burned.	Thin forests and conduct prescribed and cultural burns to reduce the risk of high-severity wildfire and promote valued plants.	Long et al. 2021[157] Marks-Block et al. 2019[158] WA DNR 2020[159]
2	Species and genotypes may be maladapted to future climate.	Plant genotypes and species considered more tolerant of increased temperatures and changing disturbance regimes.	St. Clair et al. 2022[160] NIACS 2022[161] NIACS 2022[162]
3	Increasing temperatures and other stressors threaten urban forests.	Develop silvicultural techniques to maintain urban forests.	Piana et al. 2021[163] Piana et al. 2021[164] Pregitzer et al. 2019[165]
4	Climate change adaptation plans are not typically suited to the needs of Indigenous Peoples.	Develop a Tribal climate change adaptation menu to incorporate Tribal values and cultural considerations into climate adaptation planning.	Tribal Adaptation Menu Team 2019[166]
5	More frequent and severe flooding.	Relocate and restore recreation-related infrastructure in vulnerable floodplains.	NIACS 2022[167]
6	More intense hurricanes increasing downed and damaged trees.	Increase capacity to learn from disaster and manage vegetative debris in order to recover value and sequester carbon.	Álvarez-Berríos et al. 2021[168] Wiener et al. 2020[169]

Taking into account all lands and people improves climate change vulnerability assessments, because of the many federal, state, territorial, municipal, private, Tribal, and Indigenous management policies and practices governing forests. Adaptation options differ by region, ownership, and management objectives, reflecting differences in regional climate and ecology, management history, and local values. However, general principles for adaptation hold across geographies and ownerships and are consistent with the principles of sustainable forest management. For example, in drought-prone temperate forests, reducing tree densities increases resistance (the ability to remain largely unaltered by disturbance) and resilience (the ability to recover after disturbance) to bark beetles and drought[170,171] and, when combined with fuel reduction treatments (e.g., prescribed fire), resilience to wildfire.[145,146] In fire-prone forests, reintroducing low- to mixed-severity fire and incorporating Indigenous Knowledge into fire management can reduce the risk of high-severity wildfire and promote valued ecosystem services[172,173] (Table 7.1; KM 16.3). Promoting biological diversity is also a common adaptation strategy,[150] as forest areas of high diversity are better at maintaining ecosystem functions.[174] Increasing the diversity of functional traits, such as shade tolerance, seed size, specific leaf area, ability to resprout, and bark thickness, may give forests a better chance to adapt to climate-related disturbances.[174,175]

Opportunities to better integrate social considerations of climate-driven changes in forests and forest management are emerging, as socioecological vulnerability frameworks and assessments expand their treatment of social dimensions.[176,177] For example, assessments can consider ecological changes and altered ecosystem services in light of the socioeconomic characteristics (e.g., social vulnerability) and welfare of the beneficiaries of ecosystem services, including social capacity to adapt to novel conditions. Access to forests and associated ecosystem services, including recreation, differs from urban to rural settings and with socio-economic characteristics such as racial and ethnic identity. For example, Black landowners in the South face a legacy of unequal access to forestry extension and management, as well as insecure property ownership and minimal economic return for land inherited without a will.[178] Environmental justice analyses can be used to consider access to forests, technical assistance for forest management, and ecosystem services, as well as hazardous occurrences such as wildfire smoke.[179,180]

Forest health and management are tied to socioeconomic well-being among Indigenous and Tribal Peoples, where stewardship of forest ecosystems is interrelated with cultural identity (KM 16.3).[181,182] Such perspectives lead to different adaptation options with emphasis on active management designed to maintain reciprocal relationships. For example, many Diné (Navajo) depend directly on the land for their livelihoods and cultural traditions, and forests provide social, cultural, spiritual, and economic resources. Under continued warming, substantial forest losses are projected for the Diné. Ambitious tree planting strategies have been proposed to offset these losses and meet future resource needs (e.g., for fuelwood; 50% of Diné households use wood as a primary heating source).[183]

Adapting reforestation practices, including where species are planted and which species and genotypes are planted, will facilitate adaptation to future climatic conditions. Assisted migration can help address the effects of climate change by promoting tree species and genotypes expected to survive future climates and disturbance regimes.[184] Assisted migration encompasses 1) assisted population migration within a species range, 2) assisted range expansion adjacent to a species range, and 3) assisted species migration that moves species far outside their range.[185] Specific guidance on assisted migration is rare, but tools such as hierarchical decision-making,[186] the Seedlot Selection Tool,[160] and the Managed Relocation Ecological Risk Assessment Tool[187] provide guidance.

Assisted migration and reforestation efforts are constrained by unreliable availability of climate-adapted seedling stock or other resources.[188] Adaptation interventions can focus on altering the exposure of forests to climate change or the demand for ecosystem services. Interventions include forest management that alters stand structures or composition, strengthening of disturbance response, and bolstering post-disturbance restoration.[189,190] Private forest owners' actions to adapt to climate change are socially, institutionally, and economically constrained (e.g., Andersson and Keskitalo 2018[191]); therefore, policy and market-based incentives have the potential to increase adaptation on private lands (e.g., Anderson et al. 2019[192]). Potential policies include regulations that require adaptation actions; subsidies (direct payments and tax reductions) that reduce private costs of actions or account for public benefits of private actions;[193] and taxes that increase the private costs of inaction or of actions that make forests less resilient to climate change (e.g., Hashida et al. 2020[194]). Given that future benefits from a private intervention are uncertain, subsidies (e.g., for hazardous fuels management) also reduce financial risks (e.g., Amacher et al. 2006[195]).

Effective implementation of climate adaptation requires working across landscapes with complex governances.[196] Equitable outcomes are enhanced by coproduction of knowledge (i.e., involving multiple knowledge sources and capacities from different groups of people) that determines expected risks, desired future benefits, and the capacity for implementing adaptation actions.[197]

Traceable Accounts

Process Description

Author selection centered on scientific expertise and ensuring that, to the extent possible, the author team represented a broad array of experiences. First, an outline of broad themes was developed by the chapter lead (CL) and federal coordinating lead author (CLA) based on review of previous assessments, a US Global Change Research Program (USGCRP) gap analysis, and new findings since the last National Climate Assessment.[11] The outline served as the basis for identifying the expertise necessary to complete the chapter. Next, the CL and CLA independently developed initial author lists following diversity criteria and guidance provided by USGCRP. It is important to note that prior to author selection, including the CL and CLA, the chapter was designated an all-federal-author chapter by the Federal Steering Committee, with the option to include non-federal authors as technical contributors. The CL and CLA relied heavily on the prepopulated list of individuals nominated through the USGCRP public call for authors to compile the initial author lists. The CL and CLA then worked through their initial lists of authors by chapter theme using the diversity criteria to arrive at the final list of chapter authors.

The author team met weekly to discuss chapter developments, comments, and timelines. Additional chapter authors and technical contributors were identified and added to increase depth and diversify perspectives. These decisions were informed by author team meetings, reviews and revisions, and comments received from US government agencies and the public. Consensus was built leveraging the specific expertise of chapter authors and by referring to the peer-reviewed literature, which was heavily weighted to articles published in the last five years. Engagement with the public occurred through a workshop held in January 2022 and opportunities for public review. Engagement with other chapters occurred through meetings among chapter leadership.

Key Message 7.1

Forests Are Increasingly Affected by Climate Change and Disturbances

Description of Evidence Base

Abundant peer-reviewed literature indicates that climate change has increased the frequency, spatial scale, and severity of some disturbances that drive forest change.[56,198,199] Notable examples include area burned by wildfires in the West,[200] area burned by large wildfires in the West,[13] and area burned at high severity in the West.[18] Over half (55%) of the changes in fuel aridity in western US forests are attributable directly to climate change,[12] and relationships between wildfire and climate (low precipitation/drought or interactions between temperature and precipitation) explain the trends and most of the variation in area burned.[14,15,200,201] Projections of future wildfire[14,202] indicate climatic drivers, and forest responses are expected to differ with forest type and fuels, with the potential for fuel feedbacks to eventually limit increases in area burned (Kitzberger et al. 2017,[203] but see Abatzoglou et al. 2021[16]). There is also strong and increasing evidence that warming is reducing overwintering mortality and increasing voltinism (number of generations) of some bark beetles,[26,29,63] resulting in large impacts, especially in the West, and expansions of geographic and host ranges in both the Northeast and West.[26,63] In the Southwest, exceptional drought has compromised host tree defenses, resulting in increased bark beetle impacts.[58,60,61,204] Despite well-described physical changes to forest fuels following bark beetle outbreaks, effects on wildfires are mixed. These contradictions are largely explained by the different metrics used to assess wildfires, time since the outbreak, the spatial scale of studies, and the confounding effects of fire weather and beetle impacts.[66] Pathogens, extreme weather events (hurricanes, wind, flooding), and sea level rise have less evidence supporting widespread connections between disturbance and climate, in part because attribution is difficult for phenomena that occur rarely. Continued warming and regional changes in precipitation are expected to amplify interactions among disturbance agents and further alter forest ecosystem structure and function. Evidence for shifts in tree species ranges as affected by climate change is available for some areas;[205,206,207] however, understory species range shifts will depend on whether the canopy is affected.[49,208]

Major Uncertainties and Research Gaps

A major uncertainty is the role of climate-related disturbance in landscape transformation, or the permanent transition to a different vegetation type, perhaps non-forested. Projecting future forest changes and resulting effects on ecosystem services should be predicated on an ability to simulate and anticipate the (sometimes rapid) emergence of novel vegetation types. A key research gap is whether and how much management actions may alter climate-driven disturbance effects and resulting forest ecosystem trajectories. For example, differences in forest type and management history affect fuels available to fire and how climate changes alter their flammability or susceptibility to insects or other disturbances. As a result, forest-specific management may be capable of altering some or most of the projected climate effects, all other things being equal, primarily for wildfire. Another research gap is the ability to model the hydrological responses in forested watersheds under novel combinations of climate and disturbance.

Description of Confidence and Likelihood

The vast majority of the scientific literature on forest disturbance supports a *high confidence* statement for the role of climate-related disturbance in structuring forest ecosystems, although estimates of the strength of relationships between climate and disturbance vary with mechanisms and methods. However, the mechanisms by which disturbances interact and the degrees to which they will chronically or acutely affect forests differ greatly with the type and nature of the disturbance. For example, interactions between wildfire and bark beetles are well documented and may be amplified over time, whereas interactions between drought and pathogens are poorly understood. Disturbances can rapidly alter forest structure and dynamics, as well as other resource values (e.g., recreation) and socioeconomic conditions. It is *likely* that such dynamics will continue, but it is difficult to project how much they will resemble the dynamics with which we have experience. Therefore, *high confidence* exists that future disturbances will further alter forest structure and function.

Key Message 7.2

Climate Change Affects Ecosystem Services Provided by Forests

Description of Evidence Base

Abundant peer-reviewed literature underpins how climate change is affecting ecosystem services. Most research supports that increases in air temperature and changing precipitation patterns are reducing the capacity of US forests to sequester and store carbon, especially in the West.[3] There is also strong evidence that climate change is reducing snowpacks and decreasing water supplies in the West.[125] Stream temperatures are increasing in multiple regions, reducing coldwater fish habitat.[137,138] Increases in the frequency of large wildfires in the West reduce air and water quality[103,132,134,209,210] and, when combined with an expanding wildland–urban interface (WUI),[5] *likely* increase structure losses.

Climate change affects timber by increasing the area burned by wildfires[211] and by increasing the area affected by, and the severity of, bark beetle outbreaks,[26,58] leading to increased timber salvage and lower timber values. Beetle outbreaks have also lowered scenic beauty, property values, and property tax revenues for local governments in some areas.[100] Non-timber products in some parts of the US are increasingly subjected to variable output, due to climate-related increases in disturbances and variability in temperatures and seasonality,[212] affecting benefits of cultural ecosystem services, particularly for Indigenous and Tribal Peoples.[90,213] For example, in the Midwest and Northeast, rising average winter temperatures and reduced snow depth have increased the severity of winter tick (*Dermacentor albipictus*) and brainworm (*Parelaphostrongylus tenuis*) infestations[214,215] in moose, increasing adult and calf mortality and reducing hunting opportunities.[216,217,218] Rising sea levels are leading to ghost forests, thereby changing recreation and affecting storm surge buffering capacity.[219,220] Sea level rise is also projected to exceed mangrove accretion rates in future decades, leading to loss of mangrove forests in many places.[38,39,40] In response to warmer winters, however, mangrove expansion is currently occurring along the US Gulf and Atlantic coasts, enhancing coastal protection from storms and rising seas, adding biomass carbon, improving pelican habitat, creating loss of coastal views, increasing insects, reducing fishing access, and reducing habitat for whooping cranes, an endangered species.[41] Skiing in undeveloped areas and motorized snow-based activities in the continental US are projected to be affected by climate change by midcentury, with effects varying by region, model scenario, and participation measure.[93,221]

Major Uncertainties and Research Gaps

Climate change effects on recreation values are uncertain because human values change over time and because overall effects will depend on how temperature and precipitation patterns change across forested landscapes. Furthermore, imprecise information on historical recreation activities has led to a lack of statistical significances for quantitative estimates of how climate may be affecting particular activities. Research gaps exist regarding the effects of climate change on cultural goods and services important to Indigenous and Tribal Peoples in the US.

Description of Confidence and Likelihood

Recent research provides ample evidence of the direct and indirect effects of climate change on forest ecosystem services. There is *high confidence* that multiple ecosystem services are being impacted by climate change, including coldwater fishing, multiple recreation activities, amenities from coastal forests lost to rising seas, Indigenous forest values, consumptive and nonconsumptive wildlife provisioning, and many nontimber forest products. There is *high confidence* that climate change is affecting forest carbon sequestration; the provisioning of clean water from forests; the occurrence of wildfires that destroy structures, alter habitats, and increase $PM_{2.5}$ concentrations in the atmosphere; and snowpacks in the West and Northeast. There is *medium confidence* that climate change is changing the availability of water-based and snow-based recreation. The capacity of forests to continue providing ecosystem services will be determined, in part, by changes in society and how those changes interact with future climate effects (*likely*, *high confidence*).

Key Message 7.3

Adaptation Actions Are Necessary for Maintaining Resilient Forest Ecosystems

Description of Evidence Base

Climate change vulnerability assessments provide the basis for adaptation, and there are many examples of vulnerability assessments that have been conducted for a variety of forest landowners and managers in recent years. Although frameworks and examples of adaptation planning are still more numerous than adaptation actions, the recent literature contains an increasing number of adaptation actions implemented to increase forest resistance and resilience to climate change (Table 7.1). Research on climate change effects and adaptation efforts increasingly draws on coproduction, iterative, and collaborative processes that combine different types of knowledge and participants to produce effective climate adaptation science.[222]

Although considering local context and management objectives is critical in identifying climate change adaptation options, there are general principles applicable across forest types. Adaptation principles that receive strong support in the scientific literature include promoting diversity, modifying planting practices, implementing assisted migration, and increasing resilience to disturbance. A mixture of tree species and functional traits[223] in a forest stand increases the likelihood that disturbances, such as insect and disease outbreaks, will not result in complete stand mortality; that forests will be better able to withstand changing environmental conditions; and that multiple ecosystem services can be provided.[174,224] Strong and increasing evidence exists for lowering stand density in many fire-prone forest types to 1) increase resistance and resilience to disturbances, including droughts, bark beetles, and wildfires;[145,146,157,170,225] and 2) improve residual tree growth by decreasing fuel loads, decreasing tree competition, and increasing water availability.[225,226,227]

Major Uncertainties and Research Gaps

Identification of climate change adaptation actions is based on our current understanding of ecosystem function and how management actions affect ecosystem function. However, understanding of the effectiveness of climate change adaptation actions is limited by a lack of long-term monitoring over several decades. Future monitoring will be critical for evaluating the effectiveness of adaptation actions in different contexts, especially because interactions among multiple disturbances could result in unexpected effects on ecosystems and their response to adaptation actions. Implementation of adaptation actions is still in the relatively early stages, and barriers to adaptation implementation are expected to persist, limiting the future pace, scale, and effectiveness of adaptation.

Description of Confidence and Likelihood

There is *high confidence* that changes in climate over the last several decades are already affecting the ability of forest owners and managers to meet management objectives. This is primarily because of the increasing extent of severe disturbances, primarily wildfires, bark beetle outbreaks in the West, and storms in coastal locations in the East. This is based on the proliferation of peer-reviewed literature to support climate-informed management and planning, as well as various guidelines and sources of adaptation options developed by agencies and non-governmental organizations. Based on understanding of forest ecosystems and effects of management actions, there is *medium confidence* that adaptation actions will be effective in helping maintain the provisioning of ecosystem services. Continued monitoring is needed to assess the effectiveness of adaptation actions.

References

1. Bonan, G.B., 2016: Forests, climate, and public policy: A 500-year interdisciplinary odyssey. *Annual Review of Ecology, Evolution, and Systematics*, **47** (1), 97–121. https://doi.org/10.1146/annurev-ecolsys-121415-032359

2. Oswalt, S.N., W.B. Smith, P.D. Miles, and S.A. Pugh, 2019: Forest Resources of the United States, 2017: A Technical Document Supporting the Forest Service 2020 RPA Assessment. Gen. Tech. Rep. WO-97. U.S. Department of Agriculture, Forest Service, Washington Office, Washington, DC, 223 pp. https://doi.org/10.2737/wo-gtr-97

3. Domke, G.M., B.F. Walters, C.L. Giebink, E.J. Greenfield, J.E. Smith, M.C. Nichols, J.A. Knott, S.M. Ogle, J.W. Coulston, and J. Steller, 2023: Greenhouse Gas Emissions and Removals from Forest Land, Woodlands, Urban Trees, and Harvested Wood Products in the United States, 1990–2021. Resour. Bull. WO-101. U.S. Department of Agriculture, Forest Service, Washington Office, Washington, DC, 10 pp. https://doi.org/10.2737/wo-rb-101

4. Zhang, Y., C. Song, T. Hwang, K. Novick, J.W. Coulston, J. Vose, M.P. Dannenberg, C.R. Hakkenberg, J. Mao, and C.E. Woodcock, 2021: Land cover change-induced decline in terrestrial gross primary production over the conterminous United States from 2001 to 2016. *Agricultural and Forest Meteorology*, **308–309**, 108609. https://doi.org/10.1016/j.agrformet.2021.108609

5. Mockrin, M.H., D. Helmers, S. Martinuzzi, T.J. Hawbaker, and V.C. Radeloff, 2022: Growth of the wildland-urban interface within and around U.S. National Forests and Grasslands, 1990–2010. *Landscape and Urban Planning*, **218**, 104283. https://doi.org/10.1016/j.landurbplan.2021.104283

6. AF&PA, 2022: Our Economic Impact. American Forest and Paper Association. https://www.afandpa.org/statistics-resources/our-economic-impact

7. Hartmann, H., A. Bastos, A.J. Das, A. Esquivel-Muelbert, W.M. Hammond, J. Martínez-Vilalta, N.G. McDowell, J.S. Powers, T.A.M. Pugh, K.X. Ruthrof, and C.D. Allen, 2022: Climate change risks to global forest health: Emergence of unexpected events of elevated tree mortality worldwide. *Annual Review of Plant Biology*, **73** (1), 673–702. https://doi.org/10.1146/annurev-arplant-102820-012804

8. Moser, S.C., J.A. Ekstrom, J. Kim, and S. Heitsch, 2019: Adaptation finance archetypes: Local governments' persistent challenges of funding adaptation to climate change and ways to overcome them. *Ecology and Society*, **24** (2), 28. https://doi.org/10.5751/es-10980-240228

9. USDA, 2022: Climate Resilience and Carbon Stewardship of America's National Forests and Grasslands. Secretary's Memorandum 1077-004. U.S. Department of Agriculture, Office of the Secretary, Washington, DC. https://www.usda.gov/directives/sm-1077-004

10. USDA, 2021: Action Plan for Climate Adaptation and Resilience. Departmental Regulation 1070-001. U.S. Department of Agriculture. https://www.sustainability.gov/pdfs/usda-2021-cap.pdf

11. Vose, J.M., D.L. Peterson, G.M. Domke, C.J. Fettig, L.A. Joyce, R.E. Keane, C.H. Luce, J.P. Prestemon, L.E. Band, J.S. Clark, N.E. Cooley, A. D'Amato, and J.E. Halofsky, 2018: Ch. 6. Forests. 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, 232–267. https://doi.org/10.7930/nca4.2018.ch6

12. Abatzoglou, J.T. and A.P. Williams, 2016: Impact of anthropogenic climate change on wildfire across western US forests. *Proceedings of the National Academy of Sciences of the United States of America*, **113** (42), 11770–11775. https://doi.org/10.1073/pnas.1607171113

13. Dennison, P.E., S.C. Brewer, J.D. Arnold, and M.A. Moritz, 2014: Large wildfire trends in the western United States, 1984–2011. *Geophysical Research Letters*, **41** (8), 2928–2933. https://doi.org/10.1002/2014gl059576

14. western United States: An ecological approach to nonstationarity. *Earth's Future*, **6** (8), 1097–1111. https://doi.org/10.1029/2018ef000878

15. Holden, Z.A., A. Swanson, C.H. Luce, W.M. Jolly, M. Maneta, J.W. Oyler, D.A. Warren, R. Parsons, and D. Affleck, 2018: Decreasing fire season precipitation increased recent western US forest wildfire activity. *Proceedings of the National Academy of Sciences of the United States of America*, **115** (36), E8349–E8357. https://doi.org/10.1073/pnas.1802316115

16. Abatzoglou, J.T., D.S. Battisti, A.P. Williams, W.D. Hansen, B.J. Harvey, and C.A. Kolden, 2021: Projected increases in western US forest fire despite growing fuel constraints. *Communications Earth & Environment*, **2** (1), 227. https://doi.org/10.1038/s43247-021-00299-0

17. Kennedy, M.C., R.R. Bart, C.L. Tague, and J.S. Choate, 2021: Does hot and dry equal more wildfire? Contrasting short- and long-term climate effects on fire in the Sierra Nevada, CA. *Ecosphere*, **12** (7), e03657. https://doi.org/10.1002/ecs2.3657

18. Parks, S.A. and J.T. Abatzoglou, 2020: Warmer and drier fire seasons contribute to increases in area burned at high severity in western US forests from 1985 to 2017. *Geophysical Research Letters*, **47** (22), e2020GL089858. https://doi.org/10.1029/2020gl089858

19. Jones, M.W., J.T. Abatzoglou, S. Veraverbeke, N. Andela, G. Lasslop, M. Forkel, A.J.P. Smith, C. Burton, R.A. Betts, G.R. van der Werf, S. Sitch, J.G. Canadell, C. Santín, C. Kolden, S.H. Doerr, and C. Le Quéré, 2022: Global and regional trends and drivers of fire under climate change. *Reviews of Geophysics*, **60** (3), e2020RG000726. https://doi.org/10.1029/2020rg000726

20. Parks, S.A., C. Miller, J.T. Abatzoglou, L.M. Holsinger, M.-A. Parisien, and S.Z. Dobrowski, 2016: How will climate change affect wildland fire severity in the western US? *Environmental Research Letters*, **11** (3), 035002. https://doi.org/10.1088/1748-9326/11/3/035002

21. Jain, P., X. Wang, and M.D. Flannigan, 2017: Trend analysis of fire season length and extreme fire weather in North America between 1979 and 2015. *International Journal of Wildland Fire*, **26** (12), 1009–1020. https://doi.org/10.1071/wf17008

22. Abatzoglou, J.T., A.P. Williams, and R. Barbero, 2019: Global emergence of anthropogenic climate change in fire weather indices. *Geophysical Research Letters*, **46** (1), 326–336. https://doi.org/10.1029/2018gl080959

23. Balch, J.K., B.A. Bradley, J.T. Abatzoglou, R.C. Nagy, E.J. Fusco, and A.L. Mahood, 2017: Human-started wildfires expand the fire niche across the United States. *Proceedings of the National Academy of Sciences of the United States of America*, **114** (11), 2946–2951. https://doi.org/10.1073/pnas.1617394114

24. Chiodi, A.M., B.E. Potter, and N.K. Larkin, 2021: Multi-decadal change in western US nighttime vapor pressure deficit. *Geophysical Research Letters*, **48** (15), e2021GL092830. https://doi.org/10.1029/2021gl092830

25. Bailey, R.G., 2016: Bailey's Ecoregions and Subregions of the United States, Puerto Rico, and the U.S. Virgin Islands. U.S. Geological Survey, Forest Service Research Data Archive, Fort Collins, CO. https://doi.org/10.2737/RDS-2016-0003

26. Bentz, B.J., J. Régnière, C.J. Fettig, E.M. Hansen, J.L. Hayes, J.A. Hicke, R.G. Kelsey, J.F. Negrón, and S.J. Seybold, 2010: Climate change and bark beetles of the western United States and Canada: Direct and indirect effects. *BioScience*, **60** (8), 602–613. https://doi.org/10.1525/bio.2010.60.8.6

27. Fettig, C.J., C. Asaro, J.T. Nowak, K.J. Dodds, K.J.K. Gandhi, J.E. Moan, and J. Robert, 2022: Trends in bark beetle impacts in North America during a period (2000–2020) of rapid environmental change. *Journal of Forestry*, **120** (6), 693–713. https://doi.org/10.1093/jofore/fvac021

28. O'Connor, C.D., A.M. Lynch, D.A. Falk, and T.W. Swetnam, 2015: Post-fire forest dynamics and climate variability affect spatial and temporal properties of spruce beetle outbreaks on a Sky Island mountain range. *Forest Ecology and Management*, **336**, 148–162. https://doi.org/10.1016/j.foreco.2014.10.021

29. Robbins, Z.J., C. Xu, B.H. Aukema, P.C. Buotte, R. Chitra-Tarak, C.J. Fettig, M.L. Goulden, D.W. Goodsman, A.D. Hall, C.D. Koven, L.M. Kueppers, G.D. Madakumbura, L.A. Mortenson, J.A. Powell, and R.M. Scheller, 2022: Warming increased bark beetle-induced tree mortality by 30% during an extreme drought in California. *Global Change Biology*, **28** (2), 509–523. https://doi.org/10.1111/gcb.15927

30. Dudney, J., C.E. Willing, A.J. Das, A.M. Latimer, J.C.B. Nesmith, and J.J. Battles, 2021: Nonlinear shifts in infectious rust disease due to climate change. *Nature Communications*, **12** (1), 5102. https://doi.org/10.1038/s41467-021-25182-6

31. 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

32. Trauernicht, C., E. Pickett, C.P. Giardina, C.M. Litton, S. Cordell, and A. Beavers, 2015: The contemporary scale and context of wildfire in Hawaiʻi. *Pacific Science*, **69** (4), 427–444. https://doi.org/10.2984/69.4.1

33. 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

34. Anderson-Teixeira, K.J., A.D. Miller, J.E. Mohan, T.W. Hudiburg, B.D. Duval, and E.H. DeLucia, 2013: Altered dynamics of forest recovery under a changing climate. *Global Change Biology*, **19** (7), 2001–2021. https://doi.org/10.1111/gcb.12194

35. Matthews, E.R., J.P. Schmit, and J.P. Campbell, 2016: Climbing vines and forest edges affect tree growth and mortality in temperate forests of the U.S. Mid-Atlantic States. *Forest Ecology and Management*, **374**, 166–173. https://doi.org/10.1016/j.foreco.2016.05.005

36. Hammond, W.M., A.P. Williams, J.T. Abatzoglou, H.D. Adams, T. Klein, R. López, C. Sáenz-Romero, H. Hartmann, D.D. Breshears, and C.D. Allen, 2022: Global field observations of tree die-off reveal hotter-drought fingerprint for Earth's forests. *Nature Communications*, **13** (1), 1761. https://doi.org/10.1038/s41467-022-29289-2

37. Grieger, R., S.J. Capon, W.L. Hadwen, and B. Mackey, 2020: Between a bog and a hard place: A global review of climate change effects on coastal freshwater wetlands. *Climatic Change*, **163** (1), 161–179. https://doi.org/10.1007/s10584-020-02815-1

38. Saintilan, N., N.S. Khan, E. Ashe, J.J. Kelleway, K. Rogers, C.D. Woodroffe, and B.P. Horton, 2020: Thresholds of mangrove survival under rapid sea level rise. *Science*, **368** (6495), 1118–1121. https://doi.org/10.1126/science.aba2656

39. Sasmito, S.D., D. Murdiyarso, D.A. Friess, and S. Kurnianto, 2016: Can mangroves keep pace with contemporary sea level rise? A global data review. *Wetlands Ecology and Management*, **24** (2), 263–278. https://doi.org/10.1007/s11273-015-9466-7

40. Ward, R.D., D.A. Friess, R.H. Day, and R.A. Mackenzie, 2016: Impacts of climate change on mangrove ecosystems: A region by region overview. *Ecosystem Health and Sustainability*, **2** (4), e01211. https://doi.org/10.1002/ehs2.1211

41. 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

42. Hagmann, R.K., P.F. Hessburg, S.J. Prichard, N.A. Povak, P.M. Brown, P.Z. Fulé, R.E. Keane, E.E. Knapp, J.M. Lydersen, K.L. Metlen, M.J. Reilly, A.J. Sánchez Meador, S.L. Stephens, J.T. Stevens, A.H. Taylor, L.L. Yocom, M.A. Battaglia, D.J. Churchill, L.D. Daniels, D.A. Falk, P. Henson, J.D. Johnston, M.A. Krawchuk, C.R. Levine, G.W. Meigs, A.G. Merschel, M.P. North, H.D. Safford, T.W. Swetnam, and A.E.M. Waltz, 2021: Evidence for widespread changes in the structure, composition, and fire regimes of western North American forests. *Ecological Applications*, **31** (8), e02431. https://doi.org/10.1002/eap.2431

43. Falk, D.A., P.J. van Mantgem, J.E. Keeley, R.M. Gregg, C.H. Guiterman, A.J. Tepley, D. Jn Young, and L.A. Marshall, 2022: Mechanisms of forest resilience. *Forest Ecology and Management*, **512**, 120129. https://doi.org/10.1016/j.foreco.2022.120129

44. Stanke, H., A.O. Finley, G.M. Domke, A.S. Weed, and D.W. MacFarlane, 2021: Over half of western United States' most abundant tree species in decline. *Nature Communications*, **12** (1), 451. https://doi.org/10.1038/s41467-020-20678-z

45. Crausbay, S.D., H.R. Sofaer, A.E. Cravens, B.C. Chaffin, K.R. Clifford, J.E. Gross, C.N. Knapp, D.J. Lawrence, D.R. Magness, A.J. Miller-Rushing, G.W. Schuurman, and C.S. Stevens-Rumann, 2022: A science agenda to inform natural resource management decisions in an era of ecological transformation. *BioScience*, **72** (1), 71–90. https://doi.org/10.1093/biosci/biab102

46. 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

47. Keeley, J.E., P. van Mantgem, and D.A. Falk, 2019: Fire, climate and changing forests. *Nature Plants*, **5** (8), 774–775. https://doi.org/10.1038/s41477-019-0485-x

48. IPCC, 2022: Summary for policymakers. In: *Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Shukla, P.R., J. Skea, R. Slade, A. Al Khourdajie, R. van Diemen, D. McCollum, M. Pathak, S. Some, P. Vyas, R. Fradera, M. Belkacemi, A. Hasija, G. Lisboa, S. Luz, and J. Malley, Eds. Cambridge University Press, Cambridge, UK and New York, NY, USA. https://doi.org/10.1017/9781009157926.001

49. Spicer, M.E., H.V.N. Radhamoni, M.C. Duguid, S.A. Queenborough, and L.S. Comita, 2022: Herbaceous plant diversity in forest ecosystems: Patterns, mechanisms, and threats. *Plant Ecology*, **223** (2), 117–129. https://doi.org/10.1007/s11258-021-01202-9

50. Ash, J.D., T.J. Givnish, and D.M. Waller, 2017: Tracking lags in historical plant species' shifts in relation to regional climate change. *Global Change Biology*, **23** (3), 1305–1315. https://doi.org/10.1111/gcb.13429

51. Harrison, S., E.I. Damschen, and J.B. Grace, 2010: Ecological contingency in the effects of climatic warming on forest herb communities. *Proceedings of the National Academy of Sciences of the United States of America*, **107** (45), 19362–19367. https://doi.org/10.1073/pnas.1006823107

52. Cansler, C.A., V.R. Kane, P.F. Hessburg, J.T. Kane, S.M.A. Jeronimo, J.A. Lutz, N.A. Povak, D.J. Churchill, and A.J. Larson, 2022: Previous wildfires and management treatments moderate subsequent fire severity. *Forest Ecology and Management*, **504**, 119764. https://doi.org/10.1016/j.foreco.2021.119764

53. Larson, A.J., S.M.A. Jeronimo, P.F. Hessburg, J.A. Lutz, N.A. Povak, C.A. Cansler, V.R. Kane, and D.J. Churchill, 2022: Tamm review: Ecological principles to guide post-fire forest landscape management in the inland Pacific and northern Rocky Mountain regions. *Forest Ecology and Management*, **504**, 119680. https://doi.org/10.1016/j.foreco.2021.119680

54. Prichard, S.J., P.F. Hessburg, R.K. Hagmann, N.A. Povak, S.Z. Dobrowski, M.D. Hurteau, V.R. Kane, R.E. Keane, L.N. Kobziar, C.A. Kolden, M. North, S.A. Parks, H.D. Safford, J.T. Stevens, L.L. Yocom, D.J. Churchill, R.W. Gray, D.W. Huffman, F.K. Lake, and P. Khatri-Chhetri, 2021: Adapting western North American forests to climate change and wildfires: 10 common questions. *Ecological Applications*, **31** (8), e02433. https://doi.org/10.1002/eap.2433

55. Sonti, N.F., R. Riemann, M.H. Mockrin, and G.M. Domke, 2023: Expanding wildland-urban interface alters forest structure and landscape context in the northern United States. *Environmental Research Letters*, **18** (1), 014010. https://doi.org/10.1088/1748-9326/aca77b

56. Hagmann, R.K., P.F. Hessburg, R.B. Salter, A.G. Merschel, and M.J. Reilly, 2022: Contemporary wildfires further degrade resistance and resilience of fire-excluded forests. *Forest Ecology and Management*, **506**, 119975. https://doi.org/10.1016/j.foreco.2021.119975

57. 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

58. Kolb, T.E., C.J. Fettig, M.P. Ayres, B.J. Bentz, J.A. Hicke, R. Mathiasen, J.E. Stewart, and A.S. Weed, 2016: Observed and anticipated impacts of drought on forest insects and diseases in the United States. *Forest Ecology and Management*, **380**, 321–334. https://doi.org/10.1016/j.foreco.2016.04.051

59. Hansen, E.M. and B.J. Bentz, 2003: Comparison of reproductive capacity among univoltine, semivoltine, and re-emerged parent spruce beetles (Coleoptera: Scolytidae). *The Canadian Entomologist*, **135** (5), 697–712. https://doi.org/10.4039/n02-109

60. Fettig, C.J., L.A. Mortenson, B.M. Bulaon, and P.B. Foulk, 2019: Tree mortality following drought in the central and southern Sierra Nevada, California, U.S. *Forest Ecology and Management*, **432**, 164–178. https://doi.org/10.1016/j.foreco.2018.09.006

61. Koontz, M.J., A.M. Latimer, L.A. Mortenson, C.J. Fettig, and M.P. North, 2021: Cross-scale interaction of host tree size and climatic water deficit governs bark beetle-induced tree mortality. *Nature Communications*, **12** (1), 129. https://doi.org/10.1038/s41467-020-20455-y

62. Robbins, Z.J., C. Xu, A. Jonko, R. Chitra-Tarak, C.J. Fettig, J. Costanza, L.A. Mortenson, B.H. Aukema, L.M. Kueppers, and R.M. Scheller, 2023: Carbon stored in live ponderosa pines in the Sierra Nevada will not return to pre-drought (2012) levels during the 21st century due to bark beetle outbreaks. *Frontiers in Environmental Science*, **11**, 1112756. https://doi.org/10.3389/fenvs.2023.1112756

63. Dodds, K.J., C.F. Aoki, A. Arango-Velez, J. Cancelliere, A.W. D'Amato, M.F. DiGirolomo, and R.J. Rabaglia, 2018: Expansion of southern pine beetle into northeastern forests: Management and impact of a primary bark beetle in a new region. *Journal of Forestry*, **116** (2), 178–191. https://doi.org/10.1093/jofore/fvx009

64. Miller, L.K. and R.A. Werner, 1987: Cold-hardiness of adult and larval spruce beetles *Dendroctonus rufipennis* (Kirby) in interior Alaska. *Canadian Journal of Zoology*, **65** (12), 2927–2930. https://doi.org/10.1139/z87-444

65. Morris, J.L., S. Cottrell, C.J. Fettig, R.J. DeRose, K.M. Mattor, V.A. Carter, J. Clear, J. Clement, W.D. Hansen, J.A. Hicke, P.E. Higuera, A.W. Seddon, H. Seppä, R.L. Sherriff, J.D. Stednick, and S.J. Seybold, 2018: Bark beetles as agents of change in social–ecological systems. *Frontiers in Ecology and the Environment*, **16** (S1), S34–S43. https://doi.org/10.1002/fee.1754

66. Fettig, C.J., J.B. Runyon, C.S. Homicz, P.M.A. James, and M.D. Ulyshen, 2022: Fire and insect interactions in North American forests. *Current Forestry Reports*, **8**, 301–316. https://doi.org/10.1007/s40725-022-00170-1

67. Runyon, J.B., C.J. Fettig, J.A. Trilling, A.S. Munson, L.A. Mortenson, B.E. Steed, K.E. Gibson, C.L. Jørgensen, S.R. McKelvey, J.D. McMillin, J.P. Audley, and J.F. Negrón, 2020: Changes in understory vegetation including invasive weeds following mountain pine beetle outbreaks. *Trees, Forests and People*, **2**, 100038. https://doi.org/10.1016/j.tfp.2020.100038

68. Kleinman, J.S., J.D. Goode, A.C. Fries, and J.L. Hart, 2019: Ecological consequences of compound disturbances in forest ecosystems: A systematic review. *Ecosphere*, **10** (11), e02962. https://doi.org/10.1002/ecs2.2962

69. Raymond, C., R.M. Horton, J. Zscheischler, O. Martius, A. AghaKouchak, J. Balch, S.G. Bowen, S.J. Camargo, J. Hess, K. Kornhuber, M. Oppenheimer, A.C. Ruane, T. Wahl, and K. White, 2020: Understanding and managing connected extreme events. *Nature Climate Change*, **10** (7), 611–621. https://doi.org/10.1038/s41558-020-0790-4

70. Tian, X., B. Sohngen, J.B. Kim, S. Ohrel, and J. Cole, 2016: Global climate change impacts on forests and markets. *Environmental Research Letters*, **11** (3), 035011. https://doi.org/10.1088/1748-9326/11/3/035011

71. Johnston, C.M.T. and V.C. Radeloff, 2019: Global mitigation potential of carbon stored in harvested wood products. *Proceedings of the National Academy of Sciences of the United States of America*, **116** (29), 14526–14531. https://doi.org/10.1073/pnas.1904231116

72. Anderegg, W.R.L., A.T. Trugman, G. Badgley, C.M. Anderson, A. Bartuska, P. Ciais, D. Cullenward, C.B. Field, J. Freeman, S.J. Goetz, J.A. Hicke, D. Huntzinger, R.B. Jackson, J. Nickerson, S. Pacala, and J.T. Randerson, 2020: Climate-driven risks to the climate mitigation potential of forests. *Science*, **368** (6497), 7005. https://doi.org/10.1126/science.aaz7005

73. Creutzburg, M.K., R.M. Scheller, M.S. Lucash, S.D. LeDuc, and M.G. Johnson, 2017: Forest management scenarios in a changing climate: Trade-offs between carbon, timber, and old forest. *Ecological Applications*, **27** (2), 503–518. https://doi.org/10.1002/eap.1460

74. Nepal, P., J.P. Prestemon, L.A. Joyce, and K.E. Skog, 2022: Global forest products markets and forest sector carbon impacts of projected sea level rise. *Global Environmental Change*, **77**, 102611. https://doi.org/10.1016/j.gloenvcha.2022.102611

75. Comerford, D.P., P.G. Schaberg, P.H. Templer, A.M. Socci, J.L. Campbell, and K.F. Wallin, 2013: Influence of experimental snow removal on root and canopy physiology of sugar maple trees in a northern hardwood forest. *Oecologia*, **171** (1), 261–269. https://doi.org/10.1007/s00442-012-2393-x

76. Sanders-DeMott, R., J.L. Campbell, P.M. Groffman, L.E. Rustad, and P.H. Templer, 2019: Ch. 10. Soil warming and winter snowpacks: Implications for northern forest ecosystem functioning. In: *Ecosystem Consequences of Soil Warming*. Mohan, J.E., Ed. Academic Press, 245–278. https://doi.org/10.1016/b978-0-12-813493-1.00011-9

77. Slatyer, R.A., K.D.L. Umbers, and P.A. Arnold, 2022: Ecological responses to variation in seasonal snow cover. *Conservation Biology*, **36** (1), e13727. https://doi.org/10.1111/cobi.13727

78. Sorensen, P.O., A.C. Finzi, M.-A. Giasson, A.B. Reinmann, R. Sanders-DeMott, and P.H. Templer, 2018: Winter soil freeze-thaw cycles lead to reductions in soil microbial biomass and activity not compensated for by soil warming. *Soil Biology and Biochemistry*, **116**, 39–47. https://doi.org/10.1016/j.soilbio.2017.09.026

79. Sorensen, P.O., P.H. Templer, and A.C. Finzi, 2016: Contrasting effects of winter snowpack and soil frost on growing season microbial biomass and enzyme activity in two mixed-hardwood forests. *Biogeochemistry*, **128** (1), 141–154. https://doi.org/10.1007/s10533-016-0199-3

80. Fei, S., S.N. Kivlin, G.M. Domke, I. Jo, E.A. LaRue, and R.P. Phillips, 2022: Coupling of plant and mycorrhizal fungal diversity: Its occurrence, relevance, and possible implications under global change. *New Phytologist*, **234** (6), 1960–1966. https://doi.org/10.1111/nph.17954

81. Dangremond, E.M., C.H. Hill, S. Louaibi, and I. Muñoz, 2022: Phenological responsiveness and fecundity decline near the southern range limit of *Trientalis borealis* (Primulaceae). *Plant Ecology*, **223** (1), 41–52. https://doi.org/10.1007/s11258-021-01190-w

82. Whyte, K., 2018: Settler colonialism, ecology, and environmental injustice. *Environment and Society*, **9** (1), 125–144. https://doi.org/10.3167/ares.2018.090109

83. Durglo, M., R.G. Everett, T. Incashola, M.I. McCarthy, S.H. Pete, J.M. Rosenau, T. Smith, S. Trahan, and A.A. Carlson, 2022: Ch. 7. Sčiłpálqʷ: Biocultural restoration of whitebark pine on the Flathead Reservation. In: *Climate Actions*. CRC Press, 34. https://doi.org/10.1201/9781003048701

84. Hitt, N.P., E.L. Snook, and D.L. Massie, 2017: Brook trout use of thermal refugia and foraging habitat influenced by brown trout. *Canadian Journal of Fisheries and Aquatic Sciences*, **74** (3), 406–418. https://doi.org/10.1139/cjfas-2016-0255

85. Isaak, D.J., C.H. Luce, D.L. Horan, G.L. Chandler, S.P. Wollrab, and D.E. Nagel, 2018: Global warming of salmon and trout rivers in the northwestern U.S.: Road to ruin or path through purgatory? *Transactions of the American Fisheries Society*, **147** (3), 566–587. https://doi.org/10.1002/tafs.10059

86. Redmond, M.D., F. Forcella, and N.N. Barger, 2012: Declines in pinyon pine cone production associated with regional warming. *Ecosphere*, **3** (12), 1–14. https://doi.org/10.1890/es12-00306.1

87. Voggesser, G., K. Lynn, J. Daigle, F.K. Lake, and D. Ranco, 2013: Cultural impacts to tribes from climate change influences on forests. *Climatic Change*, **120** (3), 615–626. https://doi.org/10.1007/s10584-013-0733-4

88. Fish and Wildlife Service, 2022: Endangered and threatened wildlife and plants; threatened species status with section 4(d) rule for whitebark pine (*Pinus albicaulis*). *Federal Register*, **87** (240), 76882–76917. https://www.govinfo.gov/content/pkg/FR-2022-12-15/pdf/2022-27087.pdf

89. Lynn, K., J. Daigle, J. Hoffman, F. Lake, N. Michelle, D. Ranco, C. Viles, G. Voggesser, and P. Williams, 2014: Ch. 4. The impacts of climate change on tribal traditional foods. In: *Climate Change and Indigenous Peoples in the United States: Impacts, Experiences and Actions*. Maldonado, J.K., B. Colombi, and R. Pandya, Eds. Springer, Cham, Switzerland, 37–48. https://doi.org/10.1007/978-3-319-05266-3_4

90. Mucioki, M., J. Sowerwine, D. Sarna-Wojcicki, F.K. Lake, and S. Bourque, 2021: Conceptualizing Indigenous Cultural Ecosystem Services (ICES) and benefits under changing climate conditions in the Klamath River Basin and their implications for land management and governance. *Journal of Ethnobiology*, **41** (3), 313–330. https://doi.org/10.2993/0278-0771-41.3.313

91. STACCWG, 2021: The Status of Tribes and Climate Change Report. Marks-Marino, D., Ed. Northern Arizona University, Institute for Tribal Environmental Professionals, Flagstaff, AZ. http://nau.edu/stacc2021

92. Askew, A.E. and J.M. Bowker, 2018: Impacts of climate change on outdoor recreation participation: Outlook to 2060. *The Journal of Park and Recreation Administration*, **36** (2), 97–120. https://doi.org/10.18666/jpra-2018-v36-i2-8316

93. Miller, A.B., P.L. Winter, J.J. Sánchez, D.L. Peterson, and J.W. Smith, 2022: Climate change and recreation in the western United States: Effects and opportunities for adaptation. *Journal of Forestry*, **120** (4), 453–472. https://doi.org/10.1093/jofore/fvab072

94. Wang, D., D. Guan, S. Zhu, M.M. Kinnon, G. Geng, Q. Zhang, H. Zheng, T. Lei, S. Shao, P. Gong, and S.J. Davis, 2021: Economic footprint of California wildfires in 2018. *Nature Sustainability*, **4** (3), 252–260. https://doi.org/10.1038/s41893-020-00646-7

95. EPA, 2021: Comparative Assessment of the Impacts of Prescribed Fire Versus Wildfire (CAIF): A Case Study in the Western U.S. EPA/600/R-21/197. U.S. Environmental Protection Agency, Washington, DC. https://cfpub.epa.gov/ncea/risk/recordisplay.cfm?deid=352824

96. Jones, C.G., A.G. Rappold, J. Vargo, W.E. Cascio, M. Kharrazi, B. McNally, and S. Hoshiko, 2020: Out-of-hospital cardiac arrests and wildfire-related particulate matter during 2015–2017 California wildfires. *Journal of the American Heart Association*, **9** (8), e014125. https://doi.org/10.1161/jaha.119.014125

97. Boaggio, K., S.D. LeDuc, R.B. Rice, P.F. Duffney, K.M. Foley, A.L. Holder, S. McDow, and C.P. Weaver, 2022: Beyond particulate matter mass: Heightened levels of lead and other pollutants associated with destructive fire events in California. *Environmental Science & Technology*, **56** (20), 14272–14283. https://doi.org/10.1021/acs.est.2c02099

98. Proctor, C.R., J. Lee, D. Yu, A.D. Shah, and A.J. Whelton, 2020: Wildfire caused widespread drinking water distribution network contamination. *AWWA Water Science*, **2** (4), e1183. https://doi.org/10.1002/aws2.1183

99. Nadeau, M.S., N.J. DeCesare, D.G. Brimeyer, E.J. Bergman, R.B. Harris, K.R. Hersey, K.K. Huebner, P.E. Matthews, and T.P. Thomas, 2017: Status and trends of moose populations and hunting opportunity in the western United States. *Alces: A Journal Devoted to the Biology and Management of Moose*, **53**, 99–112. https://alcesjournal.org/index.php/alces/article/view/182

100. Cohen, J., C.E. Blinn, K.J. Boyle, T.P. Holmes, and K. Moeltner, 2016: Hedonic valuation with translating amenities: Mountain pine beetles and host trees in the Colorado Front Range. *Environmental and Resource Economics*, **63** (3), 613–642. https://doi.org/10.1007/s10640-014-9856-y

101. Marcano-Vega, H., 2020: U.S. Virgin Islands Forests, 2014. Resour. Bull. SRS 227. U.S. Department of Agriculture, Forest Service, Southern Research Station, Asheville, NC, 54 pp. https://doi.org/10.2737/srs-rb-227

102. Lugo, A.E., J.E. Smith, K.M. Potter, H. Marcano Vega, and C.M. Kurtz, 2022: The Contribution of Nonnative Tree Species to the Structure and Composition of Forests in the Conterminous United States in Comparison with Tropical Islands in the Pacific and Caribbean. Gen. Tech. Rep. IITF-54. U.S. Department of Agriculture, Forest Service, International Institute of Tropical Forestry, Río Piedras, PR, 81 pp. https://doi.org/10.2737/iitf-gtr-54

103. Burke, M., A. Driscoll, S. Heft-Neal, J. Xue, J. Burney, and M. Wara, 2021: The changing risk and burden of wildfire in the United States. *Proceedings of the National Academy of Sciences of the United States of America*, **118** (2), e2011048118. https://doi.org/10.1073/pnas.2011048118

104. Maxwell, S.L., N. Butt, M. Maron, C.A. McAlpine, S. Chapman, A. Ullmann, D.B. Segan, and J.E.M. Watson, 2019: Conservation implications of ecological responses to extreme weather and climate events. *Diversity and Distributions*, **25** (4), 613–625. https://doi.org/10.1111/ddi.12878

105. Halsch, C.A., A.M. Shapiro, J.A. Fordyce, C.C. Nice, J.H. Thorne, D.P. Waetjen, and M.L. Forister, 2021: Insects and recent climate change. *Proceedings of the National Academy of Sciences of the United States of America*, **118** (2), e2002543117. https://doi.org/10.1073/pnas.2002543117

106. 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

107. Reed, K.A., A.M. Stansfield, M.F. Wehner, and C.M. Zarzycki, 2020: Forecasted attribution of the human influence on Hurricane Florence. *Science Advances*, **6** (1), 9253. https://doi.org/10.1126/sciadv.aaw9253

108. Trenberth, K.E., L. Cheng, P. Jacobs, Y. Zhang, and J. Fasullo, 2018: Hurricane Harvey links to ocean heat content and climate change adaptation. *Earth's Future*, **6** (5), 730–744. https://doi.org/10.1029/2018ef000825

109. Sobel, A.H., A.A. Wing, S.J. Camargo, C.M. Patricola, G.A. Vecchi, C.-Y. Lee, and M.K. Tippett, 2021: Tropical cyclone frequency. *Earth's Future*, **9** (12), e2021EF002275. https://doi.org/10.1029/2021ef002275

110. Brown, D.R., T.W. Sherry, and J. Harris, 2011: Hurricane Katrina impacts the breeding bird community in a bottomland hardwood forest of the Pearl River Basin, Louisiana. *Forest Ecology and Management*, **261** (1), 111–119. https://doi.org/10.1016/j.foreco.2010.09.038

111. Pan, Y., R.A. Birdsey, J. Fang, R. Houghton, P.E. Kauppi, W.A. Kurz, O.L. Phillips, A. Shvidenko, S.L. Lewis, J.G. Canadell, P. Ciais, R.B. Jackson, S.W. Pacala, A.D. McGuire, S. Piao, A. Rautiainen, S. Sitch, and D. Hayes, 2011: A large and persistent carbon sink in the world's forests. *Science*, **333** (6045), 988–993. https://doi.org/10.1126/science.1201609

112. Domke, G., C.A. Williams, R. Birdsey, J. Coulston, A. Finzi, C. Gough, B. Haight, J. Hicke, M. Janowiak, B.d. Jong, W.A. Kurz, M. Lucash, S. Ogle, M. Olguín-Álvarez, Y. Pan, M. Skutsch, C. Smyth, C. Swanston, P. Templer, D. Wear, and C.W. Woodall, 2018: Ch. 9. Forests. In: *Second State of the Carbon Cycle Report (SOCCR2): A Sustained Assessment Report*. Cavallaro, N., G. Shrestha, R. Birdsey, M.A. Mayes, R.G. Najjar, S.C. Reed, P. Romero-Lankao, and Z. Zhu, Eds. U.S. Global Change Research Program, Washington, DC, USA, 365-398. https://doi.org/10.7930/SOCCR2.2018.Ch9

113. Harris, N.L., S.C. Hagen, S.S. Saatchi, T.R.H. Pearson, C.W. Woodall, G.M. Domke, B.H. Braswell, B.F. Walters, S. Brown, W. Salas, A. Fore, and Y. Yu, 2016: Attribution of net carbon change by disturbance type across forest lands of the conterminous United States. *Carbon Balance and Management*, **11** (1), 24. https://doi.org/10.1186/s13021-016-0066-5

114. Quirion, B.R., G.M. Domke, B.F. Walters, G.M. Lovett, J.E. Fargione, L. Greenwood, K. Serbesoff-King, J.M. Randall, and S. Fei, 2021: Insect and disease disturbances correlate with reduced carbon sequestration in forests of the contiguous United States. *Frontiers in Forests and Global Change*, **4**, 716582. https://doi.org/10.3389/ffgc.2021.716582

115. Sleeter, B.M., L. Frid, B. Rayfield, C. Daniel, Z. Zhu, and D.C. Marvin, 2022: Operational assessment tool for forest carbon dynamics for the United States: A new spatially explicit approach linking the LUCAS and CBM-CFS3 models. *Carbon Balance and Management*, **17** (1), 1. https://doi.org/10.1186/s13021-022-00201-1

116. Zhou, Q., G. Xian, J. Horton, D. Wellington, G. Domke, R. Auch, C. Li, and Z. Zhu, 2022: Tree regrowth duration map from LCMAP collection 1.0 land cover products in the conterminous United States, 1985–2017. *GIScience & Remote Sensing*, **59** (1), 959–974. https://doi.org/10.1080/15481603.2022.2083790

117. Law, B.E., T.W. Hudiburg, L.T. Berner, J.J. Kent, P.C. Buotte, and M.E. Harmon, 2018: Land use strategies to mitigate climate change in carbon dense temperate forests. *Proceedings of the National Academy of Sciences of the United States of America*, **115** (14), 3663–3668. https://doi.org/10.1073/pnas.1720064115

118. Fitts, L.A., M.B. Russell, G.M. Domke, and J.K. Knight, 2021: Modeling land use change and forest carbon stock changes in temperate forests in the United States. *Carbon Balance and Management*, **16** (1), 20. https://doi.org/10.1186/s13021-021-00183-6

119. Ameray, A., Y. Bergeron, O. Valeria, M. Montoro Girona, and X. Cavard, 2021: Forest carbon management: A review of silvicultural practices and management strategies across boreal, temperate and tropical forests. *Current Forestry Reports*, **7** (4), 245–266. https://doi.org/10.1007/s40725-021-00151-w

120. Law, B.E., W.R. Moomaw, T.W. Hudiburg, W.H. Schlesinger, J.D. Sterman, and G.M. Woodwell, 2022: Creating strategic reserves to protect forest carbon and reduce biodiversity losses in the United States. *Land*, **11** (5). https://doi.org/10.3390/land11050721

121. Littlefield, C.E. and A.W. D'Amato, 2022: Identifying trade-offs and opportunities for forest carbon and wildlife using a climate change adaptation lens. *Conservation Science and Practice*, **4** (4), e12631. https://doi.org/10.1111/csp2.12631

122. Ontl, T.A., M.K. Janowiak, C.W. Swanston, J. Daley, S. Handler, M. Cornett, S. Hagenbuch, C. Handrick, L. McCarthy, and N. Patch, 2020: Forest management for carbon sequestration and climate adaptation. *Journal of Forestry*, **118** (1), 86–101. https://doi.org/10.1093/jofore/fvz062

123. Cohen, E., G. Sun, L. Zhang, P. Caldwell, and S. Krieger, 2017: Quantifying the Role of Forested Lands in Providing Surface Drinking Water Supply for Puerto Rico. Gen. Tech. Rep. SRS-197-Addendum. U.S. Department of Agriculture, Forest Service, Southern Research Station, Asheville, NC, 20 pp. https://www.fs.usda.gov/research/treesearch/54732

124. Liu, N., G.R. Dobbs, P.V. Caldwell, C.F. Miniat, G. Sun, K. Duan, S.A.C. Nelson, P.V. Bolstad, and C.P. Carlson, 2022: Inter-basin transfers extend the benefits of water from forests to population centers across the conterminous U.S. *Water Resources Research*, **58** (5), e2021WR031537. https://doi.org/10.1029/2021wr031537

125. Mote, P.W., S. Li, D.P. Lettenmaier, M. Xiao, and R. Engel, 2018: Dramatic declines in snowpack in the western US. *Npj Climate and Atmospheric Science*, **1** (1), 1–6. https://doi.org/10.1038/s41612-018-0012-1

126. Williams, A.P., B.I. Cook, and J.E. Smerdon, 2022: Rapid intensification of the emerging southwestern North American megadrought in 2020–2021. *Nature Climate Change*, **12** (3), 232–234. https://doi.org/10.1038/s41558-022-01290-z

127. Peterson, T.C., R.R. Heim, R. Hirsch, D.P. Kaiser, H. Brooks, N.S. Diffenbaugh, R.M. Dole, J.P. Giovannettone, K. Guirguis, T.R. Karl, R.W. Katz, K. Kunkel, D. Lettenmaier, G.J. McCabe, C.J. Paciorek, K.R. Ryberg, S. Schubert, V.B.S. Silva, B.C. Stewart, A.V. Vecchia, G. Villarini, R.S. Vose, J. Walsh, M. Wehner, D. Wolock, K. Wolter, C.A. Woodhouse, and D. Wuebbles, 2013: Monitoring and understanding changes in heat waves, cold waves, floods, and droughts in the United States: State of knowledge. *Bulletin of the American Meteorological Society*, **94** (6), 821–834. https://doi.org/10.1175/bams-d-12-00066.1

128. Yochum, S.E., J.A. Scott, and D.H. Levinson, 2019: Methods for assessing expected flood potential and variability: Southern Rocky Mountains region. *Water Resources Research*, **55** (8), 6392–6416. https://doi.org/10.1029/2018wr024604

129. Clifton, C.F., K.T. Day, C.H. Luce, G.E. Grant, M. Safeeq, J.E. Halofsky, and B.P. Staab, 2018: Effects of climate change on hydrology and water resources in the Blue Mountains, Oregon, USA. *Climate Services*, **10**, 9–19. https://doi.org/10.1016/j.cliser.2018.03.001

130. Hamlet, A.F., M.M. Elsner, G.S. Mauger, S.-Y. Lee, I. Tohver, and R.A. Norheim, 2013: An overview of the Columbia Basin climate change scenarios project: Approach, methods, and summary of key results. *Atmosphere-Ocean*, **51** (4), 392–415. https://doi.org/10.1080/07055900.2013.819555

131. Ren, J., J.C. Adam, J.A. Hicke, E.J. Hanan, C.L. Tague, M. Liu, C.A. Kolden, and J.T. Abatzoglou, 2021: How does water yield respond to mountain pine beetle infestation in a semiarid forest? *Hydrology and Earth System Sciences*, **25** (9), 4681–4699. https://doi.org/10.5194/hess-25-4681-2021

132. Rust, A.J., S. Saxe, J. McCray, C.C. Rhoades, and T.S. Hogue, 2019: Evaluating the factors responsible for post-fire water quality response in forests of the western USA. *International Journal of Wildland Fire*, **28** (10), 769–784. https://doi.org/10.1071/wf18191

133. Sankey, J.B., J. Kreitler, T.J. Hawbaker, J.L. McVay, M.E. Miller, E.R. Mueller, N.M. Vaillant, S.E. Lowe, and T.T. Sankey, 2017: Climate, wildfire, and erosion ensemble foretells more sediment in western USA watersheds. *Geophysical Research Letters*, **44** (17), 8884–8892. https://doi.org/10.1002/2017gl073979

134. Rust, A.J., T.S. Hogue, S. Saxe, and J. McCray, 2018: Post-fire water-quality response in the western United States. *International Journal of Wildland Fire*, **27** (3), 203–216. https://doi.org/10.1071/wf17115

135. Pennino, M.J., S.G. Leibowitz, J.E. Compton, M.T. Beyene, and S.D. LeDuc, 2022: Wildfires can increase regulated nitrate, arsenic, and disinfection byproduct violations and concentrations in public drinking water supplies. *Science of The Total Environment*, **804** (15), 149890. https://doi.org/10.1016/j.scitotenv.2021.149890

136. Rumsey, C.A., M.P. Miller, and G.A. Sexstone, 2020: Relating hydroclimatic change to streamflow, baseflow, and hydrologic partitioning in the Upper Rio Grande Basin, 1980 to 2015. *Journal of Hydrology*, **584**, 124715. https://doi.org/10.1016/j.jhydrol.2020.124715

137. Crozier, L.G., J.E. Siegel, L.E. Wiesebron, E.M. Trujillo, B.J. Burke, B.P. Sandford, and D.L. Widener, 2020: Snake River sockeye and Chinook salmon in a changing climate: Implications for upstream migration survival during recent extreme and future climates. *PLoS ONE*, **15** (9), e0238886. https://doi.org/10.1371/journal.pone.0238886

138. McDonnell, T.C., M.R. Sloat, T.J. Sullivan, C.A. Dolloff, P.F. Hessburg, N.A. Povak, W.A. Jackson, and C. Sams, 2015: Downstream warming and headwater acidity may diminish coldwater habitat in southern Appalachian mountain streams. *PLoS ONE*, **10** (8), e0134757. https://doi.org/10.1371/journal.pone.0134757

139. Ruhí, A., J.D. Olden, and J.L. Sabo, 2016: Declining streamflow induces collapse and replacement of native fish in the American Southwest. *Frontiers in Ecology and the Environment*, **14** (9), 465–472. https://doi.org/10.1002/fee.1424

140. Littell, J.S., S.A. McAfee, and G.D. Hayward, 2018: Alaska snowpack response to climate change: Statewide snowfall equivalent and snowpack water scenarios. *Water*, **10** (5), 668. https://doi.org/10.3390/w10050668

141. Littell, J.S., J.H. Reynolds, K.K. Bartz, S.A. McAfee, and G. Hayward, 2020: So goes the snow: Alaska snowpack changes and impacts on Pacific salmon in a warming climate (U.S. National Park Service). *Alaska Park Science*, **19** (1), 62–75. https://www.nps.gov/articles/aps-19-1-10.htm

142. Nash, C.S., G.E. Grant, S. Charnley, j.B. Dunham, H. Gosnell, M.B. Hausner, D.S. Pilliod, and J.D. Taylor, 2021: Great expectations: Deconstructing the process pathways underlying beaver-related restoration. *BioScience*, **71** (3), 249–267. https://doi.org/10.1093/biosci/biaa165

143. Stevenson, J.R., J.B. Dunham, S.M. Wondzell, and J. Taylor, 2022: Dammed water quality—Longitudinal stream responses below beaver ponds in the Umpqua River Basin, Oregon. *Ecohydrology*, **15** (4), e2430. https://doi.org/10.1002/eco.2430

144. Wondzell, S.M., M. Diabat, and R. Haggerty, 2019: What matters most: Are future stream temperatures more sensitive to changing air temperatures, discharge, or riparian vegetation? *JAWRA Journal of the American Water Resources Association*, **55** (1), 116–132. https://doi.org/10.1111/1752-1688.12707

145. Stephens, S.L., J.D. McIver, R.E. Boerner, C.J. Fettig, J.B. Fontaine, B.R. Hartsough, P.L. Kennedy, and D.W. Schwilk, 2012: The effects of forest fuel-reduction treatments in the United States. *BioScience*, **62** (6), 549–560. https://doi.org/10.1525/bio.2012.62.6.6

146. Stephens, S.L., A.L. Westerling, M.D. Hurteau, M.Z. Peery, C.A. Schultz, and S. Thompson, 2020: Fire and climate change: Conserving seasonally dry forests is still possible. *Frontiers in Ecology and the Environment*, **18** (6), 354–360. https://doi.org/10.1002/fee.2218

147. Peterson, D.L. and J.E. Halofsky, 2018: Adapting to the effects of climate change on natural resources in the Blue Mountains, USA. *Climate Services*, **10**, 63–71. https://doi.org/10.1016/j.cliser.2017.06.005

148. Halofsky, J., D. Peterson, K. Metlen, M. Myer, and V. Sample, 2016: Developing and implementing climate change adaptation options in forest ecosystems: A case study in southwestern Oregon, USA. *Forests*, **7** (11), 268. https://doi.org/10.3390/f7110268

149. Timberlake, T.J. and C.A. Schultz, 2019: Climate change vulnerability assessment for forest management: The case of the U.S. Forest Service. *Forests*, **10** (11), 1030. https://doi.org/10.3390/f10111030

150. Ontl, T.A., C. Swanston, L.A. Brandt, P.R. Butler, A.W. D'Amato, S.D. Handler, M.K. Janowiak, and P.D. Shannon, 2018: Adaptation pathways: Ecoregion and land ownership influences on climate adaptation decision-making in forest management. *Climatic Change*, **146** (1), 75–88. https://doi.org/10.1007/s10584-017-1983-3

151. PADEP, 2021: Pennsylvania Climate Action Plan 2021. Pennsylvania Department of Environmental Protection, Harrisburg, PA. https://www.dep.pa.gov/citizens/climate/pages/pa-climate-action-plan.aspx

152. Fischer, A.P., 2019: Adapting and coping with climate change in temperate forests. *Global Environmental Change*, **54**, 160–171. https://doi.org/10.1016/j.gloenvcha.2018.10.011

153. ITEP, 2021: Tribal Climate Change Assessments and Adaptation Plans. Institute for Tribal Environmental Professionals, 10 pp. http://www7.nau.edu/itep/main/tcc/docs/resources/9_tribalccassessmentsadaptationplans_08_27_21.pdf

154. Adaptation Partners, 2023: The Climate Change Adaptation Library for the Western United States. Adaptation Partners. http://adaptationpartners.org/library.php

155. 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

156. Sass, E.M., B.J. Butler, and M. Markowski-Lindsay, 2020: Distribution of Forest Ownerships across the Conterminous United States, 2017. Res. Map NRS-11. U.S. Department of Agriculture, Forest Service, Northern Research Station, Madison, WI. https://doi.org/10.2737/nrs-rmap-11

157. Long, J.W., F.K. Lake, and R.W. Goode, 2021: The importance of Indigenous cultural burning in forested regions of the Pacific West, USA. *Forest Ecology and Management*, **500**, 119597. https://doi.org/10.1016/j.foreco.2021.119597

158. Marks-Block, T., F.K. Lake, and L.M. Curran, 2019: Effects of understory fire management treatments on California hazelnut, an ecocultural resource of the Karuk and Yurok Indians in the Pacific Northwest. *Forest Ecology and Management*, **450**, 117517. https://doi.org/10.1016/j.foreco.2019.117517

159. WA DNR, 2020: 20-Year Forest Health Strategic Plan: Eastern Washington. Washington Department of Natural Resources. https://www.dnr.wa.gov/publications/rp_forest_health_20_year_strategic_plan.pdf

160. St.Clair, J.B., B.A. Richardson, N. Stevenson-Molnar, G.T. Howe, A.D. Bower, V.J. Erickson, B. Ward, D. Bachelet, F.F. Kilkenny, and T. Wang, 2022: Seedlot selection tool and climate-smart restoration tool: Web-based tools for sourcing seed adapted to future climates. *Ecosphere*, **13** (5), e4089. https://doi.org/10.1002/ecs2.4089

161. NIACS, 2022: The Nature Conservancy: Restoring and Connecting Forests in Cuyahoga Valley National Park. Northern Institute of Applied Climate Science. https://forestadaptation.org/adapt/demonstration-projects/nature-conservancy-restoring-and-connecting-forests-cuyahoga-valley

162. NIACS, 2022: The Nature Conservancy: Setting Northern New York Forests on Climate-Adapted Trajectories by Improving Regeneration & Forest Structure. Northern Institute of Applied Climate Science. https://forestadaptation.org/adapt/demonstration-projects/nature-conservancy-setting-northern-new-york-forests-climate-adapted

163. Piana, M.R., C.C. Pregitzer, and R.A. Hallett, 2021: Advancing management of urban forested natural areas: Toward an urban silviculture? *Frontiers in Ecology and the Environment*, **19** (9), 526–535. https://doi.org/10.1002/fee.2389

164. Piana, M.R., R.A. Hallett, M.L. Johnson, N.F. Sonti, L.A. Brandt, M.F.J. Aronson, M. Ashton, M. Blaustein, D. Bloniarz, A.A. Bowers, M.E. Carr, V. D'Amico, L. Dewald, H. Dionne, D.A. Doroski, R.T. Fahey, H. Forgione, T. Forrest, J. Hale, E. Hansen, L. Hayden, S. Hines, J.M. Hoch, T. Ieataka, S.B. Lerman, C. Murphy, E. Nagele, K. Nislow, D. Parker, C.C. Pregitzer, L. Rhodes, J. Schuler, A. Sherman, T. Trammell, B.M. Wienke, T. Witmer, T. Worthley, and I. Yesilonis, 2021: Climate adaptive silviculture for the city: Practitioners and researchers co-create a framework for studying urban oak-dominated mixed hardwood forests. *Frontiers in Ecology and Evolution*, **9**, 750495. https://doi.org/10.3389/fevo.2021.750495

165. Pregitzer, C.C., S. Charlop-Powers, S. Bibbo, H.M. Forgione, B. Gunther, R.A. Hallett, and M.A. Bradford, 2019: A city-scale assessment reveals that native forest types and overstory species dominate New York City forests. *Ecological Applications*, **29** (1), e01819. https://doi.org/10.1002/eap.1819

166. Tribal Adaptation Menu Team, 2019: Dibaginjigaadeg Anishinaabe Ezhitwaad: A Tribal Climate Adaptation Menu. Great Lakes Indian Fish and Wildlife Commission, Odanah, WI, 54 pp. https://forestadaptation.org/tribal-climate-adaptation-menu

167. NIACS, 2022: Mark Twain National Forest: Red Bluff Recreation Area. Northern Institute of Applied Climate Science. https://forestadaptation.org/adapt/demonstration-projects/mark-twain-national-forest-red-bluff-recreation-area

168. Álvarez-Berríos, N.L., S.S. Wiener, K.A. McGinley, A.B. Lindsey, and W.A. Gould, 2021: Hurricane effects, mitigation, and preparedness in the Caribbean: Perspectives on high importance–low prevalence practices from agricultural advisors. *Journal of Emergency Management*, **19** (8), 135–155. https://doi.org/10.5055/jem.0585

169. Wiener, S.S., N.L. Álvarez-Berríos, and A.B. Lindsey, 2020: Opportunities and challenges for hurricane resilience on agricultural and forest land in the U.S. Southeast and Caribbean. *Sustainability*, **12** (4), 1364. https://doi.org/10.3390/su12041364

170. Knapp, E.E., A.A. Bernal, J.M. Kane, C.J. Fettig, and M.P. North, 2021: Variable thinning and prescribed fire influence tree mortality and growth during and after a severe drought. *Forest Ecology and Management*, **479**, 118595. https://doi.org/10.1016/j.foreco.2020.118595

171. McCauley, L.A., J.B. Bradford, M.D. Robles, R.K. Shriver, T.J. Woolley, and C.A. Andrews, 2022: Landscape-scale forest restoration decreases vulnerability to drought mortality under climate change in southwest USA ponderosa forest. *Forest Ecology and Management*, **509**, 120088. https://doi.org/10.1016/j.foreco.2022.120088

172. Hessburg, P.F., S.J. Prichard, R.K. Hagmann, N.A. Povak, and F.K. Lake, 2021: Wildfire and climate change adaptation of western North American forests: A case for intentional management. *Ecological Applications*, **31** (8), e02432. https://doi.org/10.1002/eap.2432

173. Lake, F.K., 2021: Indigenous fire stewardship: Federal/Tribal partnerships for wildland fire research and management. *Fire Management Today*, **79** (1), 30–39. https://www.fs.usda.gov/treesearch/pubs/62060

174. Messier, C., J. Bauhus, F. Doyon, F. Maure, R. Sousa-Silva, P. Nolet, M. Mina, N. Aquilué, M.-J. Fortin, and K. Puettmann, 2019: The functional complex network approach to foster forest resilience to global changes. *Forest Ecosystems*, **6** (1), 21. https://doi.org/10.1186/s40663-019-0166-2

175. Grossiord, C., 2020: Having the right neighbors: How tree species diversity modulates drought impacts on forests. *New Phytologist*, **228** (1), 42–49. https://doi.org/10.1111/nph.15667

176. Berrouet, L.M., J. Machado, and C. Villegas-Palacio, 2018: Vulnerability of socio-ecological systems: A conceptual Framework. *Ecological Indicators*, **84**, 632–647. https://doi.org/10.1016/j.ecolind.2017.07.051

177. Olander, L., K. Warnell, T. Warziniack, Z. Ghali, C. Miller, and C. Neelan, 2021: Exploring the use of ecosystem services conceptual models to account for the benefits of public lands: An example from national forest planning in the United States. *Forests*, **12** (3), 267. https://doi.org/10.3390/f12030267

178. Schelhas, J., S. Hitchner, C. Johnson Gaither, R. Fraser, V. Jennings, and A. Diop, 2017: Engaging African American landowners in sustainable forest management. *Journal of Forestry*, **115** (1), 26–33. https://doi.org/10.5849/jof.15-116

179. Kramer, A.L., J. Liu, L. Li, R. Connolly, M. Barbato, and Y. Zhu, 2023: Environmental justice analysis of wildfire-related $PM_{2.5}$ exposure using low-cost sensors in California. *Science of The Total Environment*, **856**, 159218. https://doi.org/10.1016/j.scitotenv.2022.159218

180. Thomas, A., J. Sánchez, and D. Flores, 2022: A review of trends and knowledge gaps in Latinx outdoor recreation on federal and state public lands. *Journal of Park and Recreation Administration*, **40** (1). https://doi.org/10.18666/jpra-2021-11064

181. Baumflek, M., K.-A. Kassam, C. Ginger, and M.R. Emery, 2021: Incorporating biocultural approaches in forest management: Insights from a case study of Indigenous plant stewardship in Maine, USA and New Brunswick, Canada. *Society & Natural Resources*, **34** (9), 1155–1173. https://doi.org/10.1080/08941920.2021.1944411

182. 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

183. Yazzie, J.O., P.Z. Fulé, Y.-S. Kim, and A. Sánchez Meador, 2019: Diné kinship as a framework for conserving native tree species in climate change. *Ecological Applications*, **29** (6), e01944. https://doi.org/10.1002/eap.1944

184. Sáenz-Romero, C., G. Neill, S.N. Aitken, and R. Lindig-Cisneros, 2021: Assisted migration field tests in Canada and Mexico: Lessons, limitations, and challenges. *Forests*, **12** (1), 9. https://doi.org/10.3390/f12010009

185. Leech, S.M., P.L. Almuedo, and G. O'Neill, 2011: Assisted migration: Adapting forest management to a changing climate. *Journal of Ecosystems and Management*, **12** (3). https://doi.org/10.22230/jem.2011v12n3a91

186. Pérez, I., J.D. Anadón, M. Díaz, G.G. Nicola, J.L. Tella, and A. Giménez, 2012: What is wrong with current translocations? A review and a decision-making proposal. *Frontiers in Ecology and the Environment*, **10** (9), 494–501. https://doi.org/10.1890/110175

187. Karasov-Olson, A., M.W. Schwartz, J.D. Olden, S. Skikne, J.J. Hellman, S. Allen, C. Brigham, D. Buttke, D.J. Lawrence, A.J. Miller-Rushing, J.T. Morisette, G.W. Schuurman, M. Trammell, and C. Hawkins-Hoffma, 2021: Ecological Risk Assessment of Managed Relocation as a Climate Change Adaptation Strategy. Natural Resource Report. NPS/NRSS/CCRP/NRR—2021/2241. U.S. Department of the Interior, National Park Service, Fort Collins, CO. https://doi.org/10.36967/nrr-2284919.

188. Fargione, J., D.L. Haase, O.T. Burney, O.A. Kildisheva, G. Edge, S.C. Cook-Patton, T. Chapman, A. Rempel, M.D. Hurteau, K.T. Davis, S. Dobrowski, S. Enebak, R. De La Torre, A.A.R. Bhuta, F. Cubbage, B. Kittler, D. Zhang, and R.W. Guldin, 2021: Challenges to the reforestation pipeline in the United States. *Frontiers in Forests and Global Change*, **4**, 629198. https://doi.org/10.3389/ffgc.2021.629198

189. Chambwera, M., G. Heal, C. Dubeux, S. Hallegatte, L. Leclerc, A. Markandya, B.A. McCarl, R. Mechler, and J.E. Neumann, 2014: Ch. 17. Economics of adaptation. In: *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Field, C.B., V.R. Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L. White, Eds. Cambridge University Press, Cambridge, UK and New York, NY, USA, 945–977. https://www.ipcc.ch/report/ar5/wg2/

190. UNECE, 2021: Forest Sector Outlook Study, 2020–2040. ECE/TIM/SP/51. United Nations Economic Commission for Europe and the Food and Agriculture Organization of the United Nations, Geneva, Switzerland, 103 pp. https://unece.org/sites/default/files/2022-05/unece-fao-sp-51-main-report-forest-sector-outlook_0.pdf

191. Andersson, E. and E.C.H. Keskitalo, 2018: Adaptation to climate change? Why business-as-usual remains the logical choice in Swedish forestry. *Global Environmental Change*, **48**, 76–85. https://doi.org/10.1016/j.gloenvcha.2017.11.004

192. Anderson, S., T.L. Anderson, A.C. Hill, M.E. Kahn, H. Kunreuther, G.D. Libecap, H. Mantripragada, P. Mérel, A.J. Plantinga, V. Kerry Smith, 2019: The critical role of markets in climate change adaptation. *Climate Change Economics*, **10** (1), 1950003. https://doi.org/10.1142/s2010007819500039

193. Nordhaus, W., 2019: Climate change: The ultimate challenge for economics. *American Economic Review*, **109** (6), 1991–2014. https://doi.org/10.1257/aer.109.6.1991

194. Hashida, Y., J. Withey, D.J. Lewis, T. Newman, and J.D. Kline, 2020: Anticipating changes in wildlife habitat induced by private forest owners' adaptation to climate change and carbon policy. *PLoS ONE*, **15** (4), e0230525. https://doi.org/10.1371/journal.pone.0230525

195. Amacher, G., A.S. Malik, and R.G. Haight, 2006: Reducing social losses from forest fires. *Land Economics*, **82** (3), 367–383. https://doi.org/10.3368/le.82.3.367

196. Scarlett, L. and M. McKinney, 2016: Connecting people and places: The emerging role of network governance in large landscape conservation. *Frontiers in Ecology and the Environment*, **14** (3), 116–125. https://doi.org/10.1002/fee.1247

197. Wyborn, C., A. Datta, J. Montana, M. Ryan, P. Leith, B. Chaffin, C. Miller, and L. van Kerkhoff, 2019: Co-producing sustainability: Reordering the governance of science, policy, and practice. *Annual Review of Environment and Resources*, **44** (1), 319–346. https://doi.org/10.1146/annurev-environ-101718-033103

198. Coop, J.D., S.A. Parks, C.S. Stevens-Rumann, S.D. Crausbay, P.E. Higuera, M.D. Hurteau, A. Tepley, E. Whitman, T. Assal, B.M. Collins, K.T. Davis, S. Dobrowski, D.A. Falk, P.J. Fornwalt, P.Z. Fulé, B.J. Harvey, V.R. Kane, C.E. Littlefield, E.Q. Margolis, M. North, M.-A. Parisien, S. Prichard, and K.C. Rodman, 2020: Wildfire-driven forest conversion in western North American landscapes. *BioScience*, **70** (8), 659–673. https://doi.org/10.1093/biosci/biaa061

199. 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

200. Littell, J.S., D. McKenzie, D.L. Peterson, and A.L. Westerling, 2009: Climate and wildfire area burned in western U.S. ecoprovinces, 1916–2003. *Ecological Applications*, **19** (4), 1003–1021. https://doi.org/10.1890/07-1183.1

201. Abatzoglou, J.T. and C.A. Kolden, 2013: Relationships between climate and macroscale area burned in the western United States. *International Journal of Wildland Fire*, **22** (7), 1003–1020. https://doi.org/10.1071/wf13019

202. Barbero, R., J. Abatzoglou, N. Larkin, C. Kolden, and B. Stocks, 2015: Climate change presents increased potential for very large fires in the contiguous United States. *International Journal of Wildland Fire*, **24** (7), 892–899. https://doi.org/10.1071/wf15083

203. Kitzberger, T., D.A. Falk, A.L. Westerling, and T.W. Swetnam, 2017: Direct and indirect climate controls predict heterogeneous early-mid 21st century wildfire burned area across western and boreal North America. *PLoS ONE*, **12** (12), e0188486. https://doi.org/10.1371/journal.pone.0188486

204. Fettig, C.J., 2019: Socioecological impacts of the western pine beetle outbreak in Southern California: Lessons for the future. *Journal of Forestry*, **117** (2), 138–143. https://doi.org/10.1093/jofore/fvy029

205. Berner, L.T. and S.J. Goetz, 2022: Satellite observations document trends consistent with a boreal forest biome shift. *Global Change Biology*, **28** (10), 3275–3292. https://doi.org/10.1111/gcb.16121

206. Nigro, K.M., M.E. Rocca, M.A. Battaglia, J.D. Coop, and M.D. Redmond, 2022: Wildfire catalyzes upward range expansion of trembling aspen in southern Rocky Mountain beetle-killed forests. *Journal of Biogeography*, **49** (1), 201–214. https://doi.org/10.1111/jbi.14302

207. Sharma, S., R. Andrus, Y. Bergeron, M. Bogdziewicz, D.C. Bragg, D. Brockway, N.L. Cleavitt, B. Courbaud, A.J. Das, M. Dietze, T.J. Fahey, J.F. Franklin, G.S. Gilbert, C.H. Greenberg, Q. Guo, J.H.R. Lambers, I. Ibanez, J.F. Johnstone, C.L. Kilner, J.M.H. Knops, W.D. Koenig, G. Kunstler, J.M. LaMontagne, D. Macias, E. Moran, J.A. Myers, R. Parmenter, I.S. Pearse, R. Poulton-Kamakura, M.D. Redmond, C.D. Reid, K.C. Rodman, C.L. Scher, W.H. Schlesinger, M.A. Steele, N.L. Stephenson, J.J. Swenson, M. Swift, T.T. Veblen, A.V. Whipple, T.G. Whitham, A.P. Wion, C.W. Woodall, R. Zlotin, and J.S. Clark, 2022: North American tree migration paced by climate in the West, lagging in the East. *Proceedings of the National Academy of Sciences of the United States of America*, **119** (3), e2116691118. https://doi.org/10.1073/pnas.2116691118

208. De Frenne, P., J. Lenoir, M. Luoto, B.R. Scheffers, F. Zellweger, J. Aalto, M.B. Ashcroft, D.M. Christiansen, G. Decocq, K. De Pauw, S. Govaert, C. Greiser, E. Gril, A. Hampe, T. Jucker, D.H. Klinges, I.A. Koelemeijer, J.J. Lembrechts, R. Marrec, C. Meeussen, J. Ogée, V. Tyystjärvi, P. Vangansbeke, and K. Hylander, 2021: Forest microclimates and climate change: Importance, drivers and future research agenda. *Global Change Biology*, **27** (11), 2279–2297. https://doi.org/10.1111/gcb.15569

209. Buchholz, R.R., M. Park, H.M. Worden, W. Tang, D.P. Edwards, B. Gaubert, M.N. Deeter, T. Sullivan, M. Ru, M. Chin, R.C. Levy, B. Zheng, and S. Magzamen, 2022: New seasonal pattern of pollution emerges from changing North American wildfires. *Nature Communications*, **13** (1), 2043. https://doi.org/10.1038/s41467-022-29623-8

210. McClure, C.D. and D.A. Jaffe, 2018: US particulate matter air quality improves except in wildfire-prone areas. *Proceedings of the National Academy of Sciences of the United States of America*, **115** (31), 7901–7906. https://doi.org/10.1073/pnas.1804353115

211. NIFC, 2022: Wildfires and Acres. National Interagency Fire Center. https://www.nifc.gov/fire-information/statistics/wildfires

212. Ticktin, T., K. Kindscher, S. Souther, P.C. Weisberg, James L. Hummel, Susan, C. Mitchell, and S. Sanders, 2018: Ch. 3. Ecological dimensions of nontimber forest product harvest. In: *Assessment of Nontimber Forest Products in the United States Under Changing Conditions*. Chamberlain, J.L., M.R. Emery, and T. Patel-Weynand, Eds. U.S. Department of Agriculture, Forest Service, Southern Research Station, Asheville, NC, 60–81. https://doi.org/10.2737/srs-gtr-232

213. Lake, F.K., M.R. Emery, M.J. Baumflek, K.S. Friday, K. Kamelamela, L. Kruger, N. Grewe, J. Gilbert, and N.J. Reo, 2018: Ch. 4. Cultural dimensions of nontimber products. In: *Assessment of Nontimber Forest Products in the United States Under Changing Conditions*. Chamberlain, J.L., M.R. Emery, and T. Patel-Weynand, Eds. U.S. Department of Agriculture, Forest Service, Southern Research Station, Asheville, NC, 16. https://www.fs.usda.gov/research/treesearch/57298

214. 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

215. Wünschmann, A., A.G. Armien, E. Butler, M. Schrage, B. Stromberg, J.B. Bender, A.M. Firshman, and M. Carstensen, 2015: Necropsy findings in 62 opportunistically collected free-ranging moose (*Alces alces*) from Minnesota, USA (2003–13). *Journal of Wildlife Diseases*, **51** (1), 157–65. https://doi.org/10.7589/2014-02-037

216. Carstensen, M., E.C. Hildebrand, D. Plattner, M. Dexter, A. Wünschmann, and A. Armien, 2018: Causes of Non-hunting Mortality of Adult Moose in Minnesota, 2013–2017. Minnesota Department of Natural Resources. https://files.dnr.state.mn.us/wildlife/research/studies/moose/moose_findings.pdf

217. DelGuidice, G.D. and J.H. DelGuidice, 2022: 2022 Aerial Moose Survey. Minnesota Department of Natural Resources, 13 pp. https://files.dnr.state.mn.us/wildlife/moose/moosesurvey.pdf?20220524-17

218. Jones, H., P. Pekins, L. Kantar, I. Sidor, D. Ellingwood, A. Lichtenwalner, and M. O'Neal, 2019: Mortality assessment of moose (*Alces alces*) calves during successive years of winter tick (*Dermacentor albipictus*) epizootics in New Hampshire and Maine (USA). *Canadian Journal of Zoology*, **97** (1), 22–30. https://doi.org/10.1139/cjz-2018-0140

219. Smart, L.S., P.J. Taillie, B. Poulter, J. Vukomanovic, K.K. Singh, J.J. Swenson, H. Mitasova, J.W. Smith, and R.K. Meentemeyer, 2020: Aboveground carbon loss associated with the spread of ghost forests as sea levels rise. *Environmental Research Letters*, **15** (10), 104028. https://doi.org/10.1088/1748-9326/aba136

220. 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

221. Bowker, J.M. and A. Askew, 2012: Ch. 8. U.S. outdoor recreation participation projections to 2060. In: *Outdoor Recreation Trends and Futures: A technical Document Supporting the Forest Service 2010 Resources Planning Act Assessment*. Cordell, H.K., Ed. U.S. Department of Agriculture Forest Service, Southern Research Station, Asheville, NC, 105–124. https://www.fs.usda.gov/research/treesearch/42080

222. Norström, A.V., C. Cvitanovic, M.F. Löf, S. West, C. Wyborn, P. Balvanera, A.T. Bednarek, E.M. Bennett, R. Biggs, A. de Bremond, B.M. Campbell, J.G. Canadell, S.R. Carpenter, C. Folke, E.A. Fulton, O. Gaffney, S. Gelcich, J.-B. Jouffray, M. Leach, M. Le Tissier, B. Martín-López, E. Louder, M.-F. Loutre, A.M. Meadow, H. Nagendra, D. Payne, G.D. Peterson, B. Reyers, R. Scholes, C.I. Speranza, M. Spierenburg, M. Stafford-Smith, M. Tengö, S. van der Hel, I. van Putten, and H. Österblom, 2020: Principles for knowledge co-production in sustainability research. *Nature Sustainability*, **3** (3), 182–190. https://doi.org/10.1038/s41893-019-0448-2

223. Violle, C., M.-L. Navas, D. Vile, E. Kazakou, C. Fortunel, I. Hummel, and E. Garnier, 2007: Let the concept of trait be functional! *Oikos*, **116** (5), 882–892. https://doi.org/10.1111/j.0030-1299.2007.15559.x

224. Pretzsch, H., D.I. Forrester, and J. Bauhus, Eds., 2017: *Mixed-Species Forests: Ecology and Management*. Springer, Heidelberg, Germany. https://doi.org/10.1007/978-3-662-54553-9

225. Vernon, M.J., R.L. Sherriff, P. van Mantgem, and J.M. Kane, 2018: Thinning, tree-growth, and resistance to multi-year drought in a mixed-conifer forest of northern California. *Forest Ecology and Management*, **422**, 190–198. https://doi.org/10.1016/j.foreco.2018.03.043

226. Andrews, C.M., A.W. D'Amato, S. Fraver, B. Palik, M.A. Battaglia, and J.B. Bradford, 2020: Low stand density moderates growth declines during hot droughts in semi-arid forests. *Journal of Applied Ecology*, **57** (6), 1089–1102. https://doi.org/10.1111/1365-2664.13615

227. Steckel, M., W.K. Moser, M. del Río, and H. Pretzsch, 2020: Implications of reduced stand density on tree growth and drought susceptibility: A study of three species under varying climate. *Forests*, **11** (6), 627. https://doi.org/10.3390/f11060627