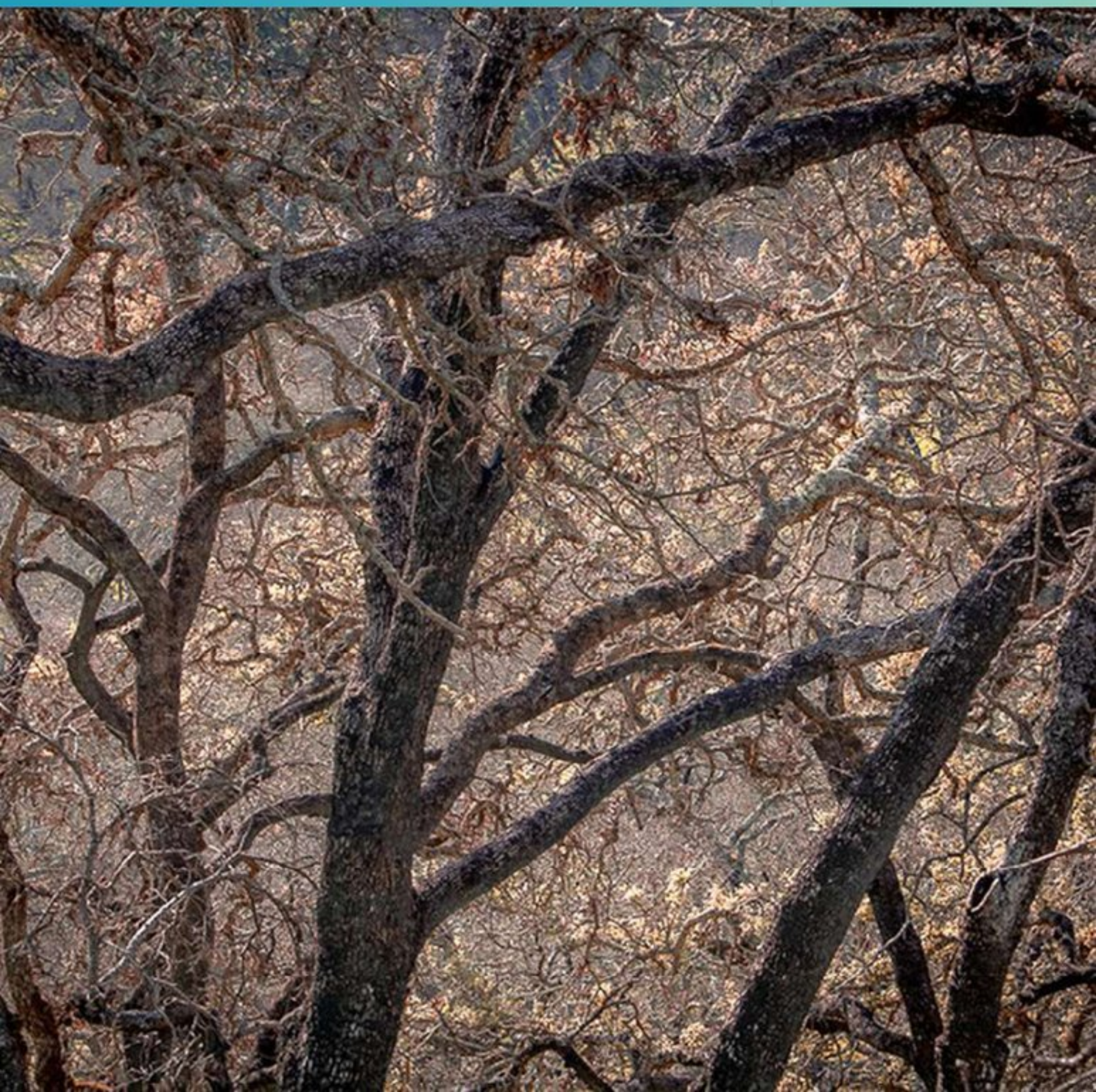


Forests



Chapter 7. Forests

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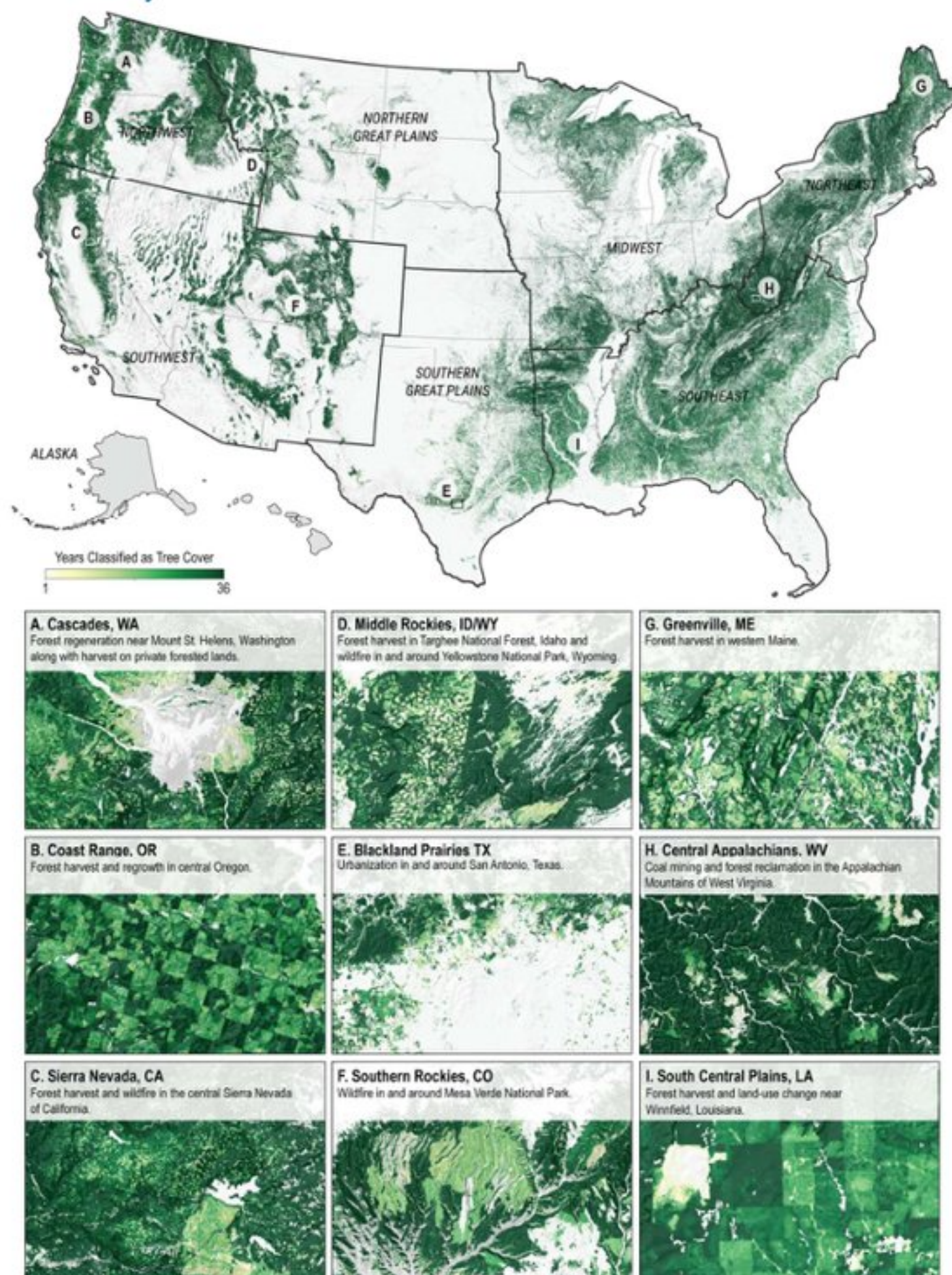
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Introduction

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

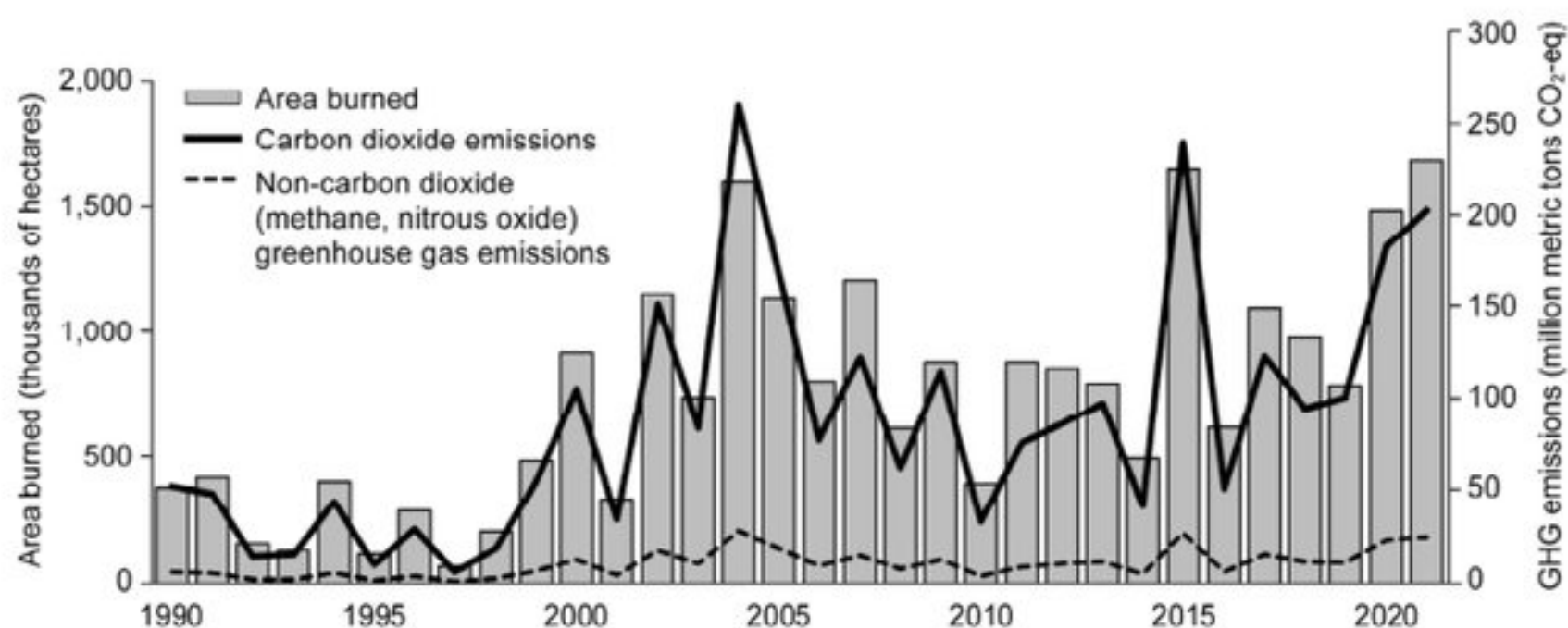


The persistence of tree cover in the United States varies due to many driving forces.

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 2021¹⁰). 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. 2018¹¹). 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



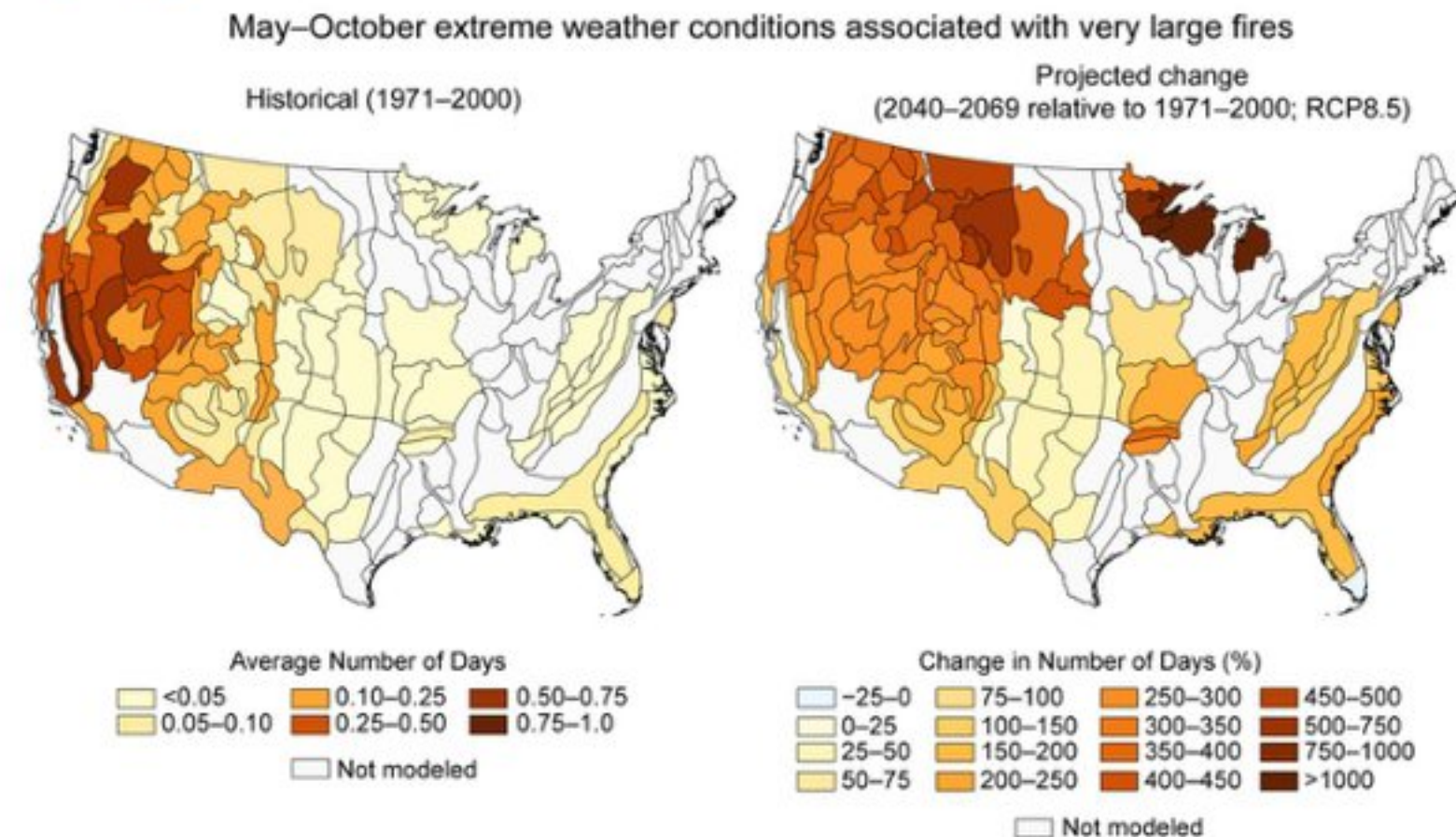
Coastal ghost forests result when trees are killed by sea level rise and saltwater intrusion.

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 decades²¹ 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 ignitions²³ 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 (CO₂)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

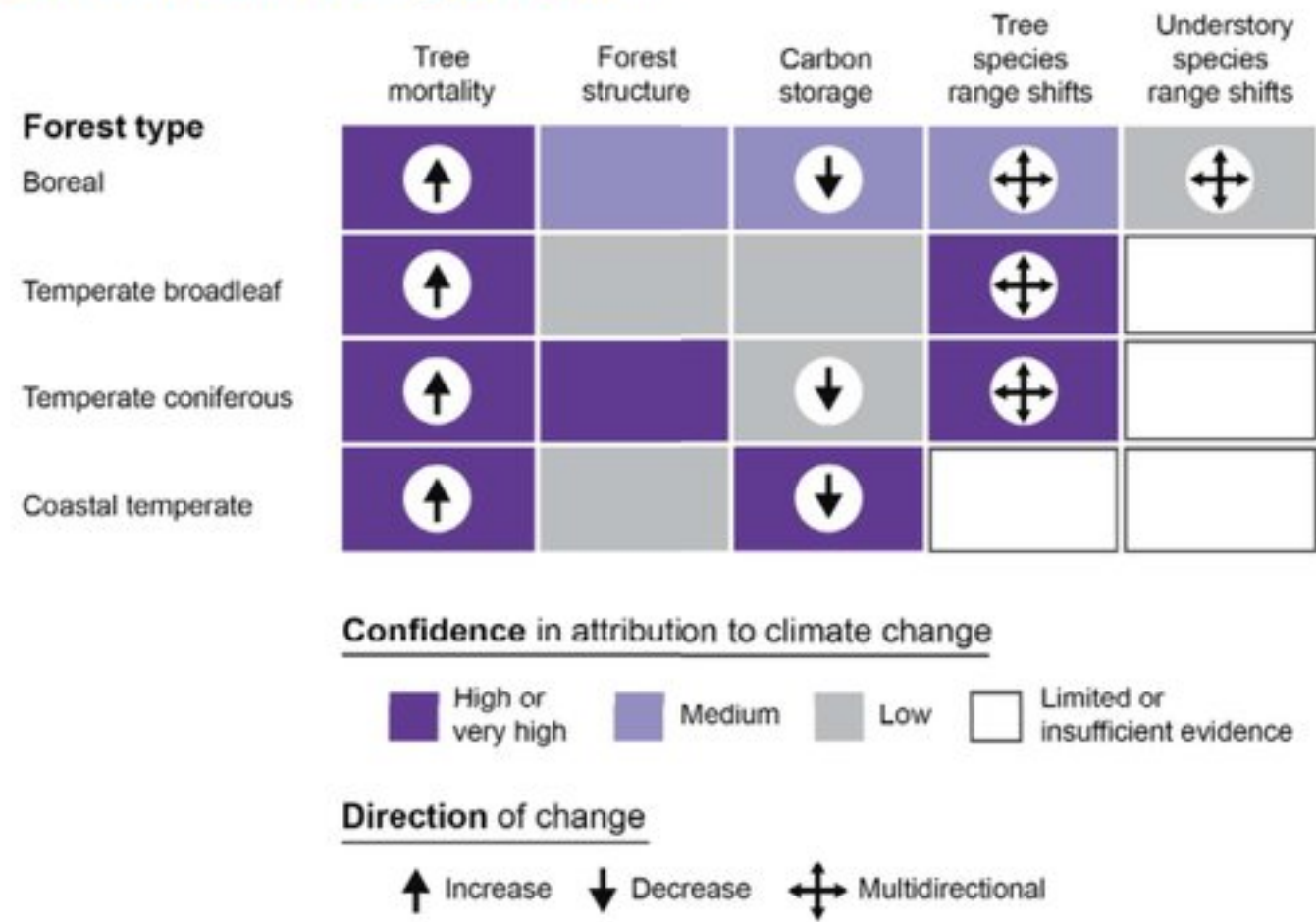
Sea level rise, another climate-related disturbance, affects the distribution, structure, and composition of forests (KM 9.2). Saltwater intrusion has reduced the health, diversity, and productivity of some coastal

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. 2021⁴⁴).

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 wildfires⁶⁶ 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. 2016⁷⁰), and the amount of carbon stored in harvested wood products (Box 7.2; KM 12.2; e.g., Johnston and Radeloff 2019⁷¹). 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. 2017⁷³). 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

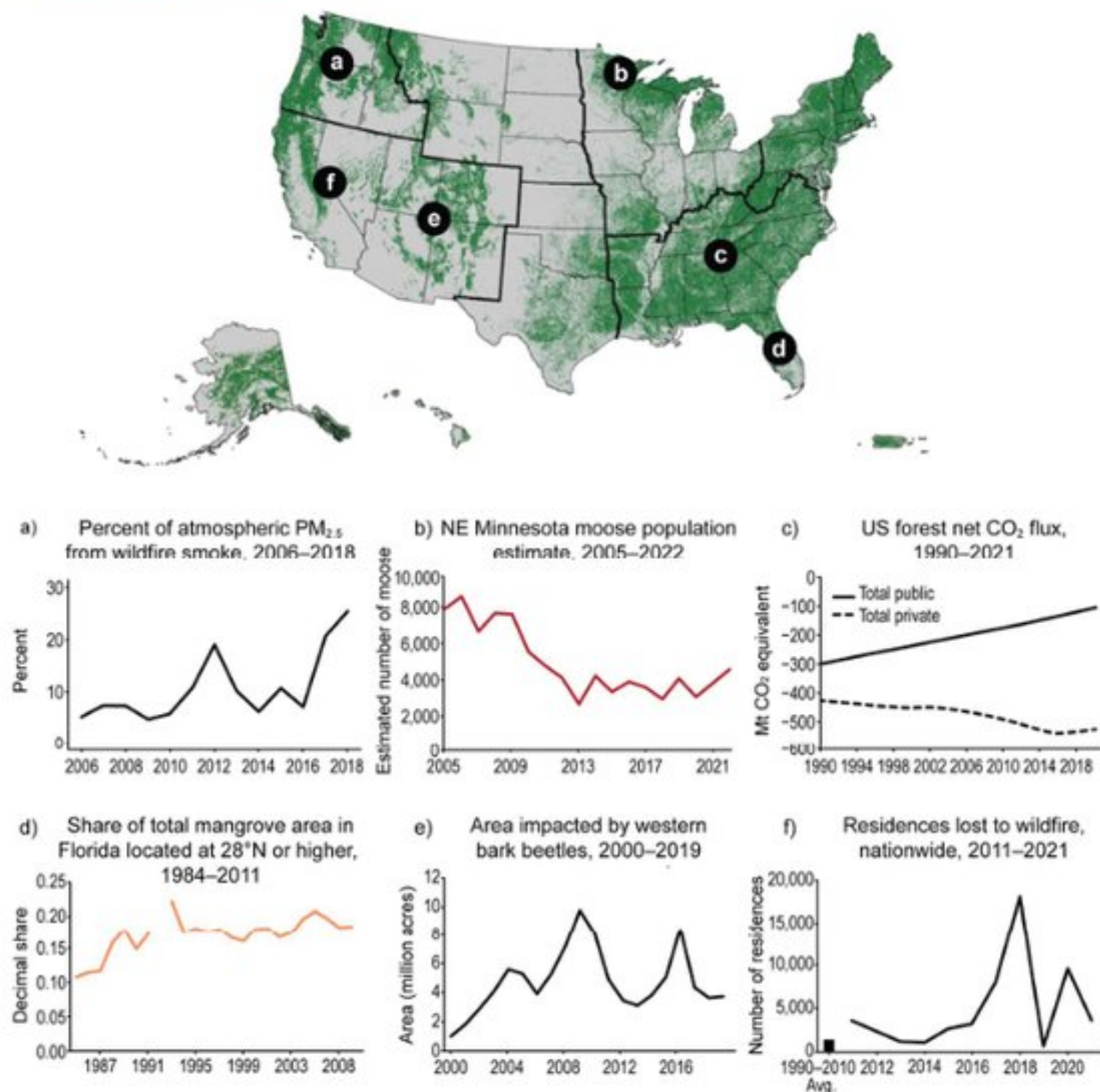
Climate change is altering the ranges and abundances of some plants and fungi used for food, medicine, and other purposes. Reduced snow depth, for example, can increase plant injury and mortality through increased exposure of tissues to frosts,^{75,76,77} as well as reduced microbial biomass and activity.^{78,79} 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 Samoa (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.

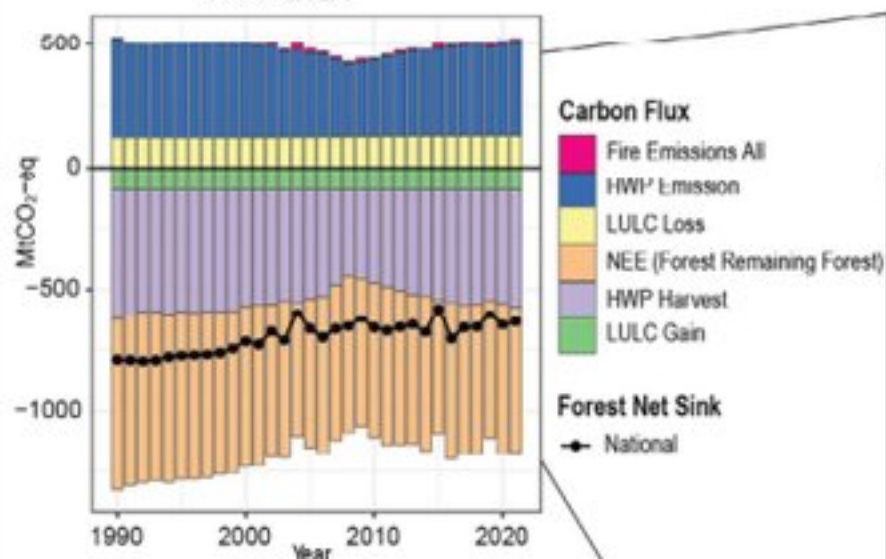
Extreme events have been linked to declines in populations of amphibians, birds, fish, invertebrates, mammals, plants, and reptiles (KM 8.2).¹⁰⁴ Recent insect population declines have been attributed, in part, to climate change, with wide-reaching consequences.^{105,106} Climate change is increasing 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. 2021¹⁰⁹). Increased intensities of hurricanes could affect the structure and function of forests and wildlife habitat (e.g., Brown et al. 2011¹¹⁰). 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

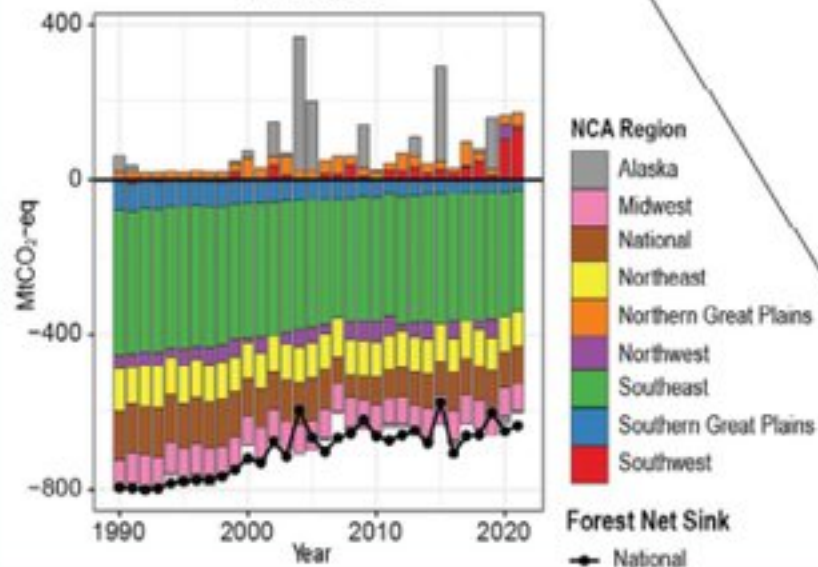
Carbon is continuously cycled between the Earth and atmosphere. Forests help regulate climate, as live plants remove carbon dioxide (CO₂) from the atmosphere through photosynthesis, facilitating maintenance and growth, and release some of that carbon through respiration. Forest ecosystems are the largest 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 CO₂ 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

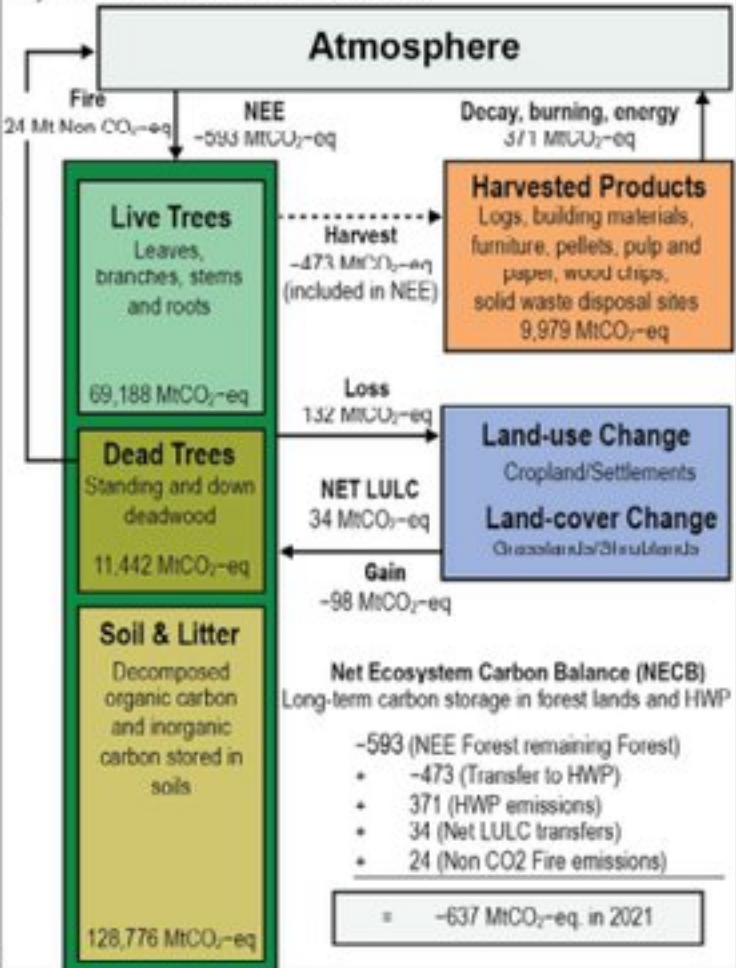
a) Forest Carbon Sources and Sinks, 1990–2021



b) Forest Carbon Sink Variability by Region, 1990–2021



c) Total Forest Carbon Stocks



Carbon stocks are values estimated for 2021. NEE (Net Ecosystem Exchange) is the net flux for forest remaining forest, which also includes harvest removals and CO₂ emissions from fire. Mt is millions of metric tone. HWP is harvested wood products. LULC is land-use and land-cover change.

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.

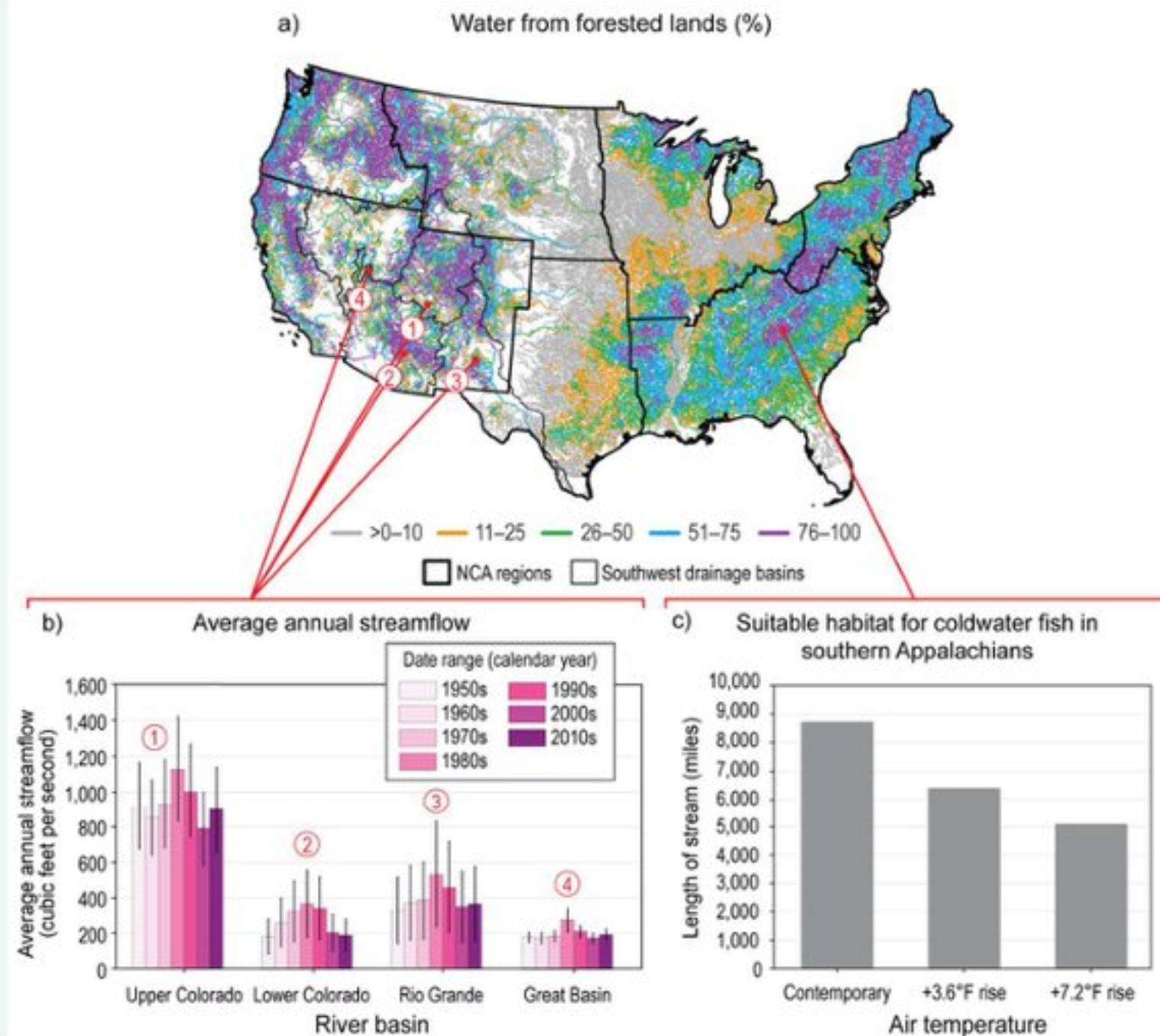
Box 7.3. Climate Change Effects on Forest Water Resources

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 landscapes¹⁴² 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 [ft³/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.

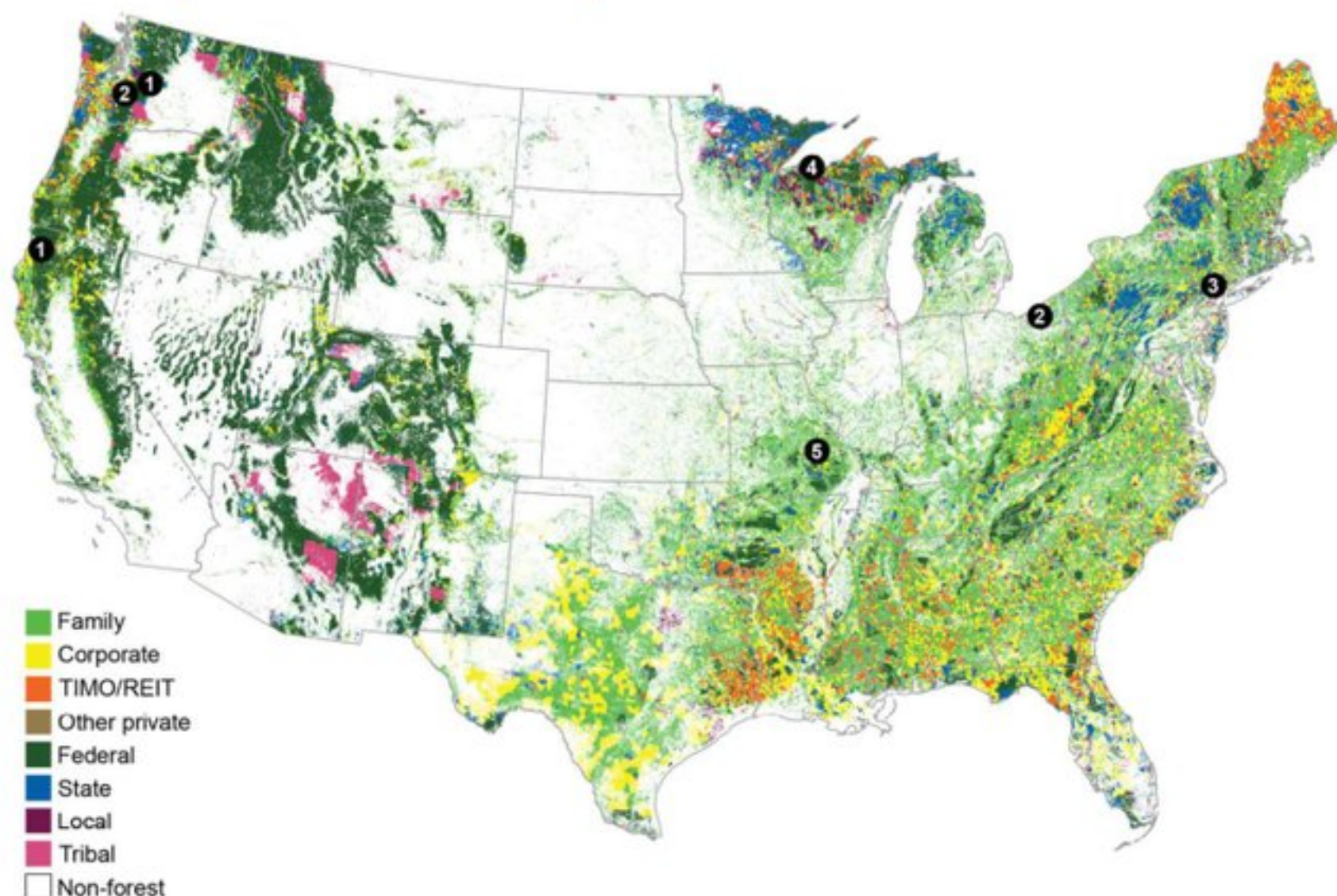
Key Message 7.3

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. 2013⁸⁷). 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 2019¹⁴⁹), state (Figure 31.1; e.g., Ontl et al. 2018;¹⁵⁰ PADEP 2021¹⁵¹), 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. 2020¹⁵⁵). 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-Berrios 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 socioeconomic 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 Tool¹⁸⁷ 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 2018¹⁹¹); therefore, policy and market-based incentives have the potential to increase adaptation on private lands (e.g., Anderson et al. 2019¹⁹²). 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. 2020¹⁹⁴). 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. 2006¹⁹⁵).

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. 2021¹⁶). 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 wildfires²¹¹ 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 traits²²³ 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.

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