6 Forests

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6 Forests

California's multiyear drought killed millions of trees in low-elevation forests.

Key Message 1

Ecological Disturbances and Forest Health

It is very likely that more frequent extreme weather events will increase the frequency and magnitude of severe ecological disturbances, driving rapid (months to years) and often persistent changes in forest structure and function across large landscapes. It is also likely that other changes, resulting from gradual climate change and less severe disturbances, will alter forest productivity and health and the distribution and abundance of species at longer timescales (decades to centuries).

Key Message 2

Ecosystem Services

It is very likely that climate change will decrease the ability of many forest ecosystems to provide important ecosystem services to society. Tree growth and carbon storage are expected to decrease in most locations as a result of higher temperatures, more frequent drought, and increased disturbances. The onset and magnitude of climate change effects on water resources in forest ecosystems will vary but are already occurring in some regions.

Key Message 3

Adaptation

Forest management activities that increase the resilience of U.S. forests to climate change are being implemented, with a broad range of adaptation options for different resources, including applications in planning. The future pace of adaptation will depend on how effectively social, organizational, and economic conditions support implementation.

Executive Summary

Forests on public and private lands provide benefits to the natural environment, as well as economic benefits and ecosystem services to people in the United States and globally. The ability of U.S. forests to continue to provide goods and services is threatened by climate change and associated increases in extreme events and disturbances.[1] For example, severe drought and insect outbreaks have killed hundreds of millions of trees across the United States over the past 20 years,[2] and wildfires have burned at least 3.7 million acres annually in all but 3 years from 2000 to 2016. Recent insect-caused mortality appears to be outside the historical context[3,4] and is likely related to climate change; however, it is unclear if the apparent climate-related increase in fire-caused tree mortality is outside the range of what has been observed over centuries of wildfire occurrence.[5]

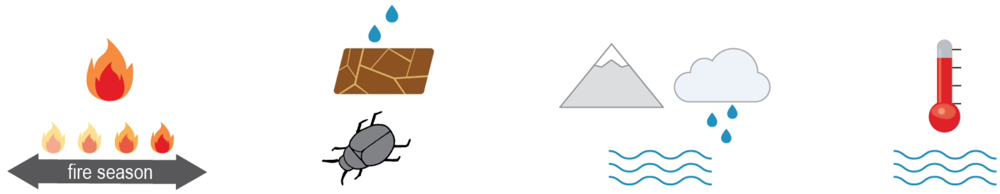
A warmer climate will decrease tree growth in most forests that are water limited (for example, low-elevation ponderosa pine forests) but will likely increase growth in forests that are energy limited (for example, subalpine forests, where long-lasting snowpack and cold temperatures limit the growing season).[6] Drought and extreme high temperatures can cause heat-related stress in vegetation and, in turn, reduce forest productivity and increase mortality.[7,8] The rate of climate warming is likely to influence forest health (that is, the extent to which ecosystem processes are functioning within their range of historic variation)[9] and competition between trees, which will affect the distributions of some species.[10,11]

Large-scale disturbances (over thousands to hundreds of thousands of acres) that cause rapid change (over days to years) and more gradual climate change effects (over decades) will alter the ability of forests to provide ecosystem services, although alterations will vary greatly depending on the tree species and local biophysical conditions. For example, whereas crown fires (forest fires that spread from treetop to treetop) will cause extensive areas of tree mortality in dense, dry forests in the western United States that have not experienced wildfire for several decades, increased fire frequency is expected to facilitate the persistence of sprouting hardwood species such as quaking aspen in western mountains and fire tolerant pine and hardwood species in the eastern United States (see regional chapters for more detail on variation across the United States). Drought, heavy rainfall, altered snowpack, and changing forest conditions are increasing the frequency of low summer streamflow, winter and spring flooding, and low water quality in some locations, with potential negative impacts on aquatic resources and on water supplies for human communities.[12,13]

From 1990 to 2015, U.S. forests sequestered 742 teragrams (Tg) of carbon dioxide (CO_2) per year, offsetting approximately 11% of the Nation's CO_2 emissions.[14] U.S. forests are projected to continue to store carbon but at declining rates, as affected by both land use and lower CO_2 uptake as forests get older.[15,16,17,18] However, carbon accumulation in surface soils (at depths of 0–4 inches) can mitigate the declining carbon sink of U.S. forests if reforestation is routinely implemented at large spatial scales.

Implementation of climate-informed resource planning and management on forestlands has progressed significantly over the past decade. The ability of society and resource management to continue to adapt to climate change will be determined primarily by socioeconomic factors and organizational capacity. A viable forest-based workforce can facilitate timely actions that minimize negative effects of climate change. Ensuring the continuing health of forest ecosystems and, where desired and feasible, keeping forestland in forest cover are key challenges for society.

Climate Change Vulnerabilities and Adaptation Options



Climate Change Vulnerabilities	Increasing wildfire area burned and fire season length	Increasing drought severity and incidence of insect outbreaks	Lower snowpack, increasing precipitation intensity, and higher winter peakflows	Lower summer streamflows and increasing stream temperatures
Adaptation Options	Reduce hazardous fuels with prescribed burning and managed wildfire	Reduce forest stand density to increase tree vigor; plant drought-tolerant species and genotypes	Implement designs for forest road systems that consider increased flooding hazard	Use mapping of projected stream temperatures to set priorities for riparian restoration and coldwater fish conservation

To increase resilience to future stressors and disturbances, examples of adaptation options (risk management) have been developed in response to climate change vulnerabilities in forest ecosystems (risk assessment) in the Pacific Northwest. Vulnerabilities and adaptation options vary among different forest ecosystems. *From Figure 6.7 (Sources: U.S. Forest Service and University of Washington).*

State of the Sector

Forests are distributed across the spectrum of rural to urban environments, covering 896 million acres (including approximately 130 million acres in urban, suburban, and developed areas), or 33% of land in the contiguous United States, Alaska, and Hawai‘i. The structure and function of these forests vary considerably across the Nation due to differences in environmental conditions (for example, soil fertility; temperature; and precipitation amount, type, and distribution), historical and contemporary disturbances, and forest management and land-use activities.

Forests on public and private lands provide benefits to the natural environment, as well as economic benefits and ecosystem services (for example, water, fiber and wood products, fish and wildlife habitat, biodiversity, recreational opportunities, spiritual renewal, and carbon storage) to people in the United States and globally. Public forests are mostly managed for non-timber resources or for multiple uses; private lands owned by corporations are mostly managed for timber production, whereas private lands owned by individuals are typically managed for multiple uses. To date, assessments of climate change vulnerability and development of adaptation options in the western United States have occurred mostly on public lands, whereas assessment and adaptation planning and implementation in the eastern United States span public and private lands, with documented examples of adaptation on most ownership types.[19,20] The ability of U.S. forests to continue to provide goods and services is threatened by climate and environmental change and associated increases in extreme weather events and disturbances (for example, drought, wildfire, and insect outbreaks; Figure 6.1), which can pose risks to forest health (that is, the extent to which ecosystem processes are functioning within their natural range of historic variation)[9] and conditions across large landscapes for years to centuries.[1]

The effects of climate change on forests in specific regions are discussed in many of the regional chapters (for example, Ch. 18: Northeast, KM 1 and 2; Ch. 19: Southeast, KM 3 and 4; Ch. 21: Midwest, KM 2; Ch. 24: Northwest, KM 1; Ch. 25: Southwest, KM 2; Ch. 27: Hawai‘i & Pacific Islands, KM 2 and 5). Rapid changes have been driven by severe drought in combination with insect outbreaks, which have killed more than 300 million trees in Texas in 2011[21] and more than 129 million trees in California from 2010 to 2017.[22] Also, mountain pine beetles have caused tree mortality across more than 25 million acres in the western United States since 2010, representing almost half of the total area impacted by all bark beetles combined in that region. Recent warming has allowed mountain pine beetles to erupt at elevations and latitudes where winters historically were cold enough to keep them in check.[4,23,24] Wildfire burned at least 3.7 million acres nationwide in 14 of the 17 years from 2000 to 2016—an area larger than the entire state of Connecticut—including a record 10.2 million acres in 2015 (an area greater than Maryland and Delaware combined). Over this same time span, annual federal wildfire suppression expenditures ranged from $809 million to $2.1 billion (Figure 6.4).

Recent insect-caused mortality appears to be far outside what has been documented since Euro-American settlement[3] and is likely related to climate change. It is unclear if the apparent climate-related increase in area burned by wildfire is outside the range of what has been observed over centuries of fire occurrence.[5] Drought, heavy rainfall, altered snowpack, and changing forest conditions are increasing the risk of low summer streamflow, winter flooding, and reduced water quality, with potential negative impacts on aquatic resources and human communities.[12,13] A changing climate and forest disturbances also interact with chronic stressors (such as fungal pathogens and nonnative species) to affect the scale and magnitude of forest responses to climate change.[25,26]

The ability of society in general and resource managers in particular to adapt to climate change will be determined primarily by socioeconomic factors, technological developments, and organizational capacity (Ch. 28: Adaptation). Although some general principles apply to adaptation (defined here as adjustments in natural systems in response to actual or expected climatic effects that moderate harm or exploit benefits) across all forests, it is biophysical variability, socioeconomic conditions, and organizational objectives that dictate local management approaches. A viable forest-based workforce in local communities can facilitate timely actions that minimize the negative effects of climate change, as long as this workforce can support the objectives of treatments aimed at building forest resilience and provide a justification for treatments (for example, prescribed fire—the purposeful ignition of low-intensity fires in a controlled setting) that help minimize potential economic loss. Reduction in forestland associated with human land-use decisions, especially conversion of forests to nonforests on private lands, is a significant impediment to providing desired ecosystem services from forests. Hence, ensuring the continuing health of forest ecosystems and, where desired and feasible, keeping forestland in forest cover are key challenges for society.

Climate Change Effects on Ecosystem Services

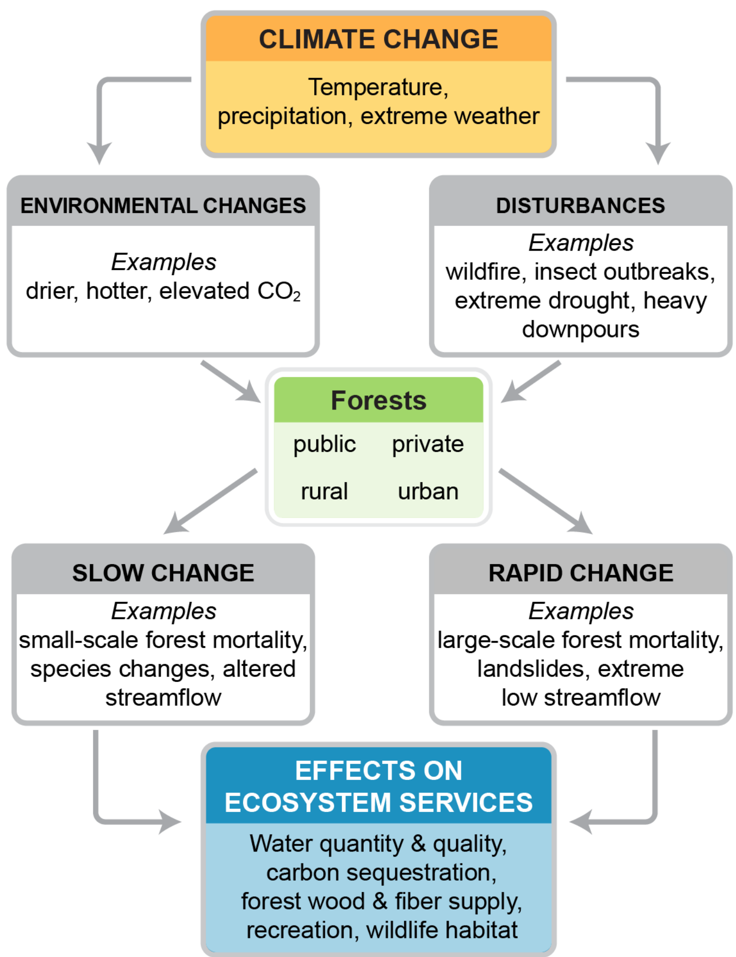


Figure 6.1: Many factors in the biophysical environment interact with climate change to influence forest productivity, structure, and function, ultimately affecting the ecosystem services that forests provide to people in the United States and globally. Source: U.S. Forest Service.

Regional Summary

Forests in the United States vary in their susceptibility to climate change due to differences in biophysical conditions and anticipated changes in future climate (see regional chapters for specific discussions). For example, eastern forests are largely expected to undergo gradual change, punctuated by rapid changes from small-scale disturbances.[26] Across most U.S. forests, an increased frequency of large-scale disturbances is expected to be the primary challenge to maintaining healthy, functional forest ecosystems in a warmer climate; however, forest disturbances resulting from human activity can add to the effects of climate in some parts of the United States.[27] Over the past decade, several large-scale disturbances have killed hundreds of millions of trees at different locations in the United States. The two Case Studies in this chapter illustrate how disturbances can cause rapid changes in the ecology and structure of forests that can result in significant social and economic effects.

Case Study: Large-Scale Tree Mortality in the Sierra Nevada

Five years of consecutive drought ended in California in 2017, with 2015 being the hottest and driest year in the historical record (since the late 1800s). The drought weakened trees and enabled extensive bark beetle outbreaks, which killed 40 million trees across 7.7 million acres of Sierra Nevada forests through 2015. Annual tree mortality increased by an order of magnitude to thousands of dead trees per square mile during this period.[28] The winters 2015–2016 and 2016–2017 brought significant precipitation to much of California, but drought stress remained high in many areas. An additional 62 million trees died in 2016, and 27 million trees died in 2017, bringing the total to at least 129 million trees since 2010.[22] Mortality was most severe at lower elevations, on southwest- and west-facing slopes, and in areas with shallow soils.[29]

Tree Mortality at Bass Lake Recreation Area

Figure 6.2: A five-year drought in California (2011–2016) led to western pine beetle outbreaks, which contributed to the mortality of 129 million trees. As a result, the structure and function of these forests are changing rapidly. Prolonged droughts are expected to become more common as the climate continues to warm, increasing stress on lower-elevation tree species. Photo credit: Marc Meyer, U.S. Forest Service.

This level of tree mortality in the Sierra Nevada is unprecedented in recorded history.[30,31] In some of the most heavily impacted areas, 70% of trees died in a single year (Figure 6.2). Much of this mortality was attributed to the western pine beetle colonizing ponderosa pine, but other tree and shrub species were also affected. Some forests once dominated by ponderosa pine are now dominated by incense cedar. This change in stand structure and composition has increased the likelihood of high-intensity surface fires and large wildfires.[31] In general, widespread tree mortality can alter local hydrology (with more water availability but also higher peak flows) and negatively affect ecosystem services (for example, decreased timber supply and decreased recreation opportunities), effects that will persist for many years.[2,32,33]

Case Study: Increased Wildfire Risk in the Southeastern United States

Southeastern landscapes are dominated by private lands and relatively high human populations, so changes in social behavior (for example, human-caused fire ignitions), policy (for example, fire suppression), and climate can affect wildfire activity.[27] Modeling studies suggest that the southeastern United States will experience increased fire risk and a longer fire season.[34,35] Although projections vary by state and ecoregion,[36] on average, the annual area burned by lightning-ignited wildfire is expected to increase by at least 30% by 2060, whereas human-ignited wildfire is expected to decrease slightly due to changes in factors driving human-ignited wildfire, including projected losses of forestland and increased efforts to suppress and prevent wildfires. Although native vegetation is well-adapted to periodic wildfire, most people living near wildlands are not. More frequent and larger wildfires, combined with increasing development at the wildland–urban interface (where people live in and near forested areas), portend increasing risks to property and human life. For example, a prolonged dry period in the southern Appalachian region in 2016 resulted in widespread wildfires that caused 15 deaths and damaged or destroyed nearly 2,500 structures in Gatlinburg, Tennessee (Figure 6.3). In a warmer climate, increased fire frequency will damage local economies and degrade air quality in the Southeast.

Fire Damage in Gatlinburg, Tennessee

Figure 6.3: In autumn 2016, a prolonged dry period and arson in the southern Appalachian region resulted in 50 major wildfires that burned over 100,000 acres in 8 states, caused 15 deaths, and damaged or destroyed nearly 2,500 structures in Gatlinburg, Tennessee. If drought or prolonged dry periods increase in this region as expected, fire risk will increase in both forests and local communities. Photo credit: Flickr user highlander411 (CC BY 2.0).

Key Message 1

Ecological Disturbances and Forest Health

It is very likely that more frequent extreme weather events will increase the frequency and magnitude of severe ecological disturbances, driving rapid (months to years) and often persistent changes in forest structure and function across large landscapes. It is also likely that other changes, resulting from gradual climate change and less severe disturbances, will alter forest productivity and health and the distribution and abundance of species at longer timescales (decades to centuries).

Rapid Forest Change—Wildfire

Most fire-prone forests (forests that are likely to burn at least once every few decades) have the ability to persist as more fires occur, but the resilience of these ecosystems depends on three factors: 1) continued presence of fire-adapted species, 2) fire intensity (the amount of heat energy released) and frequency of future fires, and 3) societal responses to increased fires. A century of fire exclusion in fire-prone forest ecosystems in the United States (especially lower-elevation ponderosa pine forests and mixed conifer forests in dry locations in the West) has created landscapes of dense forests with high flammability and heavy surface and canopy fuel loads (combustible dead and live vegetation).[37] Over the past 20 years, a warm, dry climate has increased the area burned across the Nation.[38] Large, intense wildfires in some locations[39] (Figure 6.4) have been difficult to suppress, increasing risk to property and lives, including those of firefighters.[40,41] The cost of fire suppression has also increased over time, partially driven by the high cost of protecting property in the wildland–urban interface.[42,43]

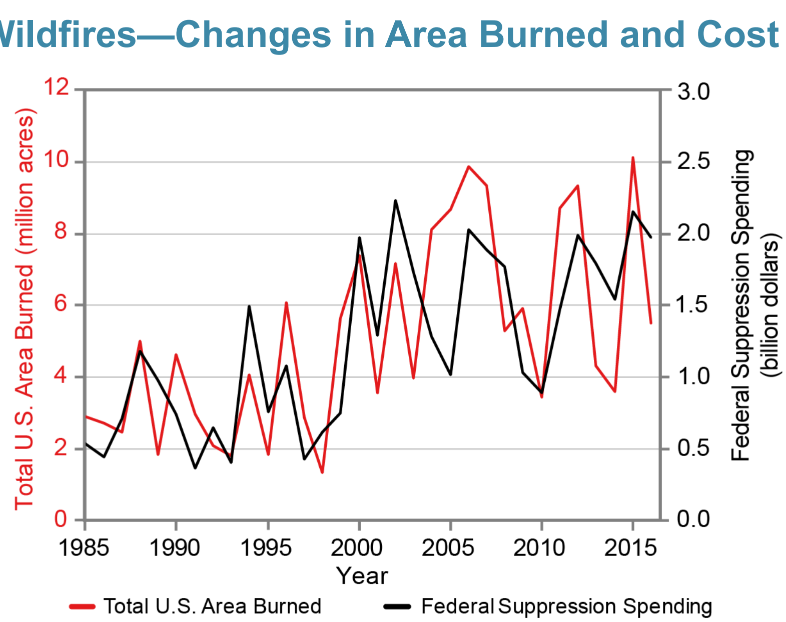


Figure 6.4: This figure shows the annual wildfire area burned in the United States (red) and the annual federal wildfire suppression expenditures (black), scaled to constant 2016 U.S. dollars (Consumer Price Index deflated). Trends for both area burned and wildfire suppression costs indicate about a fourfold increase over a 30-year period. Source: U.S. Forest Service.

The duration of the season during which wildfires occur has increased throughout the western United States as a result of increased temperatures[44,45] and earlier snowmelt.[46,47] Increased vapor pressure deficit (Ch. 21: Midwest, Figure 21.3)[48] and reduced summer precipitation[49] have deepened summer droughts in the West and thus increased wildfire risk.[50] By the middle of this century, the annual area burned in the western United States could increase 2–6 times from the present, depending on the geographic area, ecosystem, and local climate.[51,52] An increase in the area burned, however, does not necessarily translate to negative impacts to ecosystems (Figure 6.5). As the spatial extent of wildfires increases, previously burned areas will in some cases provide fuel breaks that influence the pattern, extent, and severity (the degree to which fire causes vegetation damage and mortality) of future fires.[53] Future wildfire regimes will be determined not only by climate but also by topography, fuel accumulation (as affected by plant growth and frequency of disturbances), and efforts to suppress and prevent fires.[54,55]

Wildfire risk can be reduced in low-elevation, dry conifer forests in the West and conifer forests in the South by reducing stand density (thinning), using prescribed burning, and letting some fires burn if they will not affect people. Frequent prescribed burning in fire-prone and fire-dependent (forests that require fire to maintain structure and function) southern forests has been a socially accepted practice for decades, illustrating how wildfire risk can be reduced. However, health risks from smoke produced by prescribed burning are a growing concern in the wildland–urban interface (see Ch. 19: Southeast for additional discussion about fire in the southeastern United States and Ch. 13: Air Quality, KM 2 on the effects of wildfires on health).[56]

Area Burned by Large Wildfires

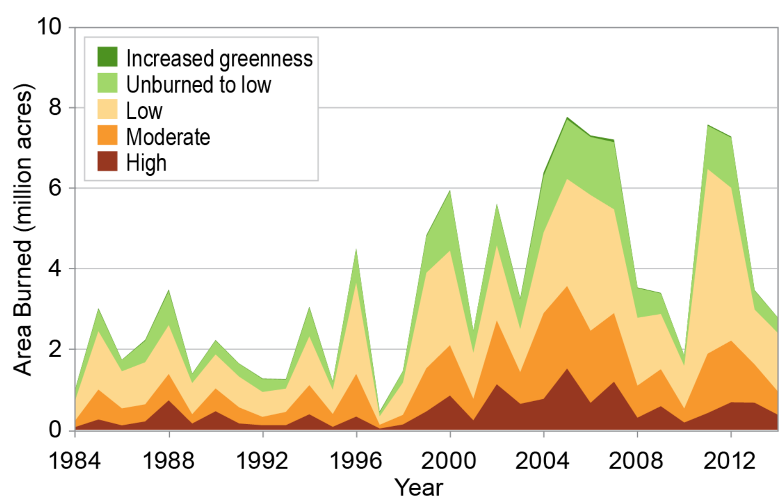


Figure 6.5: This figure illustrates the area burned by large wildfires (greater than 1,000 acres in the western United States and greater than 500 acres in the eastern United States) for 1984–2014. Although the area with moderate-to-high burn severity (amount of fire damage to the forest canopy) has increased in recent decades, it has not changed as a proportion of the total area burned (severity does vary across regions). Increases in the areas of severely burned forests will have implications for ecosystem processes, such as tree regeneration[57,58,59] and ecosystem services, including timber production, water quality, and recreation. Source: redrawn from EPA 2016.[60]

Rapid Forest Change—Insects and Pathogens

Climate change is expected to increase the effects of some insect species in U.S. forests[23,61,62] but reduce the effects of others.[63] For example, drought increases populations of some defoliating insect species[64] but decreases populations of other defoliators.[65] In some cases, fire exclusion in fire-prone forests has exacerbated the effects of insects by increasing forest density, thus reducing tree vigor (the capacity of a tree to resist stress) and resistance to insect attack.[3] Higher damage from native insects on trees with reduced vigor is expected to be one of the biggest effects of a warmer climate. Altered thermal conditions, including varying temporal patterns, will disrupt some insect life cycles, causing seasonal mismatches between insect species and tree hosts in some systems.[66]

Over the past 30 years, tree mortality caused by bark beetles in the western United States has exceeded tree mortality caused by wildfire,[2] raising concerns about the sustainability of some western forests to provide ecological goods and services over time.[67,68] Bark beetle epidemics in forests with commercially valuable tree species can negatively affect timber prices and the economic well-being of forest landowners and wood processors.[69] Many bark beetle outbreaks have been associated with drought and elevated temperature.[23,63] Recently, western pine beetles contributed to the mortality of 129 million trees weakened by a period of severe drought in California (see Case Study "Large-Scale Tree Mortality"). The southern pine beetle is the only bark beetle species in the eastern United States that causes extensive tree mortality. Although little evidence exists for drought-caused outbreaks of this beetle,[63] a recent increase in its range into the northeastern United States, facilitated by increasing winter temperatures, now threatens pine barrens in New York and Massachusetts.[70]

The northward expansion of the hemlock woolly adelgid, a nonnative species that attacks eastern hemlock, has been facilitated by higher minimum winter temperatures.[71] Similarly, the range of mountain pine beetles is expanding with warming; new breeding populations are now found in parts of the western plains and in jack pine in boreal forests in Alberta, Canada.[24,72,73] Mountain pine beetle populations are also expanding in high-elevation forests of the western United States, affecting whitebark pine and other high-elevation pine species.[4,23] Whitebark pine serves as a keystone species that quickly establishes after a disturbance and provides critical food sources for birds and mammals. Whitebark pine is expected to suffer significant mortality in the future due to the combined effects of white pine blister rust, mountain pine beetles, and a warmer climate.[74]

Fungal pathogens, especially those that depend on stressed plant hosts for colonization, are expected to perform better and have greater effects on forests as a result of climate change.[63,75,76] For example, increasing annual temperatures and precipitation in portions of New England have provided ideal conditions for outbreaks of leaf diseases in eastern white pine,[77] whereas the effects of some pathogens directly affected by climate (such as needle blights) are typically reduced in areas with decreased precipitation.[75] Timing of pathogen life cycles relative to seasonal changes in temperature and precipitation will be critical in determining where and how damage might change.

Insect and disease outbreaks often interact with other disturbances, compounding their potential effects on ecosystem services. For example, in lodgepole pine forests attacked by mountain pine beetles, the intensity of surface and crown fires increases in stands impacted by outbreaks, but typically for less than 10 years (e.g., Page and Jenkins 2007, Hicke et al. 2012, Jenkins et al. 2014[78,79,80]). Beetles have minimal effects on fire severity in some locations due to variability in topography, fuels, and fire weather.[81] A recent study in California in areas heavily affected by drought and western pine beetles (see Case Study "Large-Scale Tree Mortality") reported a greater potential for large-scale wildfires driven by the amount and continuity of combustible woody material from dying trees.[31]

Long-Term Forest Change

Forests that frequently run out of water stored in the soil during the growing season are considered water limited, whereas forests where the growing season length or productivity rate is limited by snowpack and cool temperatures are considered energy limited. A warmer climate will generally decrease tree growth in water-limited forests (many semiarid and low-elevation forests in the western United States) but may increase growth in some energy-limited forests (the majority of forests in the eastern United States and coastal Alaska and high-mountain forests with short growing seasons).[6,82] Experimental evidence shows that elevated atmospheric carbon dioxide (CO_2) can increase tree growth (especially where soil nutrients are adequate), but it is uncertain whether this increase will occur in mature forests or will continue as younger forests age.[83] Positive effects of CO_2 on growth will be negated in some species and locations (such as near urban areas) by air pollutants such as ground-level ozone (not the protective layer of ozone high in the atmosphere), where concentrations of those pollutants are high enough to cause toxic effects in plants.[84] Drought and extreme temperatures can cause heat-related stress in vegetation, in turn reducing forest productivity and reducing tree vigor.[7,8] Although the effects are complex and variable among forests, warming and elevated CO_2 can also impact below-ground processes, such as nitrogen and carbon cycling,[85] with feedbacks that may impact forest productivity.[86]

The direct effects of climate change on tree mortality and forest health will likely be obscured by the slow response times of long-lived tree species.[87] In some cases, climate-related stresses weaken trees, predisposing them to additional stresses.[88] Variability in the drought response of tree species (for example, due to differences in hydraulic characteristics) is expected to influence how some forests deal with water stress.[89] A lagged response and variability among species can make it difficult to attribute growth reductions to episodic drought, and growth reductions can persist for years.[7,90,91] For species in which seed crops depend on resources stored over several growing seasons, reproductive responses are likely to lag behind climatic variation.[92]

The rate of climate warming will influence the rate and magnitude of potential changes in forest health, competition for resources among tree species, structure, and function, affecting the growth and distribution of some tree species.[10,11] Negative effects on some species can benefit other species, and reorganization and changes in the structure of forest communities depend on the capacity of locally adapted populations to occupy new areas that become suitable as a result of climate change. For example, warming in the coastal region of the southern United States may result in the replacement of salt grass with mangrove forests (see Ch. 19: Southeast for additional information on mangrove forests).[93]

Canopy phenology (seasonal patterns of leaf emergence and flowering) responds to annual-to-decadal variation in climate,[94,95] and evidence exists that changes in canopy phenology are contributing to altered species ranges and potential increases in water and nutrient limitations.[96] Some studies report shifts in elevation ranges of terrestrial plant species in general,[97,98,99] whereas many of the studies that focus on tree species do not.[100,101,102,103] If large-scale latitudinal shifts in tree distributions are occurring, they are ambiguous at present;[10,104] however, some evidence suggests that some boreal species are shifting poleward as reproduction fails on the southern edge of their range.[105]

Key Message 2

Ecosystem Services

It is very likely that climate change will decrease the ability of many forest ecosystems to provide important ecosystem services to society. Tree growth and carbon storage are expected to decrease in most locations as a result of higher temperatures, more frequent drought, and increased disturbances. The onset and magnitude of climate change effects on water resources in forest ecosystems will vary but are already occurring in some regions.

The Millennium Ecosystem Assessment[106] defines four categories of ecosystem services: supporting, provisioning, regulating, and cultural. Recent studies have focused on defining and quantifying the full range of services provided by forests including recreation, wildlife habitat, biodiversity, cultural values, and non-timber forest products.[107,108] Here, we focus on climate change effects on two of the most important forest-based services: forest carbon dynamics (regulating and provisioning) and forest water resources (regulating and provisioning). (For additional discussion on the effects of climate on ecosystem services, see Ch. 7: Ecosystems and the regional chapters.)

Forest Carbon Dynamics

Forest productivity (Key Message 1) is one of many factors that determine carbon storage potential.[109] Typically, soil carbon is the largest and most stable carbon pool in forest ecosystems,[14,110,111,112] but increased above-ground biomass production in forests is not necessarily accompanied by higher soil carbon content. In some locations, heavy rainfall events will result in flood-related tree mortality, leading to soil erosion and losses of particulate and dissolved organic carbon from forests.[113] Increased disturbances such as harvesting, wildfire, and insect and disease damage can also release carbon stored in soils, especially where multiple disturbances occur over a short time span (Figure 6.6).[114]

The fate of carbon in forests depends, in large part, on the type, extent, frequency, and severity of the disturbance.[114,115] Severe disturbances, such as stand-replacing wildfire, typically result in the immediate release of carbon to the atmosphere,[32] a reduction in stand productivity, the transfer of carbon from live to dead pools, and an increase in decomposition.[114,115] Productivity will gradually increase following a disturbance, and decomposition will decrease as the forest recovers. The abrupt release of carbon after a disturbance transitions to net carbon uptake through forest regrowth. However, the full effect of the disturbance on atmospheric CO_2 depends on the timing of disturbance-induced CO_2 releases. Although carbon storage in biomass will increase in areas where tree growth rates rise, those increases will be small compared to the reduced storage that occurs in response to more disturbances.[18]

Forest Disturbances Across the United States

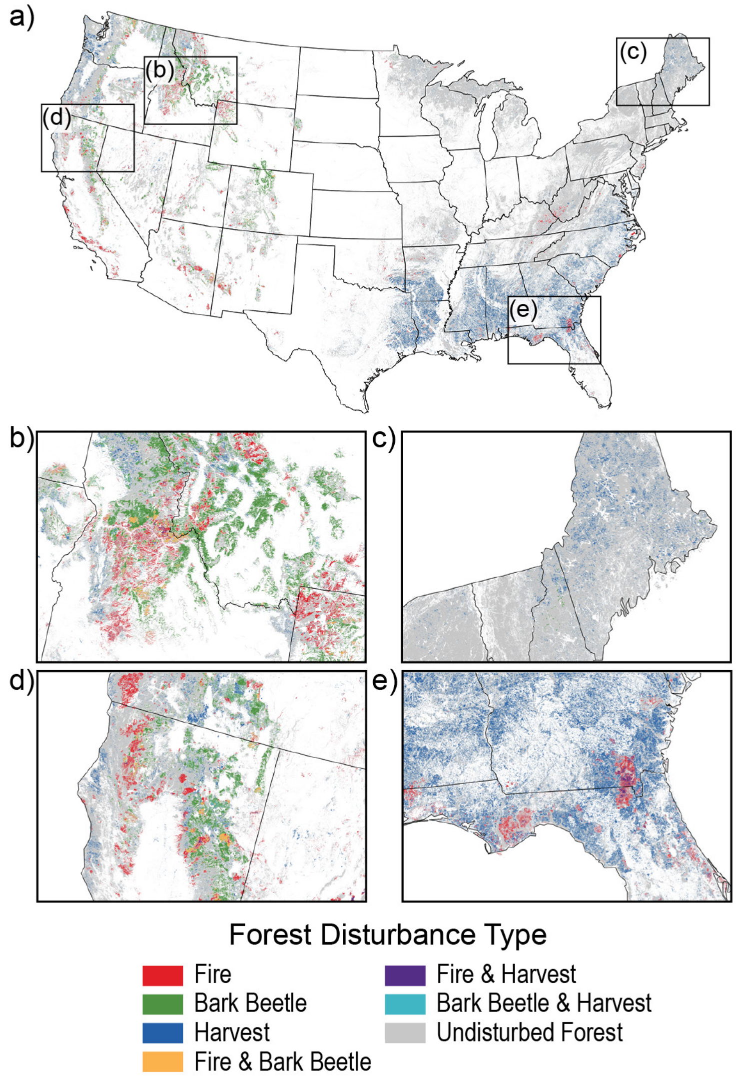


Figure 6.6: This figure shows the cumulative area of disturbed forestland across the contiguous United States for 1984–2014. The small boxes illustrate how disturbances differ regionally. Data for Alaska, Hawai'i and the U.S.-Affiliated Pacific Islands, and the U.S. Caribbean regions were not shown on the original map from the published source. Source: adapted from Williams et al. 2016.[114]

Economic and population growth will affect land-use decisions that influence forest-based carbon storage. Over the last several decades, conversion of forestland to other land uses has contributed to CO_2 emissions,[14,116] and this trend is likely to continue, although this is among the most significant sources of uncertainty in the forest carbon sink in the United States.[18,117,118] The current (2017) U.S. deforestation rate (the conversion from forest to nonforest land use) of 0.12% per year is more than offset by forest gain from afforestation (the establishment of a forest where there was no previous tree cover) and reforestation, for a net gain of forest area of 0.09% per year (679,000 acres).[14] Gains occur mostly through a transition from grasslands and croplands to shrublands, woodlands, and forests, and losses occur mostly in urban areas (see Ch. 5: Land Changes for details on forest land-use trends).[14] While some individual states have lost forestland, overall, each region of the United States (for example, northern, southern, Rocky Mountain, and Pacific coast) has gained forestland area over the past 20 years.[14,16]

Net storage of atmospheric carbon by forests (742 teragrams, or Tg, of CO_2 per year from 1990 to 2015) has offset approximately 11% of U.S. CO_2 emissions.[14] Assuming no policy intervention—and accounting for land-use change, management, disturbance, and forest aging—U.S. forests are projected to continue to store carbon but at declining rates (35% less than 2013 levels by 2037) as a result of both land use and lower CO_2 uptake as forests grow older.[15,16,17,18,42]

Although forest area has increased over the last few decades (Ch. 5: Land Changes, Figure 5.1), this trend is projected to level off by 2030, then decline gradually as human population expands and afforestation on agricultural lands slows,[18,42] with more rapid leveling in the West compared to the East. However, carbon accumulation in surface soils (at depths of 0–4 inches) resulting from reforestation activities can help mitigate declining carbon storage in U.S. forests over the long term. Surface soils in reforested areas are currently accumulating 13–21 Tg carbon per year, with the potential to accumulate hundreds more Tg of carbon within a century.[112,119]

Economic and population trends will affect national and global production and consumption of wood products, which can temporarily store carbon. The storage of carbon in and emissions from wood products contribute to carbon stores and exchanges with the atmosphere; the carbon stored in wood products accumulates as wood is harvested from forests at a rate that exceeds carbon releases from the decay and combustion of wood products already in use. The harvested wood products pool alone is not a direct sink for atmospheric carbon, but losses from the pool are a direct source of atmospheric carbon. Although the contribution of harvested wood products is uncertain, the worldwide net surplus of carbon in wood products is estimated to be approximately 8% of the established global forest sink (189 Tg carbon per year).[120] In the United States, 76% of the annual domestic harvest input to the wood products pool in 2015 (110 Tg carbon per year) was offset by release processes (84 Tg carbon per year), resulting in an increase in wood products of 26 Tg carbon.[14]

Forest Water Resources

Forested watersheds provide water for municipal water supplies, agricultural irrigation, recreation, spiritual values, and in-stream flows for aquatic ecosystems. Changes in snowfall amount, timing, and melt dynamics are affecting water availability and stream water quality. In the western United States (especially the Pacific Northwest), less precipitation is falling as snow and more as rain in winter months, leading to a longer and drier summer season (Ch. 24: Northwest).[121] Persistence of winter snowpacks has also decreased in the northeastern United States over the last few decades, with more mid-winter thaws (Ch. 18: Northeast). Changing snowmelt patterns are likely to alter snowmelt contributions to the flushing of soil nutrients into streams in both western[122] and eastern forests.[123]

Forest watersheds moderate the effects of extreme climate events such as drought and heavy rainfall, thus minimizing downstream impacts on aquatic ecosystems and human communities such as flooding, low flows, and reduced water quality. Disturbances and periodic droughts affect streamflow and water quality,[12,13,124] as do changes in forest structure that are influenced by climatic variability and change, such as leaf area and species distribution and abundance.[33] For example, drought-related bark beetle outbreaks and wildfire kill trees, reducing water uptake and evapotranspiration and potentially increasing water yield,[125] although water yield can decrease if regrowing species have higher water-use demands than did the insect- or fire-killed trees.[126]

Wildfires can also increase forest openness by killing midstory and overstory trees, which promotes earlier snowmelt from increased solar radiation. This, in turn, leads to more winter runoff and exacerbates dry summer conditions, especially in cooler interior mountains.[127,128] In warmer forests, typically in wetter climates where wildfire is currently rare, increased forest openness can in some cases increase snowpack retention.[129] Wildfires can increase erosion and sediment in western U.S. rivers,[130] as well as reduce tree cover adjacent to rivers and streams and thus increase stream temperature.[131,132] In eastern U.S. forests, the proportion of tree species with moderate water demands (mesophytes) is increasing in many areas as a result of fire exclusion, less logging and other disturbances, and possibly a warmer climate.[133,134] Mesophytes transpire more water than other species occupying the same area, thus reducing streamflow.[135,136]

Key Message 3

Adaptation

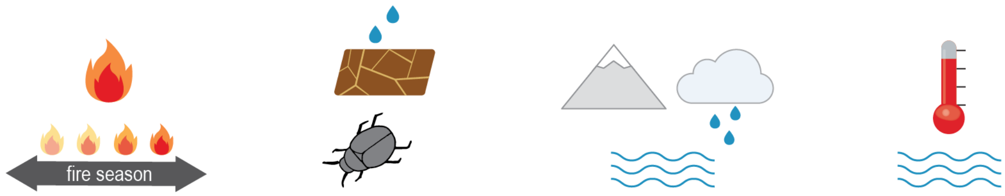
Forest management activities that increase the resilience of U.S. forests to climate change are being implemented, with a broad range of adaptation options for different resources, including applications in planning. The future pace of adaptation will depend on how effectively social, organizational, and economic conditions support implementation.

Decisions about how to address climate change in the context of forest management need to be informed by a better understanding of the risks of potential climate change effects on natural resources and the organizations that manage those resources. For example, risks posed by ecological disturbances can be reduced by first assessing specific disturbance components (such as wildfire exposure) and second identifying forest management activities that can be implemented to reduce risk.[52] However, identifying how climate change will alter biophysical conditions (risk assessment) and how forest management organizations will respond to future changes (risk management) is complex. Describing operational (technical and financial), economic, and political risks is even more difficult. Furthermore, identifying interactions among all types of risks at regional and local scales will provide land managers with the information needed to manage forests sustainably across large landscapes (Ch. 28: Adaptation).[137] To that end, recent nationwide projects examining site-specific adaptation practices help inform forest management focused on maintaining long-term productivity under future climatic conditions.[20,138,139]

Assessments of climate change effects and adaptation actions are being incorporated into resource management plans, environmental assessments, and monitoring programs of public agencies.[42,140] Adaptation planning tools and compendia of adaptation options for forest resources are now institutionalized in public land management in much of the United States (Ch. 28: Adaptation).[19,141] Adaptation actions are also being implemented by Native American tribes and communities, with an emphasis on culturally significant forest resources, such as flora and fauna, which in turn affect sovereignty and economic sustainability.[142] Adaptation is especially urgent for Native American communities affiliated with reservations where place-based traditional medicine, ceremonial practices, and methods of gathering and hunting for food contribute to cultural identity (Ch. 15: Tribes).[143]

Implementing climate change adaptation measures in forest management requires an understanding of the effects of climate change on different types of forests, forest-related

Climate Change Vulnerabilities and Adaptation Options



Climate Change Vulnerabilities	Increasing wildfire area burned and fire season length	Increasing drought severity and incidence of insect outbreaks	Lower snowpack, increasing precipitation intensity, and higher winter peakflows	Lower summer streamflows and increasing stream temperatures
Adaptation Options	Reduce hazardous fuels with prescribed burning and managed wildfire	Reduce forest stand density to increase tree vigor; plant drought-tolerant species and genotypes	Implement designs for forest road systems that consider increased flooding hazard	Use mapping of projected stream temperatures to set priorities for riparian restoration and coldwater fish conservation

Figure 6.7: To increase resilience to future stressors and disturbances, examples of adaptation options (risk management) have been developed in response to climate change vulnerabilities in forest ecosystems (risk assessment) in the Pacific Northwest. Vulnerabilities and adaptation options vary among different forest ecosystems. Sources: U.S. Forest Service; University of Washington.

enterprises, and resource-dependent communities (Figure 6.7). However, even if the potential magnitude and consequences of climate change are well understood and viable management responses exist, adaptation measures cannot occur unless management organizations (on public and private lands) have the capacity (people and financial resources, enabled by policy) to implement management responses.[144]

Fortunately, many ongoing practices that address existing forest management needs—stand density management, surface fuel reduction, control of invasive species, and aquatic habitat restoration—contribute to the goal of increasing resilience to higher temperatures, drought, and disturbances.[127,144,145,146,147] Fuel treatments across large landscapes have the additional benefit of creating defensible space for fire suppression, especially near the wildland–urban interface. Resource managers are evaluating how these practices can be modified and implemented to address future climate risks.[141] For example, forest managers in dry western U.S. forests are considering greater reductions in stand density to increase forest resistance and resilience to fire, insects, and drought.[148] Implementation of these practices can be costly, often confront legal and administrative barriers,[149] and must consider economic tradeoffs associated with management of other natural resources.[55]

Applications of these and other practices vary as a function of ownership objectives, timber and non-timber wood product markets, policy constraints, and setting (urban, rural, or wildland–urban interface). For example, land managers in regions where short-rotation, plantation management of forest tree species is common (for example, private lands in the southern United States and Pacific Northwest) have the flexibility to periodically shift species and genetic composition of trees to align with future changes in climate and disturbance regimes.[150] A significant amount of adaptation has occurred on public lands, including actions that reduce climate-related risks to water resources such as 1) design of sustainable forest road systems that take into account increased flooding hazard, including upsizing culverts to match projected streamflows; 2) joint planning and design of fuel treatments (including prescribed burning) and watershed restoration to create resilient terrestrial and aquatic ecosystems;[127] 3) comprehensive mapping of projected stream temperatures to set priorities for riparian restoration and cold-water fish conservation;[151] and 4) supporting viable American beaver populations to facilitate retention of cool water in forested aquatic systems (Figure 6.8).[140]

Applying climate change adaptation management activities over large areas of forestland will be challenged by projected declines in the size of the forest sector workforce and receding timber product outputs in some parts of the country.[42] Declines in the workforce mean fewer skilled workers who can carry out management actions, although collaborative efforts by nongovernmental organizations are emerging to assist with climate change adaptation.[152] Low timber product output, the result of abundant supplies of timber and low demand for primary and secondary timber products,[153] means lower prices for timber, which have trended downward since the late 1990s (e.g., Timber Mart-South 2018[154]), thereby providing fewer opportunities to offset treatment costs with sales of timber removed. As a result, weak timber markets mean reduced incentives for private forest owners to actively manage forests in ways that enhance climate resilience. However, multiorganization collaboration, widespread availability of adaptation options,[155,156] and a growing list of examples of on-the-ground implementation bode well for the future of climate-informed forest management. Flexible management approaches that promote learning and sharing among interested parties can help accelerate implementation.

Reintroducing Beavers to Build Climate Resilience

Figure 6.8: Engineering by beavers encourages the slow release of water to downstream users and keeps water cool for migrating salmon and other aquatic species. Reintroduction of beavers throughout the western United States is helping to retain these functions in forested watersheds, increasing resilience to a warmer climate and reduced snowpack in mountains. Photo credit: Sarah Koenigsberg, courtesy of The Beaver Believers.

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California forest: Nathan Stephenson, U.S. Geological Survey.

Traceable Accounts

Process Description

Lead authors, chapter authors, and technical contributors engaged in multiple technical discussions via teleconference between September 2016 and March 2018, which included a review of technical inputs provided by the public and a broad range of published literature as well as professional judgment. Discussions were followed by expert deliberation on draft Key Messages by the authors and targeted consultation with additional experts by the authors and technical contributors. A public engagement webinar on May 11, 2017, solicited additional feedback on the report outline. Webinar attendees provided comments and suggestions online and through follow-up emails. Strong emphasis was placed on recent findings reported in the scientific literature and relevance to specific applications in the management of forest resources.

Key Message 1

Ecological Disturbances and Forest Health

It is very likely that more frequent extreme weather events will increase the frequency and magnitude of severe ecological disturbances, driving rapid (months to years) and often persistent changes in forest structure and function across large landscapes (*high confidence*). It is also likely that other changes, resulting from gradual climate change and less severe disturbances, will alter forest productivity and health and the distribution and abundance of species at longer timescales (decades to centuries; *medium confidence*).

Description of evidence base

Many ecological responses to climate change in U.S. forests are mediated though disturbance, because the occurrence and magnitude of most major forest disturbances are sensitive to subtle changes in climate.[1] Published literature since the Third National Climate Assessment (NCA3) continues to show an increase in the frequency of large (thousands to hundreds of thousands of acres) ecological disturbances in forests across the United States. There is strong evidence that these changes, in combination with accumulated fuels, have resulted in larger wildfires in recent years (the past 10 to 20 years),[2,38,39] making them harder to suppress and increasing human health and safety concerns for nearby communities[40] and wildland firefighters.[157] Fire suppression costs continue to increase in response to larger fires and an expanding wildland–urban interface.

Although the increasing size and costs of fighting wildfires are known with high certainty,[158] short- and long-term effects on forests vary according to the ability of tree species to survive or regenerate after wildfire.[159] Future fire regimes and their impacts on U.S. forests will be governed by climate as well as topography, ecosystem productivity, and vegetation adaptations to fire. For example, altered distribution and abundance of dominant plant species may affect the frequency and extent of future wildfires (Ch. 29: Mitigation). The potential of an area to reburn (that is, burn again after experiencing a previous fire) will depend on how the previous fire was suppressed, the severity of that fire, how rapidly fuel accumulated after the fire, and postfire management activities.[53] These variables create uncertainty in predicting the spatial distribution, number, and sizes of wildfires in future decades.

The published literature contains strong evidence that insects are causing rapid changes in forest structure and function across large landscapes. Causal factors are primarily elevated temperatures, droughts, and water stress, which exert indirect effects mediated through host tree species and direct effects on insects. For example, in western North America, several species of bark beetles have had notable outbreaks over the past 30 years, and some have exceeded the spatial extent of what has been previously documented, affecting ecosystem services at broad spatial scales.[3] The spatial extent of recent outbreaks of mountain pine beetles represents an area larger than the 11 smallest U.S. states combined, and insect outbreak models project increased probabilities of mountain pine beetle population success in the future.[23] In addition, evidence suggests that climate change is expanding the range of bark beetles in both the western and eastern United States,[66,70,71] caused by higher minimum temperatures associated with climate change. For example, whitebark pine is expected to suffer significant mortality in future decades due to the combined effects of white pine blister rust, mountain pine beetles, and climate change.[74]

The magnitude and direction of defoliator responses to climate change vary, limiting our ability to project the effects of climate change[69] and preventing generalizations about climate-related effects on defoliators, despite their importance throughout the United States. Fungal pathogens that depend on stressed plant hosts for colonization are expected to perform better and have greater impacts on forests.[63,75,76] In contrast, some pathogens directly affected by moisture availability (for example, needle blights) are expected to have reduced impact.[75]

Mounting evidence suggests that some bird and insect populations show changes in distribution that align with temperature increases in recent decades (Ch. 7: Ecosystems).[160,161,162,163] These species groups are characterized by short generation times, high mobility, or both. Some evidence suggests that the rate of climate change is outpacing the capacity of trees and forests to adjust, placing long-lived tree populations at risk. Species distribution models concur that climate change can affect suitable habitat,[11] although it is unclear if these effects are translating into species range shifts. Some studies report shifts in elevation ranges,[97,98] whereas others do not.[100,101,103] In summary, evidence indicates substantial effects of climate change on forest health but varied capacity for tree species to relocate as conditions change.

Understanding and predicting the effects of climate change on forests are obscured by the slow response times of long-lived trees.[87] Increasing evidence suggests that climate-related stresses weaken trees, predisposing them to additional stresses that take many years to be observed,[88] and that growth reductions following drought can persist for years.[7,90,91] For species in which seed crops depend on resources stored over several growing seasons, it is likely that reproductive responses will lag behind climate variation.[92] Recent studies in the eastern United States suggest that changes in tree species composition (such as an increased proportion of mesophytes) over the past few decades in some forests are contributing to lower streamflow[136] and increased vulnerability of forests to drought.[164] Warming temperatures and changing precipitation are altering leaf phenology (for example, earlier spring leaf-out and later leaf fall) in some areas, which is likely to affect forest carbon and water cycling.[95,165]

Major uncertainties

Although wildfire frequency and extent are very likely to increase in a warmer climate, spatial and temporal patterns of fire are difficult to project, especially at smaller than regional scales. The effects of a warmer climate are well known for some insect species (such as bark beetles), but the effects of long-term thermal changes on most insect species and their community associates are uncertain. Scientific information on the effects of climate change on fungal pathogens is sparse, making projections of forest diseases uncertain. It is possible to project that some tree species will have decreased growth and others increased growth, but the magnitude of growth changes is uncertain. Finally, species distribution and abundance are likely to change in a warmer climate, but the magnitude, geographic specificity, and rate of future changes are uncertain.

Description of confidence and likelihood

Published literature and model projections imply *high confidence* that more frequent extreme weather events will increase the frequency and extent of large ecological disturbances, driving rapid (months to years) and often persistent changes in forest structure and function across large landscapes. Forests are long-lived and inherently resilient to climatic variability, so long-term monitoring (of, for example, growth and productivity, structure, regeneration, and species distribution and abundance) will be needed to confirm the direct effects of incremental changes in temperature. As a result, there is *medium confidence* that changes resulting from direct (but gradual) climate change and less severe disturbances will occur in the context of altered forest productivity, health, and species distribution and abundance that occur at longer timescales (decades to centuries).

Key Message 2

Ecosystem Services

It is very likely that climate change will decrease the ability of many forest ecosystems to provide important ecosystem services to society. Tree growth and carbon storage are expected to decrease in most locations as a result of higher temperatures, more frequent drought, and increased disturbances (*medium confidence*). The onset and magnitude of climate change effects on water resources in forest ecosystems will vary but are already occurring in some regions (*high confidence*).

Description of evidence base

Altered forest conditions caused by a changing climate are likely to influence the quantity and quality of many of the ecosystem services that humans derive from forests, and climate change is expected to increase the frequency and severity of natural disturbances in the coming decades and to reduce forest growth in most places.[18] Extreme high temperatures can also cause heat-related stress in vegetation and exacerbate drought conditions, potentially increasing tree mortality and reducing forest productivity.[7,166] Positive effects of carbon dioxide (CO_2) on growth will be negated in some species and locations by low soil fertility[167] and by air pollutants such as ground-level ozone, where concentrations of those pollutants are high enough to cause toxic effects in plants.[84]

Most evidence suggests that increased carbon sinks (caused by higher growth rates and more forest area in some regions) will not be sufficient to offset higher emissions from increased disturbances and enhanced release of carbon from decomposition in the future.[114,168,169,170] U.S. forests are projected to continue to sequester carbon but at declining rates caused by land-use change and aging forests.[18] In the western United States, the aging of forests, coupled with disturbance dynamics, is projected to diminish carbon sequestration to negligible levels by around 2050, and some forests (for example, dry western forests with frequent fire and some eastern hardwood forests) will likely become a carbon source.[18] Younger productive forests in the eastern United States portend high carbon uptake rates, although harvest-related emissions substantially reduce the net effect on atmospheric carbon.

Land-use change that increases forest cover (such as cropland converted to forestland) is a major contributor to reductions in atmospheric CO_2,[116] but this conversion is expected to slow in the near future.[118] The estimated net carbon flux in the United States associated with forestland conversion is approximately zero, with gains in forestland constituting +23 teragrams (Tg) of carbon per year and losses resulting in emissions of −23 Tg carbon per year over the last decade. The estimated emissions constitute decades, and in some cases centuries, of accumulated carbon within forest ecosystems, which is abruptly or gradually released to the atmosphere during conversion from forest to nonforest land. In contrast, gains in forestland represent carbon sequestration only from new growth of live biomass and the accumulation of newly dead organic matter over the 20 or so years since the renewal of forest cover.

Economic conditions and population growth will affect national and global production and consumption of wood products, which can temporarily sequester carbon (currently 189 Tg carbon per year, or 8% of the global forest sink).[120] Increases in wood products carbon are contingent on a sustained or increasing rate of harvest removals of forest carbon or on a shift toward forest products that exist for long periods of time before they are no longer suitable for reuse or recycling. In the United States, 76% of the annual domestic harvest input to the wood products pool in 2015 (110 Tg carbon) was offset by release processes (84 Tg carbon), yielding a corresponding net increase in wood products of 26 Tg carbon.[14] However, if harvest rates decline (as they did in 2007–2009, during the last economic recession), net additions to wood products will likely be lower than emissions from wood harvested in prior years.[14] Looking ahead, carbon storage in wood products is expected to increase by 7–8 Tg carbon per year over the next 25 years.[171]

Snowfall amount, timing, and melt dynamics are affecting water availability and stream water quality in the western United States, where less precipitation is falling as snow and more as rain in winter months, leading to longer and drier summer seasons.[121] Furthermore, rapid opening of forests in the western United States by wildfire has caused faster spring snowmelt through increased solar radiation and decreased reflectivity of radiation from charcoal,[128] leading to drier summer conditions that offset increased water yield following a disturbance.[127] The persistence of winter snowpack in the northeastern United States has declined over the last few decades; mid-winter thaws have become more common, and snowmelt flushing of mobilized soil nutrients into streams has become less common, although increased variability in climate–hydrology interactions can alter flushing.[172]

Major uncertainties

It is difficult to identify geographically specific changes in forest conditions at fine scales because of high spatial variability in forest structure and function and variability in projections of climate change and how it will affect large disturbances (drought, wildfire, insect outbreaks). Uncertainties about the rate and magnitude of climate change effects on carbon sequestration are moderately high, because it is difficult to project future trends in forest cover and socioeconomic influences on forest management (for example, demand for wood products, bioenergy). Although empirical evidence for young trees indicates that atmospheric enrichment of CO_2 can enhance tree growth, few long-term data on mature trees are available on which to base inferences about long-term forest productivity.[173] Temporal patterns and magnitude of carbon sequestration, especially after 2050, will be affected by uncertainties related to future land-use conversions (from forests to other uses and vice versa) and the production of wood products.

Description of confidence and likelihood

Because of variability in forest structure and function and species-level variation in adaptive capacity to climate change, it is difficult to project future changes in forest conditions at smaller than regional scales. Hence, there is *medium confidence* about how ecosystem services will be affected in different forest ecosystems, including effects on tree growth and carbon storage, as a function of higher temperature, more frequent drought, and increased disturbance. Observations from recent droughts and changing snowfall/snowmelt dynamics provide *high confidence* that climate change effects on water are already occurring in some regions, although the onset and magnitude of future effects will vary regionally.

Key Message 3

Adaptation

Forest management activities that increase the resilience of U.S. forests to climate change are being implemented (*high confidence*), with a broad range of adaptation options for different resources, including applications in planning (*medium confidence*). The future pace of adaptation will depend on how effectively social, organizational, and economic conditions support implementation (*high confidence*).

Description of evidence base

Climate change vulnerability assessments and adaptation planning efforts for forest ecosystems have been conducted at many locations (for example, forests in the western United States and upper Midwest) over the last decade.[19,140,141,144,174] These efforts have produced a broad range of adaptation options, including climate-informed practices for forest density management, water management, road management, and restoration.[19,144,175]

In general, practices that mitigate stressors in forest and aquatic systems increase resistance (the ability of a system to withstand a perturbation) and resilience (the ability of a system to return to a previous state after a perturbation) to climate change.[127,144] For example, restoring riparian vegetation helps to stabilize stream banks and provides shade to streams, thus helping to moderate stream temperatures.[127] Similarly, culvert replacement under forest roads can improve fish passage and reduce damage from flooding events.[127] Tools are now available to help in the prioritization of aquatic and riparian habitat restoration.[150]

There is strong evidence that stand density management can increase forest resistance and resilience to disturbances, including wildfire and bark beetle infestations in dry forest types. A growing body of evidence suggests that reducing stand density in most forest types can increase forest resilience to drought by increasing soil water availability and decreasing competition.[146,148,176] Reductions in stand density, combined with hazardous fuel treatments, can increase resilience to wildfire by reducing wildfire intensity and crown fires in western dry conifer forests and southern conifer forests.[141,145,174] Evidence also suggests that stand density management can reduce the incidence of bark beetles and subsequent mortality in some coniferous forests (for example, lodgepole pine forests).[177] All of these practices—in addition to "firewise" practices near buildings and infrastructure on public and private lands [178] and the use of prescribed fire where possible—improve the resilience of organizations and communities to increased frequency of wildfire.[179]

Wildfire has been an important disturbance in aquatic ecosystems for millennia,[180] and its frequency will increase in the future. Management responses to changing climate and fire regimes will need to be developed in the context of how past land use impaired aquatic function. Coordinating restoration in adjacent riparian and forest habitats can help ensure that beneficial effects of fire are retained across the aquatic–terrestrial interface.[181]

Examples of on-the-ground implementation of adaptation options to increase ecosystem resistance and resilience to climate change are emerging in the scientific literature.[138,139,141] However, exploration of potential management actions is more common than on-the-ground action,[18,19,127,140,145,175] suggesting that implementation is still in the early stages.

Major uncertainties

Evidence for the long-term effectiveness of climate change adaptation is derived primarily from our current understanding of how specific actions (for example, forest thinning, restoration of riparian systems, conservation of biodiversity) sustain the functionality of terrestrial and aquatic systems.[127] Physical and biological conditions of ecosystems are constantly changing, and interactions among multiple ecosystem stressors could have unforeseen outcomes on ecosystem composition, structure, and function. Thus, the long-term effectiveness of adaptation actions for increasing forest resistance and resilience to climate change is uncertain until a sufficient time series of monitoring data is available, requiring decades of observations.

The future pace of adaptation and barriers to its implementation are also uncertain, and it is expected that many forest management challenges will persist in the future. However, new challenges and barriers may emerge,[182] and it is difficult to predict how society and organizations will respond.

Description of confidence and likelihood

There is *high confidence* that climate change adaptation planning in forest management is occurring, particularly in U.S. federal agencies (especially national forests in the western and northeastern United States) (Ch. 28: Adaptation)[19,140,175] and Native American tribes.[142] Because of the limited number of examples in the scientific literature, there is *medium confidence* that adaptation planning is progressing to the application stage, where forest management plans are altered and on-the-ground management activities are implemented to mitigate the effects of climate change. However, there is *high confidence* that future progress in climate change adaptation planning and implementation will depend on social, organizational, and economic conditions.

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