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Future of America's Forests and Rangelands

Forest Service 2020 Resources Planning Act Assessment

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Abstract

The 2020 Resources Planning Act (RPA) Assessment summarizes findings about the status, trends, and projected future of the Nation's forests and rangelands and the renewable resources that they provide. The 2020 RPA Assessment specifically focuses on the effects of both socioeconomic and climatic change on the U.S. land base, disturbance, forests, forest product markets, rangelands, water, biodiversity, and outdoor recreation. Differing assumptions about population and economic growth, land use change, and global climate change from 2020 to 2070 largely influence the outlook for U.S. renewable resources. Many of the key themes from the 2010 RPA Assessment cycle remain relevant, although new data and technologies allow for deeper and wider investigation. Land development will continue to threaten the integrity of forest and rangeland ecosystems. In addition, the combination and interaction of socioeconomic change, climate change, and the associated shifts in disturbances will strain natural resources and lead to increasing management and resource allocation challenges. At the same time, land management and adoption of conservation measures can reduce pressure on natural resources. The RPA Assessment findings and associated data can be useful to resource managers and policymakers as they develop strategies to sustain natural resources.

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Executive Summary

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The 2020 Resources Planning Act (RPA) Assessment is the sixth report prepared in response to the mandate in the 1974 Forest and Rangeland Renewable Resources Planning Act (Public Law 93–378, 88 Stat 475, as amended). This report addresses lands across all ownerships and summarizes findings about the status, trends, and projected future of U.S. forests, forest product markets, rangelands, water, biodiversity, outdoor recreation, and the effects of socioeconomic and climatic change upon these resources. The results can inform resource managers and policymakers as they develop strategies to sustain natural resources. Important differences are found regionally and locally, and those unique patterns highlight the need for flexible adaptation and management strategies. The Forest Service, an agency of the U.S. Department of Agriculture, will continue to use the results to inform strategic planning and forest planning.

The 2020 RPA Assessment outlook for U.S. resources provides projected futures across four RPA scenarios that contain differing assumptions about U.S. and global population and economic growth, technology change, bioenergy preferences, openness of international trade, wood-energy consumption, and global climate change from 2020 to 2070.

Land development will continue to threaten the integrity of forest and rangeland ecosystems.

Developed land use in the United States has continued the expansion reported in the 2010 RPA and Update to the 2010 RPA, but this expansion has slowed. Developed land use area is projected to continue expanding in the future—with increases ranging between 42 and 58 percent by 2070 across the four RPA scenarios, from an estimated 97.7 million acres in 2020. These increases in developed land occur at the expense of all other land uses including forests and rangelands. Although forest land area has been lost to development since 1982, gains to forests from other land uses, primarily from converted pasture, have more than offset these losses, resulting in a net increase in forest land area. These conversions to forest land are also projected to slow. Continued land use conversion, driven principally by increased developed land use, is ultimately projected to lead to net losses of forest land of between 1.9 and 3.7 percent by 2070 and net rangeland losses of between 1.0 and 2.3 percent. The greatest increases in developed land use by 2070 are projected for the RPA South Region. Resulting loss of forest land is projected to be highest in the RPA South Region, while rangeland loss is highest in the Pacific Coast.

As developed land area has expanded, the juxtaposition of developed land with rural and natural lands has also increased. The "wildland-urban interface"—the area where developed and natural land uses meet or intermix—increased by 33 percent between 1990 and 2010, to cover 10 percent of all land and 14 percent of forest land in 2010. Although future projections of the wildland-urban interface were not included in this Assessment, the area of landscapes dominated by developed land is projected to increase by 66 to 114 percent between 2020 and 2070. The distribution and density of future development in relation to natural lands can have implications for the resources they provide. In terms of interior forest area (a proxy for the degree of forest fragmentation), the western and Southeast subregions are projected to experience a decrease of interior forest area, while increases are projected in the northern and eastern subregions, suggesting that different locations will experience different effects to the remaining forest lands.

The increasing presence of developed lands in areas formerly dominated by agricultural and natural land uses has the potential to introduce a wide range of threats to forest and rangeland over large areas. The highest rates of forest and rangeland invasion by nonnative plants across the United States have occurred near developed land uses. Risks to biodiversity from land development include destruction of critical habitats, reduction in connectivity among habitats, and displacement or isolation of wildlife populations. These multiple pressures increase the long-term vulnerability of wildlife and biodiversity to climate change. Land development is projected to be a dominant threat to wildlife and biodiversity across most of the Eastern United States, and a high risk to wildlife and biodiversity in the areas of the Western United States near large urban areas.

Land development pressures on nearby forests and rangelands also reduce their ability to provide ecosystem goods and services such as biodiversity, carbon sequestration, wood and fiber, recreational opportunities, and clean air and water. Although water use has been declining nationally, it is expected to increase in areas experiencing rapid population growth associated with urbanization. These increases in water use are projected to occur largely in the southern and western regions of the country, which are already experiencing water stress. Land development is also projected to lead to increasing strains on the ability of forests and rangelands to provide nature-based outdoor recreation, with declines in per capita recreation availability in locations experiencing land development. In addition, the loss of forest land alters both the amount of total carbon stored in the Nation's forests and the rate at which forests accumulate carbon—because less forest land is available for sequestration.

The combination and interaction of socioeconomic change, climate change, and the associated shifts in disturbances will strain natural resources and lead to increasing management and resource allocation challenges.

Socioeconomic change, climate change, and natural disturbances will alter the future health and productivity of natural ecosystems. Uncertainty about the magnitude of these changes drives RPA examination of alternative plausible futures. Policymakers and resource managers can use RPA results to identify areas of potential future stress, and to strategically initiate or enhance targeted management and adaptation actions.

By 2070, droughts are projected to occur more often, last longer, and be more intense. In the majority of examined climate futures, droughts are projected to occur most often in forest and rangeland ecosystems of the RPA Rocky Mountain Region and the southern portion of the Pacific Coast Region. Some of the fastest growing regions of the country are projected to become the driest, exposing more people to water shortages. Projected increases in exposure to drought indicate future challenges for managers and policymakers. Adaptation options such as increasing reservoir storage have limited ability to curtail shortage, and even groundwater mining—the most promising short-term adaption option—has limited availability to curtail shortage in the long term. In many areas, water shortages are already driving transfers of water from agriculture to urban users. Such transfers are likely to become more common.

Future droughts can also lead to reductions in rangeland health and productivity. Recent drought events may be responsible for reduced rangeland health in Arizona, New Mexico, southeast Colorado, northwest Texas, western Oklahoma, and southwest Kansas. In Texas, severe drought in 2011 and 2012 corresponded with widespread reductions in rangeland production, as well as forest mortality. Prolonged droughts in the Southwestern United States and California are creating conditions that have not been experienced since Euro-American settlement. Changes in climate are also expected to shorten the rangeland growing season primarily due to nutrient limitations, leading to decreases in forage availability and associated declines in ungulate success. These novel conditions will create challenges for rangeland managers trying to balance the sustainable production of domestic ungulates with other ecosystem services, such as maintaining forage reserves for native ungulates and other species.

The average annual area burned by large wildfires in forests and rangelands from 2000 to 2017 was more than double the average from 1984 to 1999. The total area of high-severity fires, as well as the volume of trees killed annually by fire, is expected to increase further by 2070. The largest increases in fire-killed tree volumes are projected to happen disproportionately in the Western United States among Douglas-fir, ponderosa pine, and pinyon/juniper forests, as well as woodland hardwoods. Shifts in the fire regime patterns pose threats to those ecosystems, some of which are adapted to lower severity fire. Escalating fire activity also poses threats to human health and property, particularly in the growing wildland-urban interface. In addition, smoke from wildfire influences where and when visitors take outdoor recreation trips. Visitors could choose to avoid fire-prone areas, reducing economic benefits while leading to increased recreation-associated strains and overuse among other forest ecosystems.

As described above, certain forest ecosystems and locations are projected to be disproportionately affected by changing conditions. Dominant forest types in the Rocky Mountain Region including Douglas-fir and ponderosa pine are projected to lose area, growing stock volume, and carbon. These expectations raise concerns about the sustainability of these forests, as well as the wildlife, recreation, and forest product manufacturing sectors that depend upon them. Rising sea levels in the Southern and Eastern United States have already led to transitions of coastal forests into saltwater marshes. Although not explicitly modeled in this report, further projected increases will continue this transition and increase destruction of residential housing in coastal areas, causing greater pressure for land development away from coasts. Over large areas, such effects could increase demand for wood products for rebuilding, leading to increased timber and product prices as well as increased timber harvesting.

Pressure from future disturbance (including wildfire), forest conversion to developed land, and forest aging, along with rising demand for forest products, is projected to influence carbon futures both in terms of the amount of carbon forests store (carbon stocks) and annual rate at which forests store carbon through forest growth (carbon stock change). Currently, carbon accumulation through growth both in forests and in the amount of carbon stored in harvested wood offsets more than 10 percent of economy-wide carbon emissions annually. However, forest growth rates are projected to slow as forests age, disturbance increases, and forests are converted to other land uses. Under RPA scenarios where demand for wood products and the conversion of forests to other land uses are both high, the forest ecosystem is projected to become a net carbon source. While the increased demand for wood products under these scenarios is projected to lead to a substantial annual increase in carbon stored in harvested wood, this would only partially offset carbon emissions from the forest ecosystem. This partial offset would lead to a reduced sink strength and the likelihood that the forest sector would become a net carbon source.

Biodiversity in the conterminous United States is highest in the North and South RPA Regions; however, projections for the coming decades indicate that these regions are the most vulnerable to the stress of land use change in the form of land conversion to development, expansion of agricultural areas, and development of energy infrastructure and mining. The relatively small federally managed land base in the North and South Regions, which can serve as conservation refugia to some biodiversity, is unlikely to counteract any widespread biodiversity losses in those regions in the coming decades. Although the Pacific Coast and Rocky Mountain Regions have expansive areas of Federal lands, their associated biodiversity is projected to be under high climate stress, in part due to their locations at high elevations. Climate change may compromise the ability of federally managed lands to provide climate refugia, and may force land managers to consider modifying management approaches to account for warmer temperatures, increased intensity of precipitation events, and the potential for greater numbers of extreme events such as drought, heat, and wildfire.

Although per capita participation in outdoor recreation activities was relatively stable in the years leading up to 2020, population growth has led to an increase in the number of participants, and this growth is expected to continue under most future scenarios. However, the per capita area available for forest recreation is projected to shrink in most regions by 2070. When combined with increasing participation, existing forest recreation areas in these locations will be in high demand. Developed recreation sites and recreation infrastructure are particularly likely to face high demand because activities that require developed infrastructure—for example, historic site visitation, picnicking, motorized boating, developed skiing, and day hiking—are projected to see large gains in recreation consumption. In addition, increased frequency and severity of disturbance associated with climate change may reduce the availability and condition of recreation opportunities, with recreationists opting to recreate in different seasons or in different locations to avoid disturbance.

Land management and adoption of conservation measures can reduce pressure on natural resources.

Management actions can play key roles in avoiding or mitigating the impacts of disturbances and changing climate in some ecosystems at local and landscape scales. In some forests, treatments such as thinning and prescribed fire have been effective at ameliorating drought impacts and have shown the potential to reduce the occurrence of high-severity fires. Active forest management has also been used to improve forest growth and health, including the development of forest plantations, which focuses timber production on a smaller land base. Continued improvements in management techniques and the use of genetically improved planting stock in forests managed for timber can increase the amount of timber available for forest products and reduce harvesting pressure on other forests.

Technological advances and adoption of technology and other conservation measures have led to decreases in water use, even as human population has increased. From 2005 to 2015, surface freshwater withdrawals decreased in 64 percent of counties nationwide. During the same period, domestic withdrawals for household use fell by 10 percent nationally despite an 8-percent increase in population. Many of these gains in efficiency have been driven by technological advances such as requirements for low-flow toilets and community regulations that prohibit nonessential turf or incentivize their removal. Recent efficiency increases in irrigation for agriculture and cooling methods for thermoelectric power plants, especially in water-scarce regions, have led to a 7-percent decrease in irrigation withdrawals and a 34-percent decrease in thermoelectric withdrawals over this same time period. These and other advances in efficiency are key components of social adaptation to water scarcity and could help to mitigate some impacts on society under projected drier conditions and increasingly frequent drought.

Policy changes can also lead to natural resource improvements. The Clean Air Act Amendments of 1990 have resulted in substantial sulfur and nitrogen emissions reductions, with the highest reduction in the North Region. These reductions have enabled some ecosystems to recover from years of impacts from acid rain and eutrophication, increasing resilience to climate change and providing improved wildlife habitat. Some ecosystems have even recovered to the point of allowing the reintroduction of previously extirpated species, including brook trout in the Adirondack Mountains in New York. Projections developed outside of RPA indicate continued reduction of sulfur and nitrogen deposition through 2070 across the United States.

Shifts in urbanization patterns have led to slowdowns in certain trends that were projected in the 2010 RPA, with an associated reduction in resource impacts over what was previously expected. The conversion rate to developed land use increased from 1982 to 1997, then declined until 2012. Land cover data suggest that this rate continued to decline after 2012. Although the area of developed land continues to increase, the declining rate of transition shows a lower rate of impacts to natural areas than was projected. Similarly, although forest cover fragmentation increased from 2001 to 2016 in all RPA regions over a wide range of spatial scales, the rate of forest cover loss and fragmentation decreased after 2006 in all regions. The interior forest area actually increased in the South Region after 2006. Under the new projections, although the overall forest area is expected to decrease across all scenarios, the share of more-contiguous forest is projected to increase in the South Central, Northeast, and North Central Subregions.

Looking Forward

The RPA legislation recognizes the importance of forests and rangelands in contributing to the American public's well-being and quality of life. Maintaining forests and rangelands that are productive and provide a range of ecosystem services starts with continual monitoring and analysis of the effects of changing socioeconomic trends and a changing climate on these resources. Across all futures evaluated in this Assessment, a growing economy and shifts in land use are projected to lead to increased pressures on U.S. forests and rangelands, and greater demand for the goods and services they provide. Projected climate change, in concert with associated changes in interacting disturbances such as wildfire and drought, directly affects natural ecosystems and will present new challenges for resource managers.

The futures presented in this report are based on a continuation of current U.S. natural resource management policies in the face of projected changes in climate, demographic and economic conditions, and social values. Our results highlight a number of areas in which policymakers and land managers may experience pressure to change current policies or develop new approaches. The negative effects on the environment, economy, and society portrayed by many of the scenarios in this RPA Assessment are not foregone conclusions. Some of the negative effects can be modified or reduced by timely actions from policymakers and land managers and by advanced management approaches that emerge from investments in science and technology. The RPA Assessment also points to several areas in which changes in choices or technology have recently reduced pressure on natural resources. Additionally, some of the futures may present opportunities for new and improved resource uses and management approaches.

Forests and rangelands exist within broader and dynamic societal and ecological contexts. The many land uses, economic sectors, and competing and changing resource demands across the United States complicate how governments, organizations, and landowners allocate the scarce economic resources they manage. The RPA Assessment seeks to improve understanding of the multiple and interacting factors that have created current trends and how we expect these factors and others to affect renewable natural resources in the future. This focus is a unique contribution that provides important information to policymakers and resource managers as they develop strategies for sustaining the Nation's renewable natural resources.

Chapter 1

Key Findings of the 2020 RPA Assessment

U.S. Department of Agriculture, Forest Service. 2023. Key Findings of the 2020 RPA Assessment. In: U.S. Department of Agriculture, Forest Service. 2023. Future of America's Forest and Rangelands: Forest Service 2020 Resources Planning Act Assessment. Gen. Tech. Rep. WO-102. Washington, DC: 1-1–1-11. Chapter 1. https://doi.org/10.2737/WO-GTR-102-Chap1

The 2020 Resources Planning Act (RPA) Assessment explores the present condition and 50-year outlook for the Nation's forest and rangeland resources. This chapter follows the organization of the resource-specific chapters (Chapters 4 through 11). Each section provides the key findings of the corresponding chapter, as well as the results that support those findings. Key findings apply to the conterminous United States unless otherwise specified.

Land Resources

Developed lands continue to encroach on natural ecosystems and agricultural areas, with about half of new developed lands converting from forest or rangeland.

In all RPA regions, the developed land area generally exhibited the largest net gains of all land uses from 1982 to 2012. As a result, development was a primary driver of net changes in most nondeveloped land uses. About half of new developed lands converted from forest or rangeland, while most of the remainder converted from agriculture (crop and pasture) land uses. The rate of transition to developed land use from other land uses increased from 1982 until 1997. Although the area of developed land continued to increase after 1997, the rate of transition began to decrease.

Developed lands are projected to continue to expand in all scenarios, although less than projected in the 2010 RPA Assessment. The expansion of developed lands varies across regions and is projected to be larger under high socioeconomic growth scenarios and smaller under hotter climate futures.

The RPA land use change models describe future dynamics of privately-owned land, where the choices between forest, rangeland, agriculture, and developed land uses are driven principally by the relative economic returns to those land uses. A continued increase of developed land area is projected under all RPA scenario-climate futures, but more so for RPA scenarios with higher levels of population and income growth and less so under hotter climate futures. The increase in developed lands is projected to occur at slower rates than previously projected in the 2010 RPA Assessment. Prior projections were based on data from 1982 to 1997, when rates of new development were increasing, while the 2020 RPA land use change models used data from 2000 to 2012, when rates were decreasing from the peak (or highest rate) in 1997. The decline in the rate of development results in smaller projected conversions from nondeveloped to developed land.

The regional differences in projected increases of developed land area are generally larger than within-region differences attributable to RPA scenarios. The largest projected increases in developed land area appear in the RPA South Region and smallest in the Pacific Coast and Rocky Mountain Regions.

Forest land area increased slightly over the past decades, mostly at the expense of pasture and crop land areas. This trend is expected to shift to decreasing forest area under all scenarios, although at lower rates than projected by the 2010 Assessment.

Net gains from other land uses, principally crop and pasture land, offset forest losses to developed land from 1982 to 2012, resulting in a slight net increase in forest land area. Non-Federal forest land area increased slightly in the North and South Regions, stayed stable in the Rocky Mountain Region, and decreased slightly in the Pacific Coast Region. Privately owned forest land area is projected to decline in the future, although the projected 50-year net loss is 35 to 55 percent lower than was projected in the 2010 Assessment. While 91 percent of current privately owned forest land is projected to remain in forest use in 2070, most of the loss is projected to convert to developed land. The projected decreases in forest land area are largest in the South Region and relatively small in all other regions.

Forest cover fragmentation slowed over the past decade but continues overall and is expected to continue into the future for the western and southeastern subregions, while decreasing slightly in the north and central subregions.

Forest land cover fragmentation increased in all RPA regions from 2001 to 2016, although at a decreasing rate after 2006. A net loss of 2.6 percent of forest cover from 2001 to 2016 resulted in an overall net loss of 6.4 percent of the "interior" forest cover, with regional losses of interior forest ranging from 2.7 percent in the South Region to 12.3 percent in the Rocky Mountain Region. The analysis indicated stabilization or recovery of interior forest in the North and South Regions after 2006.

Projections hold that interior forest area will decrease under most RPA scenario-climate futures, except for projected increases under a "hot" climate future. The projected national decreases are relatively small across scenario-climate futures, especially when compared to regional changes. Four RPA subregions are projected to gain interior area (Northeast, North Central, South Central, and Great Plains Subregions) while four others are projected to lose interior area (Pacific Southwest, Pacific Northwest, Intermountain, and Southeast Subregions).

Changes in unfragmented forest land cover are more dynamic in private forests of the South, while changes in the West are slower and concentrated in public lands.

The overall dynamics (i.e., gain and loss) of "core" forest cover (unfragmented forest cover in the vicinity of forest land use) from 2001 to 2016 were greatest on privately owned land in the South Region, likely reflecting the relatively larger areas of harvest and subsequent forest regeneration in that region. In contrast, most of the net change (primarily net loss) of core forest cover occurred on public land in the Pacific Coast and Rocky Mountain Regions

Most forest lands remain in "natural" landscapes, but an increasing proportion is expected to be in "interface" landscapes near developed or agriculture use in the future.

Forest tends to be the dominant land cover where it occurs; however, developed or agriculture land cover near forest poses ecological risks. In both 2001 and 2016, 88 percent of forest cover area was in landscapes dominated by natural land covers (forest, grass, shrub, water, wetland, or barren cover occurring in at least 60 percent of the neighborhood area), while 31 percent was in "interface" landscapes containing at least 10 percent of developed or agriculture land cover.

Considering all land area (not just forest land), the period 2001 to 2016 saw a net decrease in natural-dominated and noninterface area in all RPA regions, alongside a net increase in developed-dominated and developed interface area. Agriculture-dominated and agriculture interface area decreased in all regions except the Rocky Mountain Region. Projections suggest a continuation of those regional trends under all RPA scenario-climate futures, except for a reversal of agriculture trends in the Rocky Mountain Region. This leads to a decrease in natural-dominated and agriculture-natural interface lands, alongside an increase in developed-natural interface lands.

Economic and regional factors tend to be more important drivers of land use area changes than changes in climatic conditions.

Land use projection models stemming from integrated scenarios of socioeconomic and climatic change indicate that socioeconomic factors tend to be more important drivers of future land use area change than do changes in climatic conditions. Similarly, the future patterns of land use change are driven more by the socioeconomic components of the RPA scenario than by projected climatic factors, except in less-modified landscapes where both drivers had about the same degree of impact. In the economic land value models underlying the land use projections, the financial returns to developed and agricultural land uses often far exceed the return to alternative land uses. Therefore, when land development returns are projected to be high, as in the high-growth RPA scenario, conversion to developed land is accelerated regardless of the climate impact. However, this accelerated effect is dampened as temperatures rise in the future.

Disturbances to Forests and Rangelands

The annual area of fire in forests and rangelands has increased since 1984. The average annual area burned between 2000 and 2017 was more than double the pre-2000 average.

Fire is essential in many forest and rangeland ecosystems, but changes in fire regimes can threaten those ecosystems. In forests, large fires burned 0.13 percent of the total forest area on average annually between 1984 and 2000, increasing to 0.37 percent annually between 2000 and 2017 (a 189-percent increase). In rangelands, the total area burned per year averaged 0.45 percent of the total area since 2000, representing an increase of 119 percent over the pre-2000 average of 0.19 percent per year. Increasing fire area trends occurred for forests and rangelands in all RPA regions except for the North Region, where fire is relatively rare. These increases in area burned have posed challenges for management and can impact the ability of forests and rangelands to provide clean water, carbon sequestration, and other ecosystem goods and services.

The two western RPA regions have generally had higher exposure to fire and drought than the eastern regions, as well as the greatest rates of tree mortality caused by insects and diseases. In contrast, forests in the RPA South Region have experienced the highest rates of harvest removals.

Forest and rangeland ecosystems experience a variety of disturbances that differ across regions. On average, larger forest and rangeland areas burned annually in the RPA Pacific Coast and Rocky Mountain Regions than in the eastern regions from 2000 to 2017. The highest annual burned area averages occurred in the Rocky Mountain Region, with 403,000 ha of forests and 638,000 ha of rangelands burning per year. In the Pacific Coast Region an average of 259,000 ha of forests and 218,000 ha of rangelands burned per year. Forests in those two regions also had the greatest areas of moderate- and high-severity fires. Forests and rangelands in the Pacific Coast Region and rangelands in the Rocky Mountain Region were exceptionally dry during the mid-2010s. A major drought also occurred in Texas and other parts of the South Region from 2011 to 2012, impacting both forests and rangelands. Summaries of forest canopy mortality from insect and disease agents show generally higher rates in the two western RPA regions than in the eastern regions. While the RPA South Region generally had lower rates of fire, drought, and insect and disease agents, it had the highest annual area of forest harvesting, accounting for more than 65 percent of all removals in the United States each year from 1986 to 2010. Consideration of these regional differences in disturbances can help direct management and policy efforts aimed at helping forests adapt to changing conditions.

The highest rates of invasion by nonnative plants occur near agricultural and developed land uses, primarily in forests in the RPA South Region and portions of the North Region, and rangelands in the Pacific Coast Region.

Invasion of forest and rangeland ecosystems by nonnative plants can cause ecological and economic impacts. Forests in the RPA South Region had the highest rate of invasion (58 percent), based on data collected from 2005 to 2018, followed by the North Region (55 percent). Forests in the two western regions were considerably less invaded (8 percent in the Rocky Mountain Region and 5 percent in the Pacific Coast Region). Within the two eastern regions, forests in counties in the southeastern, mid-Atlantic, and Midwestern States were most likely to be invaded by nonnative plants. Those counties tend to contain agricultural or developed land uses or are located near major metropolitan areas. Invasion rates of rangelands by nonnative plants were highest in the Pacific Coast Region, peaking in coastal California where several counties near San Francisco and Los Angeles host more than 300 nonnative plant species. Collection of consistent data on invasion by nonnative plants has only recently begun in both forests and rangelands across the United States, resulting in sparse data in some locations. As more data are added, additional regional and national patterns may emerge, thus providing better information to prioritize management of invasive species.

Fire-caused tree mortality in forests is expected to increase by 2070. The highest rates of fire mortality are expected if climate follows the hot or dry climate futures under any of the high warming RPA scenarios.

The annual volume of forest trees killed by fire is expected to increase over time across the United States and in each RPA region under all RPA scenario-climate futures. Annual fire mortality volume is projected to increase nationally between 55 and 108 percent from 2020 to 2070. In forests of the RPA Rocky Mountain and Pacific Coast Regions, where fire activity is highest, fire mortality volume is projected to increase between 20 and 55 percent (Rocky Mountain Region) and between 63 and 100 percent (Pacific Coast Region). In addition to increases in fire mortality volume, increases in the annual area of moderate-severity fires are expected in all RPA regions by 2070 under all RPA scenarios. In the Pacific Coast and South Regions, the area of high-severity fires is also expected to increase. In the Rocky Mountain and North Regions, projections indicate that increase or decrease in the area of high-severity fires depends on the RPA scenario-climate future. The greatest increases in fire mortality volume and in areas of moderate- and high-severity fires by 2070 were generally projected by the RPA dry or hot climate model projections under a high warming future (RPA scenarios HL, HM, and HH). The smallest increases were projected by the least warm climate model projection, regardless of the RPA scenario.

Drought exposure for forests and rangelands is expected to increase by 2070, and forest and rangeland ecosystems in the Southwest are expected to experience the most substantial increases.

The amount of forest land and rangeland experiencing drought is projected to increase under all RPA climate futures. More than 50 percent of the Nation's forests and rangelands are projected to be exposed to moderate, severe, or extreme drought in most years during mid-century (2041 to 2070) by the dry and hot climate projections under a future with high atmospheric warming. Under this same warming future, the middle climate projection also identifies greater than 50-percent exposure to drought for both forests and rangelands in many years during that period. Wetter conditions and lower levels of atmospheric warming result in lower percentages of forest area exposed to drought. Many forest and rangeland ecosystems in the Southwest could see large increases in drought exposure by mid-century, compared to recent levels of exposure (1989 to 2018). These ecosystems include the pinyon/juniper woodlands forest type group and the grassland and creosotebush desert scrub rangeland vegetation types.

Forest Resources

Important forest types are expected to lose area due to forest loss, conversion to planted pine following harvest, climate, and succession. These forest types include aspen/birch in the RPA North Region, oak/gum/cypress in the South, Ponderosa pine in the Rocky Mountains, and hemlock/Sitka spruce in the Pacific Coast Region.

Forests provide many goods and services. Some of these goods and services are specific to individual forest types, and knowledge of how those types are projected to change is therefore important. Most forest community types are expected to lose area between 2020 and 2070 due to a combination of conversion to other land uses, harvest and planting to a different species, climate effects, and succession to other forest community types. The extent of major forest types in the eastern RPA regions are projected to change more than the forest types in the western RPA regions. The projected areas of commercially important forest types such as loblolly/shortleaf and Douglas-fir vary more in response to different RPA scenarios than to different climate projections, while other types such as longleaf/slash pine and maple/beech/birch are more sensitive to the climate projection. Compared to other forest types, aspen/birch forests are projected to lose the most area by 2070. Oak/gum/cypress forests are also projected to decline in area, with a substantial portion lost to loblolly/shortleaf forests. Loblolly/shortleaf forests are among the few forest community types projected to increase in area by 2070.

Timberland growing stock volume is projected to increase through 2050. Post-2050, growing stock volume trajectories depend on roundwood demand and land use choices.

Future forest volume is influenced by shifts in productivity, land use choices, management actions and objectives, and markets. Timberland growing stock volume is projected to increase until 2050. After 2050, the projected trajectories of growing stock volumes vary across RPA scenarios. Under RPA scenarios with lower demand for roundwood and less forest loss, growing stock volume is projected to continue to increase through 2070. Under RPA scenarios with higher roundwood demand and increased forest loss, volume is projected to decrease from 2050 to 2070 but remain larger than in 2020. While scenarios with higher roundwood demand suggest futures with reduced volume, the 39- to 46-percent increases in harvesting for products in those scenarios support an expanding forest products sector. The future growing stock volume trajectories and their sensitivity to roundwood demand and land use change differ regionally, pointing to regional variability in both projected forest trends and the pressures driving those trends.

Aboveground biomass carbon density (carbon per unit area) is projected to increase by 17 to 25 percent over 2020 densities by 2070, while annual carbon stock change is projected to decrease, indicating carbon saturation of U.S. forests. The forest ecosystem is projected to become a net source of CO_2 by 2070 under futures that include high roundwood demand and net forest loss.

Forests provide a suite of ecosystem services, including the storage and sequestration of carbon. The density of aboveground biomass carbon is projected to be between 66.8 Mg ha^{-1} and 71.7 Mg ha^{-1} in 2070, representing an increase over the average density value in 2020, and an even larger increase over the 1990 value. Specifically, the average hectare of forest in 2070 is projected to have 17 to 25 percent more carbon stored in aboveground biomass than the average forest hectare had in 2020, and 51 to 62 percent more than 1990. The pool of carbon in aboveground biomass is projected to continue to increase over the projection period, although at a decreasing rate due to conversion of forests to other land uses, forest disturbances, and aging. These results suggest that the forest ecosystem carbon sink will saturate in the future, with total aboveground carbon stocks leveling off by 2070. Forests may become a net CO_2 source by 2070 depending on forest conversion and roundwood demand.

Projections suggest that harvested wood carbon annual stock change rates in 2070 will be greater than net forest ecosystem annual stock change rates under moderate- and high-growth future scenarios.

In 2019, forest sector carbon stock change was attributed to forest ecosystem carbon pools (73 percent), harvested wood carbon pools (14 percent), and land use conversions to forest (13 percent). Annual stock change rates across the forest sector are expected to decrease from 2030 to 2070, although the amount of carbon in the forest ecosystem is still projected to increase over this period. At the same time, an increase in wood products derived from U.S. roundwood is projected, particularly under moderate and high economic growth scenarios. The greater annual production of wood products in the United States in those scenarios leads to harvested wood carbon (harvested wood products in use and harvested wood stored in solid waste disposal sites) accumulating at an increasing annual rate. As a result, the carbon stock change rate in harvested wood carbon is expected to become larger than the forest ecosystem carbon stock change rate as early as 2060 under the moderate and high economic growth scenarios. This suggests that as forests mature and are increasingly affected by land use change and disturbance, the harvested wood carbon pools will become increasingly important for offsetting emissions from other sectors of the economy.

Although forest area increased 3.6 percent between 1977 and 2017, forest area is projected to decrease between 2020 and 2070, with net losses primarily driven by conversion to developed uses.

Total forest area of the conterminous United States in 2017 was 635.3 million acres, an increase of 3.6 percent from 612.4 million acres in 1977; however, forest area is projected to decrease across all RPA scenarios to between 619 and 627 million acres in 2070. Forest area projections generally vary more in response to different RPA scenarios than to different climate projections. The amount of future forest loss differs regionally: the South and Pacific Coast Regions are projected to lose the largest amounts of forest area. Loss of forest affects a range of ecosystem services. For example, between 194 and 517 million metric tons of carbon in the soil are expected to be transferred from forests to other land uses from 2020 to 2070 because of forest conversion.

There are an estimated 9.6 million family forest ownerships across the United States, and they control more forest land than any other ownership category (39 percent excluding interior Alaska).

Across the United States, an estimated 9.6 million family forest ownerships (i.e., individuals, families, trusts, estates, and family partnerships) guide and manage forests, with ownership patterns varying substantially among regions. Nationally, excluding interior Alaska, family forest ownerships control more forest land than any other ownership group. More than half of the forest land in the South and North Regions, 56 percent and 52 percent, respectively, is owned by millions of family forest owners. Most family forest owners have relatively small forest holdings (62 percent own less than 10 acres), but the majority of acres are in relatively larger forest holdings (58 percent of family forest acreage is in holdings of at least 100 acres). Focusing on family forest acreage for ownerships with 10+ acres of forest land, nearly half is owned by people who have commercially harvested trees, yet only a relatively small portion of family forest land is owned by people who have written management plans (23 percent) or recently received management advice (34 percent). Through outreach and education, the forestry community can help family forest owners meet their needs now and in the future.

Forest Products

The future of U.S. markets is shaped by strong growth in emerging economies, stable to slightly growing domestic demands, and by policy factors related to energy embedded in alternative scenarios. U.S. timber production and consumption are projected to remain strong, with varying levels of growth across RPA scenarios, but with important changes in the product mix.

Projections of roundwood production are expected to exceed pre-recession (2007 to 2009) levels by 2070. Growth in roundwood production is projected to exceed growth in domestic consumption across most scenarios, the difference adding to U.S. net exports. Higher economic growth domestically and internationally (RPA scenarios HH and LM) favors stronger export markets for product categories in which the United States currently is already a net exporter: softwood and hardwood roundwood, hardwood lumber, nongraphics paper (i.e., other paper and paperboard), and wood pellets. Under these same high economic growth scenarios, import-dependence on wood-based panels moderates, while import-dependence on softwood lumber deepens.

In all scenarios, U.S. newsprint production and consumption declines to historically low levels by 2070, while printing and writing paper also declines, but at a slower rate. Meanwhile, projections of other paper and paperboard are tied more closely to economic growth and rising overall demand for paper for packaging. Projected U.S. wood pellet production varies widely by scenario, depending on global policy and shifts in preferences as defined by the RPA scenarios.

U.S. industrial roundwood production is projected to rise faster than derived product manufacturing demand, resulting in the United States capturing a growing share of global industrial roundwood export markets.

Climate change is expected to increase timber growth rates, allowing timber inventories (stocks) to rise despite growing production of industrial roundwood. In addition, technology change enables manufacturers to produce more output per unit of wood input. These trends result in a market where industrial roundwood supply grows faster than demand in the United States, leading to rising exports of wood products to developing economies such as China and India. Industrial roundwood consumption in Asian markets is projected to exceed that of the North American market in most scenarios by mid-century.

The U.S. South is projected to remain the dominant timber producing region in the world, producing around 10 percent of total industrial roundwood under all RPA scenarios.

The inventory of standing timber in the South has rapidly accumulated since the recession (2007 to 2009), which has led to a rising ability of timber producers to supply the market, especially softwood roundwood in the South. The South produced around 16 percent of global softwood industrial roundwood and around 6 percent of hardwood industrial roundwood in 2015. Even though demand for roundwood rises significantly in most scenarios through mid-century, due in large part to rapid economic development in China and India, the United States maintains its market share through 2070. Depending on future population and economic growth, the average global price of hardwood industrial roundwood is projected to rise by 19 to 219 percent and softwood by 3 to 127 percent between 2015 and 2070. In the United States, projections indicate price increases of 4 to 51 percent for hardwood and 12 to 82 percent for softwood.

The U.S. paper sector has undergone a transition related to declining demand for graphics paper and the shift in global markets to overseas paper production in the last 20 years that is projected to continue into the foreseeable future.

The U.S. production of newsprint has declined from a high of 6.7 million metric tons in 2000 to around 1 million metric tons in 2018. Newsprint production and consumption are projected to decline to historically low levels by 2070, along with the production and consumption of printing and writing paper, albeit at a slower rate. Although industrial capacity to produce these two categories of paper is projected to decline nationally as manufacturing facilities close along with declining demand, no such declines are anticipated for other uses of paper. In fact, growth in other paper and paperboard is projected to continue to rise through to 2070, offsetting the declines from newsprint and printing and writing paper. Consequently, U.S. total wood pulp production is projected to grow by 8 to 39 percent nationally between 2015 and 2070, depending on the scenario.

Overseas demand for hardwood roundwood and lumber provides a base of support for domestic U.S. production.

The U.S. housing industry has historically provided strong markets for softwood roundwood, but moving forward, markets for hardwood roundwood are less tied to the growth in residential housing. The size of the domestic market for the U.S. manufacture of wood furniture and other uses is projected to stagnate over the coming decades, implying greater relative importance of hardwood roundwood and lumber export markets. All scenarios project stable export markets for hardwood industrial roundwood and hardwood lumber.

Projected futures in the production and consumption of wood to generate energy depend on policy assumptions and consumer preferences and vary widely by RPA scenario.

Policy choices and consumer preferences related to the carbon benefits of wood energy can have strong implications for the future of the industry. Our RPA scenarios aim to capture a broad range in bioenergy demand consistent with the scenarios' assumptions about future socioeconomic conditions, and thus show the range in possible futures for the wood pellet market. Specifically, the market for wood pellets is projected to not grow significantly or even decline under lower and moderate-growth scenarios (RPA scenarios HL and HM), while high-growth conditions associated with RPA scenario HH and favorable policy conditions inherent in the moderate-growth scenario LM result in wood pellet production projections that more than double by 2070 to over 20 million metric tons.

If current policies encouraging wood use in energy production are maintained in Europe, the United States is projected to have a durable and growing wood pellet export market through 2070. Across all RPA scenarios, future pellet production does not exceed 4.2 percent of total wood production.

Although pellets represent a small fraction (less than 2 percent) of all roundwood consumed, wood pellets have grown rapidly, destined to the European Union (EU) in support of that region's renewable energy policies. Europe is the world's largest wood pellet producer and consumer, mainly owing to the EU's binding renewable energy targets for 2020 and 2030, and other environmental legislation. The gap between the supply and demand within the EU is contributing to the increasing importance of global wood pellet trade. Prospects for domestic production and export of wood pellets depend in large part on strong overseas markets, which are largely maintained currently by EU policies. Wood pellet manufacture would not rise to much more than 4.2 percent of all roundwood consumption by 2070 under RPA scenario LM and would remain less than 1 percent under scenario HL. Concerns about the sustainability and carbon implications of wood pellets as an energy source would therefore be most pronounced under the LM and least under the HL scenarios, but in both cases would not define substantial changes in overall production/carbon at the sector level.

Rangeland Resources

Rangeland health is relatively unchanged since the 2010 RPA Assessment. The greatest overall impacts to rangeland health have been observed in the Pacific Coast Region and in the southwestern part of the United States due to increases in invasive annual grasses and drought.

Relatively healthy rangeland conditions were found on approximately 75 percent of non-Federal rangeland from 2011 to 2015 and between 79 to 86 percent of rangelands managed by the U.S. Bureau of Land Management from 2011 to 2018. Despite the overall healthy conditions, recent data suggest that an increasing extent and magnitude of invasive annual grasses is reducing rangeland health.

Reductions in rangeland health are especially acute in the Pacific Coast Region, predominantly from invasive annual grasses, while the Southwestern United States has experienced reductions in rangeland health from reduced hydrologic function and biotic integrity, which seem to be linked to novel drought conditions. It is currently unclear whether these effects are transitory, but the impacts of invasive annual grasses are often irreversible and present numerous management challenges.

Rangeland production is increasing in northern parts of the rangeland extent and decreasing in the south, with corresponding changes in bare ground. Interannual variability in productivity is increasing in most areas at the same time, with the largest changes since 2000 having occurred in the Southwestern United States. Current production trends are projected to intensify in the future and become more variable on an interannual basis.

Productivity changes have led to minimal changes in overall national forage availability, but regional and local impacts have been significant. Annual production has been increasing across the northern extents of conterminous United States rangelands, especially the northern Great Plains and eastern Washington and Oregon. Increases in the annual production across the northern Great Plains have been primarily due to increased growing season precipitation since 1984 and the subsequent increase in rangeland woodiness, while increases in eastern Washington and Oregon were probably due to the increased cover and extent of invasive annual grasses, especially cheatgrass *(Bromus tectorum)*. In contrast, rangeland productivity has been decreasing across the southern extent of rangelands, most notably in the desert Southwest and southern California. Decreases in those areas are driven by the acute drought conditions that have been pervasive for years to decades. In addition to asymmetric changes in the amount of production across rangelands, interannual variation in production is also increasing, especially since 2000. The highest interannual variability in productivity occurs in the South and Pacific Coast Regions.

Projections suggest that many of the trends that have been observed since 1984—including decreased production in the South, increased production in the North, and greater interannual variability—will continue and possibly intensify in the future. The Southwest is projected to experience the largest and most widespread reductions in rangeland productivity, especially in desert areas, followed by the southern plains and Four Corners area. The northern Great Plains, especially North Dakota, South Dakota, and Montana, are projected to experience the largest gains in productivity.

Rangelands have been steadily converted to developed and agricultural land uses. Urbanization is projected to be responsible for most of the future reduction in rangeland extent, especially in the Pacific Coast Region.

Non-Federal rangelands occupied about 163 million ha in 2017, representing a loss of 6 million ha (3.6 percent) since 1982. Most losses were driven by net movement of 2.3 million ha to developed uses (urban and rural transportation infrastructure) followed by about 1.2 million ha to crop land. Hotspots of urban growth rates have been observed since 2010 in area dominated by rangelands such as those near Bozeman, MT; Boise, ID; and Phoenix, AZ. These hotspots of growth are projected to continue in the near future. While rangeland losses are expected to be minor nationally—decreasing just 2.7 percent by 2070—regional and local impacts are expected to be significant, especially when considering issues such as habitat connectivity and wildlife migration routes. The Pacific Coast Region is projected to lose the most rangeland area, about 6 percent of the current base, but some counties within that region may lose up to 25 percent of their rangelands to urbanization. Under a high atmospheric warming future, 61 counties are projected to exhibit losses exceeding 3 percent in the Pacific Coast Region.

Water Resources

Both per capita water use and total water use are declining in many parts of the country.

Water use is driven by changes in socioeconomic and climate variables, with the relative influence of drivers varying by sector. Household water use is driven largely by population, but also by policies and technologies aimed at water conservation. Increased use of high-efficiency appliances, low-flow toilets, and programs to limit outdoor turf have led to remarkable declines in water use in many communities, even in places with population growth—domestic water use decreased by 10 percent from 2005 to 2015 despite an 8-percent increase in population. Per capita household withdrawals fell from 98 gallons per day in 2005 to 82 gallons per day in 2015. During the same period, surface freshwater withdrawals decreased in 64 percent of counties in the conterminous United States to about 322 billion gallons per day. Irrigation withdrawals fell by 7 percent, and thermoelectric withdrawals fell by 34 percent. Some of those reductions in water use were necessary due to extreme droughts throughout the last two decades.

Despite reductions in water use, many regions increasingly experience water shortages due to extended dry periods.

From households to agriculture to industry, meaningful changes in human behavior and conservation practices have resulted in reductions of water use. Nevertheless, large regions of the United States face increasing water scarcity. Droughts are increasing in frequency and duration. Water shortage occurs when demands are partially or fully unmet, a condition also referred to as socioeconomic drought. Much of the United States experienced at least moderate water shortages during the period of 1986 to 2015. The southern Great Plains and Rocky Mountain Subregions, southern California, and northern Florida already experience high-intensity shortages of less than a month in length, as well as relatively less intense shortages with duration equal to or greater than 6 consecutive months.

Projected changes in national consumptive water use range from a 9-percent decrease to a 235-percent increase, with the largest impacts resulting from the needs of agriculture in response to climate change.

Across RPA scenarios and climate projections, changes in domestic water use are projected to range from a 55-percent decrease to a 2-percent increase. Despite projected decreases in household water use, changes in total consumptive water use are projected to range from a 9-percent decrease to a 235-percent increase by 2070. In most places, increases or decreases in water use depend on agriculture's response to changes in precipitation and temperature. Nationally, agriculture accounts for 42 percent of total water withdrawals, so changes in agricultural water use have the largest impact on aggregate water use. Over the last few decades, irrigation practices have become more efficient. Across the Western United States, both acres irrigated and water applied per acre have fallen. In the East, however, irrigation has become more widespread to ensure more reliable farm yields. Future water use depends on whether trends in the East continue and how western farmers respond to drier conditions, particularly in the southern Great Plains, Intermountain, and Pacific Southwest Subregions, for which results across climate projections are highly varied.

Changes in projected aggregate water yield by mid-century range from a 25.7-percent increase under a wet future to a 10.9-percent decrease under a dry future.

Climate model projections for precipitation and water yield (which is strongly correlated with precipitation) are more varied than projections for temperature. The RPA projections associated with a dry future anticipate decreases in water yield in the South, Southeast, and Great Plains, whereas increases in water yield are projected in these same regions under wet and hot RPA futures. Water yield projections consistently increase for the much of the Western United States but decrease in the Southwest. Much warmer temperatures in the South are projected to increase potential evapotranspiration more than for any other region, amplifying the effects of decreased precipitation and leading to further declines in water yield.

Short-duration droughts are likely to turn into long-duration droughts, and the intensity of drought is likely to increase substantially. Under higher future atmospheric warming, droughts lasting more than a year are projected to occur four times more often and increase in intensity by 76 percent.

Droughts can be characterized by how often they occur and how long they last. Both short- and long-term droughts are projected to increase in intensity and duration in the southern Great Plains, and short-term droughts are projected to last longer in the middle Great Plains, Southwest, and South. Extreme droughts that may be relatively infrequent today are projected to become more frequent by mid-century, especially under a future with high atmospheric warming. Under this future, droughts that last longer than 3 years are projected to be more than 19 percent more severe on average (while shortages increase by 19 percent), and droughts lasting more than 10 years are projected to occur about 6 times more often.

Adaptation options like increased reservoir storage have limited ability to curtail shortage in the long term. Responses to climate change will probably require substantial transfers from agriculture to urban users, which could have serious negative impacts on rural communities.

As water scarcity increases and droughts become more frequent, economic pressure will likely shift water use between sectors and regions. Longer term responses to climate change might require transfers from agriculture to urban users, which could have serious negative impacts on rural communities. Past droughts, as well as increasing competition with municipal water uses, have led some farmers to rely more on groundwater than in the past. Aquifers throughout the country are being drawn down at rates that far exceed their recharge rates. Communities have also sought to increase their reservoir storage, which might provide short-term relief, but is often contentious and ultimately relies on sufficient water yield to fill the reservoirs, an increasing problem throughout the Nation. In areas that rely heavily on hydroelectric power, reservoir levels may become low enough to affect power generation.

Biodiversity: Wildlife and Aquatic Biota

Trends from breeding bird surveys indicate population declines in at least 20 percent of all bird species across habitat types since the 1950s/1960s, and in more than 50 percent of species that occupy grasslands or are ground nesting. These declines are linked to land use modifications of habitats as well as introduced species and loss of habitat connectivity.

Wild bird populations have long been considered good indicators of environmental threats like landscape change because changes in habitat affect the abundance and diversity of bird species that occupy a particular region. In addition, many bird species are highly migratory, making them vulnerable to changes in land use and climate at different stages of their lifecycle as they move among environments, some of which are outside the United States. Population declines and variability over long- and short-term time periods reflect ongoing stress on existing avian fauna. Data from long-term breeding bird surveys show declines in population sizes. Grassland bird species had the greatest declines in long-term trends, with 54 percent of species showing significant decreases, while only 4 percent had significant increases. Several categories of harvested birds, including species of geese and ducks, have remained stable over the long-term, but webless migratory birds, including American woodcock and mourning dove, are in decline.

Concentrations of imperiled taxa with a listing status under the Endangered Species Act are found across the country, with particular concern in Peninsular Florida and Hawaii for birds, and in the RPA North and South Regions for fishes, crayfish, and mussels.

Increasing numbers of species across taxa are being listed under the Endangered Species Act, with few species delisted due to conservation. Current patterns of distribution reflect cumulative counts of federally listed imperiled species over time. Concentrations of federally listed imperiled taxa are found across the country, with hotspots in Peninsular Florida and Hawaii for birds, and in the North and South Regions for fishes, crayfish, and mussels. Among forest-associated species, the greatest proportion of possibly extinct and at-risk species is found among amphibians.

Watersheds of the RPA North and South Regions are most vulnerable to compounded land use stress. Regardless of RPA region, development stands out as the largest overall land use stressor for native ecosystems.

Land use pressures including land conversion, human population growth, expansion of agricultural areas, and development of energy infrastructure and mining are most pronounced in watersheds of the Eastern United States, specifically the RPA North Region and areas of the South Region, where fewer Federal lands exist to fill the role of ecological reserve. Managers in the East may therefore face more intense land use pressures than in the West, where increased pressures are associated with population and agricultural centers in Washington, Idaho, California, and pockets of the Rocky Mountains. This spatial pattern varies from climate-driven stress, which is generally highest in the North and Pacific Coast Regions.

Areas of potential high climate stress were consistently found in mountainous areas of the RPA North, Rocky Mountain, and Pacific Coast Regions, with pockets of stress identified in arid regions of the Rocky Mountain Region.

Climate change is affecting terrestrial and aquatic habitats in the United States, resulting in large-scale shifts in the range and abundance of native fauna. Projections identified several areas where a majority of the plausible futures predict high stress for native species in response to climate change: mountains in the Pacific Coast, Rocky Mountain, and South Regions; large areas from New York to Maine in the North Region; and lower elevation lands in southern New Mexico, southern Arizona, Oklahoma, and Texas. The consistency of high stress in these areas suggests that wildlife managers will likely see changes in wildlife habitat and wildlife distributions. Areas of high elevation throughout the Pacific Coast and Rocky Mountain Regions are projected to experience high stress under the both the RPA hot and dry model projections. Higher elevations in the eastern part of the conterminous United States appear to experience more stress under hot projections than dry projections.

Federal lands with a lower risk of development or land conversion, such as those managed by the National Forest System and U.S. National Park Service, are projected to be under higher climate stress compared with other lands, potentially limiting their future ability to function as climate refugia for native biota.

National Forest System and U.S. National Park Service lands contain many federally listed species, making them critical for the protection and recovery of imperiled biota. However, these lands are projected to experience greater climate stress than the rest of the country due to factors such as their locations, often in higher elevations. Thus, climate-driven stress projected for Federal lands may limit their future ability to function as refugia. This becomes particularly relevant when land use change projections for private land across much of the country anticipate permanent conversion to developed land use.

Outdoor Recreation and Wilderness

Publicly managed recreation resources, at all levels of government, provide most opportunities for outdoor recreation.

The recreation opportunities offered by governments vary in their types, natural settings, and locations relative to population centers. For those living in or visiting urban and peri-urban areas, local public lands generally offer the most-accessible spaces for nature-based outdoor recreation. Local government public lands typically offer opportunities to engage in the most-popular outdoor recreation activities, such as walking/hiking, viewing nature and wildlife, and simply relaxing in the outdoors, and often accommodate those with a wide range of skills and abilities. State park agencies and other State-level agencies focused on forestry, wildlife, land conservation, or other natural resources also provide public recreation opportunities. There are more than 2.2 million acres of State park land across the United States. Among RPA regions, the North Region has the greatest number of State park acres. Seven Federal agencies provide the majority of recreation opportunities on nearly 400 million acres of federally managed lands. In general, Federal lands are most common in the West but are present in every RPA region. Private lands are less accessible and most opportunities on these lands accrue to landowners.

Per capita participation in outdoor recreation activities has been relatively stable in recent years but population growth has led to an increase in the number of participants.

About 50 percent of the U.S. population engages in outdoor recreation. That participation rate has remained stable since 2007, before increasing to about 54 percent of the population in 2020. Of the activities commonly associated with forests, rangelands, and other open spaces, hiking, camping, and freshwater fishing are consistently the most-popular, with between 13 and 15 percent of the population engaging in those activities. Before 2020, participation had been increasing slightly for hiking, declining for camping, and remaining steady for fishing. Although participation rates have been mostly steady, the number of outdoor recreation participants has increased with a growing U.S. population. Between 2008 and 2018, an additional 15 million people engaged in outdoor recreation, with most of that increase attributed to hiking, which had a net increase of 18 million participants.

Forest recreation resource availability per capita is expected to continue to decline in future decades for locations experiencing population growth.

Declines in the per capita availability of forests for recreation are projected under moderate and high levels of future economic and population growth. In these RPA scenarios, projected losses in per capita non-Federal forest area are found in every RPA region and are most significant in the far north of the North Region, the northern portions of the Pacific Coast Region, and the southern portions of the Rocky Mountain Region. Some gains in per capita non-Federal forest recreation area are projected under scenarios with lower future economic and population growth. When gains are projected to occur, they are most common in the northern areas of the North and Rocky Mountain Regions. Federal forest recreation area has been generally stable over the last several decades and is not projected to grow substantially. In the presence of continued population growth, however, per capita area of Federal forests is projected to decline. Likewise, the area of State-managed forests in the United States has remained steady in recent years and is not expected to grow. There have been some gains in the size of U.S. State park systems in recent years, but most of those gains appear to trace to administrative changes among State agencies rather than expansion of the area under State ownership.

Greater income and population growth generally result in higher rates of per capita participation in outdoor recreation.

Modest changes (frequently declines) in per capita participation rates in outdoor recreation are projected for the coming decades. In general, projected per capita participation is greater under RPA scenarios that assume the highest income growth. The exceptions to that pattern are hunting, motorized off-road recreation, and developed site camping, where projected per capita participation is lowest under the highest rates of income and population growth. The greatest numbers of participants are projected under the highest income and population growth RPA scenarios for almost all activities and for all RPA regions. In many cases, the high rates of population growth in the RPA scenarios overwhelm any projected declines in per capita participation rates, increasing the total number of participants. This is especially true in regions like the RPA South, where we project large population gains in future decades.

Continued population growth results in a greater number of outdoor recreation participants, even potentially offsetting any declines in per capita participation.

The number of participants engaging in a recreation activity in the future reflects both changes in per capita participation over time and the size of the future population. Although there may be meaningful changes (increases or decreases) in per capita participation and average number of days of engagement for individual activities (the per capita consumption measure for recreation), population growth typically magnifies (for increases) or offsets (for decreases) those changes. Projected national and regional losses in the numbers of participants engaging in activities in 2040 and 2070 relative to 2012 are primarily confined to the high warming-low U.S. growth RPA scenario (HL). Potential declines in the numbers of participants in 2040 and 2070 extend into the high warming-moderate U.S. growth scenario (HM) nationally and for several regions for hunting, motorized snow use, cross-country skiing and snowshoeing, and floating. Projected declines in participation for hunting extend into the high warming-high U.S. growth scenario (HH) in the RPA North Region, reflecting the steep projected decline in per capita hunting participation in the face of both high atmospheric warming and strong population and economic growth.

Greater atmospheric warming is projected to have a negative influence on recreation engagement in many activities and little positive influence.

Participation rates in 6 of 17 activities exhibited marked responsiveness to the level of future atmospheric warming. In all cases, future climatic change, as influenced by increasing levels of atmospheric warming, led to lower participation rates and reductions in the average number of times each year that people recreate across all climate futures. Motorized snow use and cross-country skiing and snowshoeing were the activities that exhibited the greatest negative response to higher atmospheric warming. Within the RPA scenarios and their associated assumed level of atmospheric warming, the specific RPA climate projections also influenced participation in outdoor recreation in many activities. When unique patterns were present, they most frequently occurred for the hot, dry, and least warm climate futures. Although there is generally a lot of variability across the activities, hot and dry climate futures tend to yield lower participation rates, while the least warm climate future tends to yield higher participation rates.

Projections of consumption, measured as annual days of recreation, show increases across most activities, with the greatest numbers of recreation days in activities of a general or broadly accessible nature, i.e., day hiking, viewing nature, developed site use, and developed site camping.

Continued growth is projected in the total number of days of engagement annually in outdoor recreation. Growth in days of engagement is projected despite projected declines in the average number of days that each participant recreates. The projected growth in days of recreation is largely determined by the magnitude of projected population increase, and thus the number of potential recreationists. For almost all activities, the projected growth in the number of recreation participants overwhelms any projected changes in the average number of days spent recreating per participant. Total days of engagement in outdoor recreation activities are therefore projected to be greatest when projected population is greatest. Day hiking, viewing nature, developed site use, and developed site camping are projected to account for the greatest numbers of days of recreation in future decades, consistent with current patterns.

Chapter 2

Introduction

U.S. Department of Agriculture, Forest Service. 2023. Introduction. In: U.S. Department of Agriculture, Forest Service. 2023. Future of America's Forest and Rangelands: Forest Service 2020 Resources Planning Act Assessment. Gen. Tech. Rep. WO-102. Washington, DC: 2-1–2-7. Chapter 2. https://doi.org/10.2737/WO-GTR-102-Chap2.

The 2020 Resources Planning Act (RPA) Assessment is the sixth report prepared in response to the mandate in the 1974 Forest and Rangeland Renewable Resources Planning Act (P.L. 93-378, 88 Stat 475, as amended), which requires the Secretary of Agriculture to assess the Nation's renewable resources every 10 years. The RPA Assessment is intended to provide reliable information on the status, trends, and projected future of the Nation's renewable natural resources on all forests and rangelands on a 10-year cycle. While not required by the authorizing legislation, the U.S. Department of Agriculture, Forest Service also prepares mid-cycle updates to decadal RPA Assessments. The 2020 RPA Assessment focuses on past, current, and projected future availability and condition of forests, forest product markets, rangelands, water, biodiversity, and outdoor recreation, as well as the effects of socioeconomic and climatic change upon these resources.

The RPA legislation recognizes the importance of our forests and rangelands in contributing to the American public's well-being and quality of life. The American public continues to depend on our forests and rangelands to provide a variety of ecosystem services. Maintaining productive forests and rangelands requires continual monitoring and analysis of the effects of changing social expectations and a changing climate on these resources. The RPA Assessment improves our understanding of the multiple and interacting factors that we expect to affect renewable natural resources in the future. This focus is a unique contribution that provides important information to policymakers and resource managers as they develop strategies for sustaining the Nation's renewable natural resources. This chapter provides an overview of the 2020 RPA Assessment, describing the scope of RPA analysis, the document organization, and the framing context for the Assessment.

Scope of the Analysis

The RPA Assessment reports on a body of targeted research funded by the USDA Forest Service to address the RPA legislative mandate, providing both historical trends and projecting plausible futures of forest and rangeland resources. Based on an understanding of the historical trends, our research focuses on analyzing the influences of multiple drivers of change on renewable natural resources 50 years into the future, with the goal of informing and enabling planning to prevent future resource degradation and shortage. The analyses in the RPA Assessment respond to the mandated national all-lands focus and include renewable natural resources and related economic sectors for which the USDA Forest Service has management responsibilities: forests, forest products, rangelands, water, biodiversity, and outdoor recreation. We examine potential direct and indirect effects of socioeconomic and climatic change on future resource trends by incorporating demographic, economic, and climatic variables into our models. We continue to target our research to improve understanding of the multiple and interacting factors that we expect to affect renewable natural resources through a coherent and integrated view of the future.

We capitalize on areas where the USDA Forest Service has research capacity. The RPA Assessment draws upon the expertise of other Federal agencies that have responsibilities for national analyses by using their data and incorporating their reports by reference. For example, we rely on information from the U.S. Environmental Protection Agency about water quality. Likewise, we do not analyze renewable energy, with the exception of wood-based bioenergy, because the U.S. Department of Energy conducts comprehensive analyses of the energy sector. We also draw upon the work of our research and technology partners in the university sector, who are acknowledged and heavily cited throughout the Assessment.

Our analyses typically have a national focus, which requires either nationally consistent data or data that can be consistently compiled to the national level. The national focus often creates data constraints that limit analyses in some resource areas and often restrict analyses to the conterminous United States. For some resource areas, analyses are conducted at a subnational geographic extent to reflect the geographic extent of the resource. For example, our rangeland analyses focus on the Western United States, where most rangeland is found. The results of the analyses throughout the subsequent chapters often will be presented for both the entire United States and for the four RPA Assessment regions (figure 2-1). Other regional definitions are used for specific resource analyses and are described in the resource chapters.

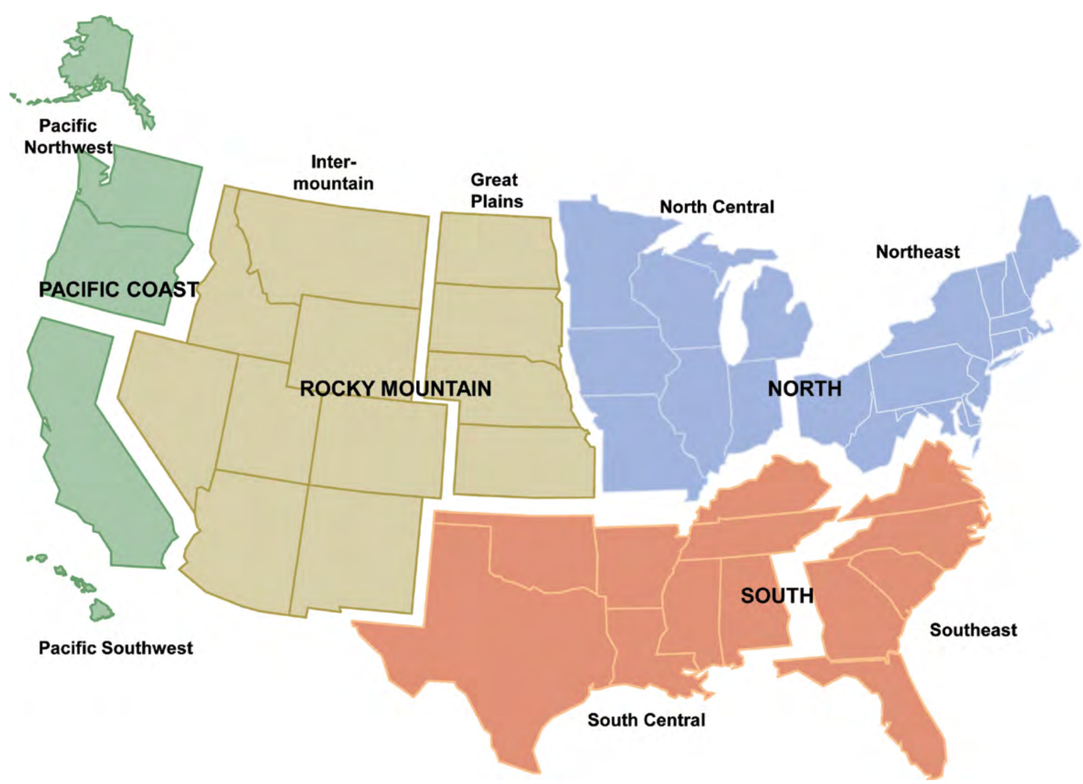
While the RPA Assessment focuses primarily on national analyses, the data supporting these analyses are available at varying spatial resolutions, and, therefore, the geographic scale of our results also varies. As a result, terminology about the "scale" of the analyses can be confusing, especially because scale is defined differently across disciplines. In the absence of a universal definition, we have tried to clearly define the context for scale in these analyses by specifying when we are referring to extent, resolution, or some other characteristic of scale.

The selection of English versus metric units in reporting RPA results continues to be challenging. While scientific outlets are primarily in metric units, English units are still commonly used in U.S. discussions and analyses. As a result, we have taken a hybrid approach in this Assessment to follow standard conventions. Metric units are used in many chapters because metric has become the predominant unit in both technical and policy discussions (i.e., Disturbance, Forest Products, Rangeland Resources, Biodiversity), while other chapters provide English units because of common usage in the United States (i.e., Land Resources, Outdoor Recreation). Both sets of units are used in the Forest Resources and Water Resources Chapters: English units are used for forest area and volume reporting and water use due to common usage among U.S. audiences, while metric units are used for carbon accounting and water yield to maintain consistency with the scientific community and international reporting. We have provided results in both English and metric units in the Conclusions section of each chapter to meet the needs of all audiences.

Document Organization

Preceding this introduction, the 2020 RPA Assessment key findings are presented by individual resource topic (the Key Findings of the 2020 RPA Assessment Chapter). Following this introduction, we describe the future scenarios used as

Figure 2-1. RPA Assessment regions and subregions.



the basis for the 2020 RPA Assessment projections (the Scenarios Chapter). The remaining chapters present results by resource area or resource sector and include both chapter and section key findings.

The information presented in these chapters begins with historical information that is tracked across RPA Assessment reporting cycles. Changes in historical trends are of particular interest because future projections are influenced by historical trends. Future resource conditions, demand, and supply are projected for 50 years (2020 to 2070 in this RPA Assessment cycle) for those resources for which sufficient data were available. The RPA analyses typically assume that policies affecting resource conditions remain consistent over the projection period. This assumption is more challenging in the scenario framework used for the 2020 RPA Assessment, especially given international efforts to address climate change effects. As described in the Scenarios Chapter, jointly achieving climate and socioeconomic futures may require policy or technology changes, although the means may vary widely across local, national, and global scales. Individual resource analyses will address whether significant changes in socioeconomic and climatic drivers are likely to shift resource trajectories.

This document summarizes the results of analyses that are documented in more detail in a series of technical supporting documents referenced throughout the chapters that follow. These supporting documents provide more details on data, methods, and results. RPA Assessment supporting technical documents are available on the USDA Forest Service's RPA Assessment web page as they become available: https://www.fs.usda.gov/research/inventory/rpaa.

Framing Context

Population, income, and climatic factors are all key drivers of resource demands that affect the future status of forests and rangelands—increasing population and per capita income have been shown to increase demand for goods and services, as have changing climatic factors including increasing temperatures. Changes in climate can also affect the future condition and supply of resources, with profound and highly variable impacts on forest and rangeland resources. Not only is the effect of climate change on temperature and precipitation projected to be variable across the United States, but individual resources are projected to respond differently to changes in climate. The changing climate will likely benefit some ecosystems, species, and associated goods and services at the expense of others.

It is therefore important to compare the plausible future condition and availability of forest and rangelands resources under the changing climate with plausible future demand to identify potential future shortages of important forest and rangeland resources. Following the precedent established in the 2010 RPA Assessment, the current Assessment uses a scenario approach to project resource futures based on the anticipated effects of changes in population and income (available at the county scale) and climate (available at a 4-km^2 scale) on forests and rangelands. We construct a range of scenarios by combining assumptions about our key drivers (see the Scenarios Chapter) and provide guidance on their application (see the Scenarios Chapter, the sidebar Using Scenarios and Projections in Resource Management Planning). For context, the following provides a brief overview of recent global and national population, economic, and climatic trends, as well as global trends in forest and rangeland area—national trends in forest and rangeland area are covered in depth in the Land Resources, Forest Resources, and Rangeland Resources Chapters.

Population Growth

Global population grew from 6.9 billion in 2010 to 7.7 billion in 2019 and is projected to reach approximately 10.5 billion by 2070 (United Nations 2019a). The percentage of the global population living in urban areas was 55 percent in 2018, up from 30 percent in 1950 (United Nations 2019b). Estimates and projections of global urbanization indicate that the growing number of city dwellers may account for almost the entire future growth of the human population. The United Nations projects that 68 percent of the world's population will be living in urban areas by 2050 (United Nations 2019b).

Unlike many high-income (per capita) countries where population is declining, the U.S. population continues to increase. The 2020 Census indicated that the U.S. population increased 6.3 percent between 2010 and 2020 (slower than the almost 10-percent increase between 2000 and 2010), exceeding 328 million in 2019. Although the U.S. population continues to grow, it did so at the slowest rate since the 1930s; the U.S. annual rate of population growth dropped from 0.73 percent in 2011 to 0.50 percent in 2020 (USCB 2021a), rates consistent with low net-immigration (USCB 2021b). Regional population growth was faster in the South and West than in the Midwest and Northeast. Overall, the South and West accounted for more than 80 percent of the U.S. population increase. The States with the highest numeric increases were, in descending order, Texas, Florida, California, Georgia, Washington, and North Carolina. These six States accounted for approximately half of the overall increase in the last decade.

Eighty-six percent of the U.S. population in 2020 lived in a metropolitan statistical area, and population in these areas grew at a faster rate (9 percent) than the overall U.S. rate (USCB 2021c). The 2020 Census data on urban areas were not yet available; however, the growth in population in metropolitan statistical areas will likely be mirrored by growth in urban areas.

Although the South and West had the largest increases in population, the U.S. population is still concentrated on the two coasts. And while only three States—Illinois, Mississippi, and West Virginia—lost population in the last decade, depopulation occurred in more than half of U.S. counties, continuing decades of population loss in areas such as Appalachian counties in eastern Kentucky and West Virginia, many Great Plains counties, and a group of counties around the Mississippi Delta. Many counties along the Great Lakes and the Northern U.S. border either lost population or grew at very low rates (USCB 2021c).

Economic Outlook

The global economy has gone through considerable change during the last several decades. The 1970s saw oil price shocks; the 1980s were a time of general deflation of commodity prices; the 1990s saw many high-income (per capita) countries, including the United States, shifting from industrial to service sectors; and the 2000s included a global recession that had major effects on the global and U.S. economy, especially in the real estate and housing construction sectors. The decade of 2010 to 2020 saw gradual economic growth from the nadir of the 2007 to 2009 recession, with increasing global sovereign debt and consistently low inflation, as well as rising income inequality within most high-income countries occurring alongside decreasing inequality between countries (United Nations 2020; World Bank 2016).

Global gross domestic product (GDP) increased 24 percent between 2010 and 2020, from $66.2 to $81.9 trillion (constant 2010 USD) (World Bank 2021). The rate of GDP growth in high-income countries was outpaced by the rate observed in emerging markets, led by but not limited to China. Global commodity trade held steady as a share of global GDP until the end of the decade, when several countries enacted higher tariffs, withdrew from existing and proposed new trade agreements, and otherwise took steps to limit cross-border flows of selected commodities. The arrival of COVID-19 at the end of the first quarter of 2020 in the United States and many other nations brought about a sharp contraction of the global economy. While this contraction was worse than the 2007 to 2009 financial crisis, growth returned more quickly due to fiscal support in a few large economies and the development and distribution of vaccines (International Monetary Fund 2021). Central bank actions to fight inflation in the United States and other economies, geopolitical uncertainty, and continued supply-chain disruptions make it difficult to project the future global economic trajectory.

The U.S. economy in the 2010s, growing out of the recession that began at the end of 2007, experienced the first recession-free decade since record-keeping began in the 1850s and ended the decade with historic lows in unemployment. Wage growth was slow for most of the decade, leading to a rise in wealth inequality as the stock market continued to rise. The arrival of COVID-19 in 2020 brought about the sharpest economic shock to the U.S. economy since the Great Depression. The recession was the shortest on record, at 2 months, and U.S. real GDP exceeded its pre-COVID level by the second quarter of 2021 (USDC Bureau of Economic Analysis 2021). Unemployment, which peaked at almost 15 percent in April 2020, proceeded to steadily fall, reaching pre-COVID-19 levels again in April 2022 (USBLS 2022). The arrival of COVID-19 variants, ongoing product supply chain disruptions, and the need for global vaccine deployment to bring an end to the pandemic produce, at the timing of this writing, an uncertain short-run future for the United States and the world.

Climate

Globally, each decade since 1980 has been successively warmer than the preceding decade, with the most recent decade (2010s) being around 0.36 degrees Fahrenheit (0.2 degrees Celsius) warmer than the previous decade (2000s) (Blunden and Arndt 2020). The 2010s was the warmest decade on record for the planet, with a surface global temperature of +1.48 °F (0.82 °C) above the 20th-century average. The combined land and ocean temperature has increased at an average rate of 0.13 °F (0.08 °C) per decade since 1880; however, the average rate of increase since 1981 has been more than twice that rate (0.32 °F / 0.18 °C) (NOAA 2021a). The 10 warmest years in the 1880 to 2020 record have all occurred since 2005, with 7 of the warmest years occurring since 2014. In addition, hot extreme events such as heatwaves have increased in frequency and intensity over most land area since the 1950s. Although warming has not been uniform across the planet, the upward trend in the globally averaged temperature shows that more areas are warming than cooling. Global impacts of this warming include shrinking arctic summer sea ice, thawing permafrost, increasing sea level rise, and the alteration of geographical ranges and lifecycles of many plant and animal species. Total annual precipitation over land areas worldwide has increased at an average rate of 0.1 inches per decade since 1901 (Blunden and Arndt 2020) and heavy precipitation events have become more frequent and intensified over the global land area where data are available (IPCC 2021); however, because higher temperatures lead to more evaporation, increased water stress on plants, and higher water use by people, increased precipitation will often not increase the amount of available water, especially at critical times (Blunden and Arndt 2020). As with warming trends, precipitation trends have also not been uniform across the planet. For example, agricultural and ecological drought in western North America has increased since the 1950s (IPCC 2021).

Based on a 126-year record, the average annual temperature for the conterminous United States is increasing at an average rate of 0.16 °F (0.09 °C) per decade—the increase rises to an average rate of 0.48 °F (0.27 °C) per decade when examining temperatures since 1970 (Blunden and Boyer 2020). The average annual temperature for Alaska has increased at a higher average rate of 0.31 °F (0.17 °C) per decade over the 96-year record—with the increase rising to an average rate of 0.90 °F (0.50 °C) per decade since 1970. Nine of North America's 10 warmest years have occurred since 2001, with the year 2016 being warmest year on record with a temperature departure of +3.46 °F (1.92 °C). For the conterminous United States, 2021 ranked as the fourth-warmest year in average annual temperature in the 127-year record, with the six warmest years having all occurred since 2012 (NOAA 2022). Maine and New Hampshire had their second-warmest year on record in 2021 (NOAA 2022), while 10 States across the Southwest, Southeast, and East Coast had their second-warmest year on record in 2020. No areas observed below-average annual temperatures (NOAA 2021b). Annual average precipitation has increased by 4 percent across the United States since 1901, with strong regional differences, including increases over the Northeast, Midwest, and Great Plains and decreases over parts of the Southwest and Southeast (Easterling et al. 2017). Alaska shows little change in annual precipitation (+1.5 percent), while Hawaii shows a decline in annual precipitation of more than 15 percent (Easterling et al. 2017). In any given year between 1895 and 2010, around 14 percent of the Nation experienced moderate to severe drought, on average (Hayes et al. 2012). The three longest drought episodes in the United States occurred in the 1930s, the 1950s, and the early 21st century. The most recent drought, during the early 21st century, started in individual regions across the conterminous United States. By September 2012, two-thirds of the conterminous United States was in drought, with the drought not breaking until 2014 (Heim 2017). Across most of the country, heavy precipitation extreme events have increased in both intensity and frequency since 1901, with the largest increases occurring in the Northeast (Easterling et al. 2017).

Forests and Rangelands

The Food and Agriculture Organization (FAO) estimates global forest area to be about 10 billion acres, covering 31 percent of the total global land area (FAO 2020). The FAO forest area estimate is primarily related to land use, meaning that an area without trees may be considered forest, while agricultural and urban areas with tree cover may be considered as land uses other than forest. The five most forest-rich countries, in descending order, are the Russian Federation, Brazil, Canada, the United States, and China. These countries account for more than half (54 percent) of the total global forest area. U.S. forest land accounts for 7.6 percent of the world's forest area.

The rate of global deforestation remains substantial but continues to show signs of decreasing, from 12.8 million acres of forest lost per year during the 2000s to 11.6 million acres per year during the 2010s. The largest net losses occurred in Africa, where the rate of loss increased from the previous decade, followed by South America, where the rate of loss in the 2010s declined by 50 percent. Deforestation results in the loss of ecosystem services provided by forests, including the provision of food, fuel, and fiber; carbon storage; flood and erosion control; and opportunities for recreation and cultural enrichment. Large-scale planting of trees is significantly reducing the net loss of forest area globally, through a combination of afforestation and natural expansion of forest. Asia had the highest net gain of forest area from 2010 to 2020, although the rate of gain declined from the previous decade. The area of planted forest continues to increase, albeit at a decreasing rate, accounting for 7 percent of total global forest area (FAO 2020).

Rangelands—defined in the *Rangelands Atlas* as land on which the vegetation is predominantly grasses, grass-like plants, and forbs or shrubs that are grazed or have the potential to be grazed by livestock and wildlife—cover 54 percent of the world's land surface (ILRI 2021). Rangelands are found in every region of the world and provide a variety of services including providing wildlife habitat, storing carbon, and supporting large rivers and wetlands. Rangelands around the world are currently experiencing threats from both development and climate change (ILRI 2021).

The United Nations has projected that 70 percent more food needs to be grown by 2050 to support the growing world population (FAO 2011). This growing demand will continue to put pressure on forest and rangelands, both domestically and globally.

Uncertainty and the Case for Scenarios

In the chapters that follow, we describe historical trends in resource conditions and use. As we look to the future, uncertainties in demography, economics, and climate—and the potentially wide-ranging effects on natural resources—underpin the need to project alternative plausible futures using a scenario-based structure. Here, we review the sources of these uncertainties and outline the justification for our use of scenarios in projecting the future availability and condition of the Nation's renewable resources.

Before the 2010 RPA Assessment, the United States and the world had been experiencing growing trade liberalization as a result of repeated rounds of General Agreement on Tariffs and Trade/World Trade Organization agreements. The United States and the world then experienced two global recessions: 2007 to 2009 and 2020. Growing trade frictions among the world's largest trading nations and blocs occurred in the 2010s, and collections of countries had incomplete success establishing inclusive plurilateral agreements such as the Trans-Pacific Partnership. World investors altered their behavior in the last decade, reducing foreign direct investment, with implications for trade and manufacturing. In contrast, the United States experienced increased foreign investment in the wood products sector over the past decade, notably in the U.S. South, for the production of lumber and wood pellets for energy.

Layered over the uncertain national and global environments and declining trade growth over the past 10 years are the increasing effects of climate change. The 2016 Paris Agreement—a legally binding international treaty that sets out a framework to avoid global climate change, including the role of forests—affects how policymakers and other decisionmakers see and manage forests (United Nations Framework Convention on Climate Change 2015). In discussions and negotiations following the 2016 Paris Agreement, forest-sector actors are considering how forests can mitigate climate change through both active management and the use of wood to produce energy and substitutes for more carbon-intensive building materials, as well as how forests are directly affected by climate-change processes. In the latter category, forests are increasingly threatened by altered rates and intensities of catastrophic disturbances. These deleterious effects of climate change carry with them possible impacts on the provision of many ecosystem goods and services (including water quality and quantity, recreation opportunities, wildlife habitat provision), the costs of managing forest-based insect and disease epidemics, and the challenges of maintaining and growing healthy urban forests. Climate change may also be contributing to accelerated net growth of timber, which can benefit timber growers and wood product manufacturers, potentially improve the relative comparative advantage of the U.S. forest products sector and raise the attractiveness of forests as a land use.

Given the recent variability in economic and climatic variables and the uncertainties surrounding their future development, we use a set of scenarios to project alternative plausible futures (see the Scenarios Chapter); those futures are strongly influenced by population and economic assumptions, along with projections of future climate change. Scenarios are not assigned likelihoods, nor are any scenarios intended to be “accurate” per se. Rather, these constructed scenarios provide a means of qualitatively and quantitatively understanding how a range of socioeconomic and climate conditions interact through time to create different natural resource futures. Global and, in most scenarios, U.S. populations are projected to continue increasing in the future. The outlook for economic growth is more uncertain, particularly in the short term, but the longer term growth trend is expected to be positive, although generally slower than in recent decades. Inequality—which has been linked to rapid technological change, urbanization and migration, and climate change—can either rise with these trends or fall if they are harnessed to foster a more sustainable world (United Nations 2020). The RPA Assessment outlook for U.S. resources is based on scenarios with varying assumptions about global economic growth, global wood energy consumption, forest products trade, domestic population and economic growth, and global climate change. Our analyses indicate the importance of these factors in assessing the alternative resource futures and likely challenges for future renewable resource management. Managers and policymakers can therefore apply our findings to evaluate potential ways of reducing the likelihood of unwanted futures and increasing the chances for desired futures.

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Chapter 3

Future Scenarios

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The Resources Planning Act (RPA) Assessment uses a set of scenarios of coordinated future climate, population, and socioeconomic change to project the availability and condition of renewable resources over the next 50 years. Since its inception in 1974, RPA Assessments have always looked 5 decades into the future, but approaches have varied. Before the 2010 RPA, futures generally were constructed based on consensus views on key socioeconomic variables affecting demands for goods and services from forests and rangelands, resulting in one likely future. Variations on that future were explored but limited in scope (e.g., low and high population growth), and were often focused on variables specific to forest product markets (e.g., low and high housing starts and alternative assumptions about softwood imports from Canada). Given rapid globalization in recent decades, these limited socioeconomic "futures" became insufficient to address the forces driving natural resource change nationally.

Beginning with the 2010 RPA Assessment, a set of integrated scenarios has been used to frame the resource analyses. This approach and analytical framework were designed to better incorporate global linkages and interactions between natural resources, extend our analytical capability to evaluate the potential effects of climate change, and more clearly the describe complexity and uncertainty associated with projecting future conditions and trends (USDA Forest Service 2012). We continue this approach to develop scenarios for the 2020 RPA Assessment. These scenarios depict coherent interdependent futures for global and U.S. population dynamics, socioeconomic factors, and climate change. They also provide qualitative and quantitative inputs to the RPA domestic resource analyses, which project resource conditions and trends to 2070. The scenarios used in the 2020 RPA Assessment are described in this chapter.

Key Findings

- The RPA Assessment analyzes the potential effects of global and national trends on all U.S. forest and rangelands over the next 50 years.
- A carefully selected set of scenarios, defining and integrating plausible future climate, population, and economic conditions, are used to organize projection work.
- All resource areas (e.g., forests, water, recreation, and wildlife) use the same set of scenarios or a subset (e.g., climate only) to define a plausible range of natural resource availability and condition over a 50-year period, establishing a consistent and coordinated approach.
- The downscaled projections of socioeconomic and climatic change developed from the scenarios can be used alongside RPA resource projections to inform planning, strategic thinking, and policy deliberation about the future for natural resource management and policy needs.

Framing the RPA Assessment Scenarios

Scenarios are used to explore alternative futures and are intended to provide a framework for objectively evaluating a plausible range of future resource outcomes. This approach is particularly useful when there is considerable uncertainty about the trajectories of the driving forces behind political, economic, social, and ecological changes (Alcamo et al. 2003, IPCC 2007). A globally linked scenario approach is important for the RPA Assessment because global conditions and trends in these variables increasingly affect domestic natural resources. Well-defined global scenarios provide a coherent framework for evaluating outcomes across resource analyses. Consistency in their construction allows managers and policymakers a deeper understanding of the connections and interactions among these variables as well as insight into potential options for enhanced adaptation or mitigation.

A scenario approach can use both qualitative and quantitative methods to visualize alternative futures based on different socioeconomic or institutional assumptions. The use of the term "scenario" can be confusing because scenarios are used for various purposes, or in reference to specific types of scenarios (see Moss et al. 2008, USGCRP 2010). For the RPA Assessment, we have adopted the approach used by the Intergovernmental Panel on Climate Change (IPCC). The scenarios represent plausible futures to better understand how systems may respond to different rates of change or how different decisions may alter resource trajectories (Moss et al. 2008). Scenarios are not assigned likelihoods, nor are any scenarios intended to be "accurate" per se. Rather, these constructed scenarios provide a means of qualitatively and quantitatively understanding how a range of socioeconomic and climate conditions could interact through time to create different natural resource futures. Scenarios are ultimately used to derive socioeconomic and climate projections, which refer to model-derived estimates of the future.

Although we reviewed and considered global scenarios constructed by other research groups (see Kok et al. 2015 for an evaluation of global scenarios), we selected the combination of the IPCC-based climate and socioeconomic scenarios as the basis for the 2020 RPA Assessment for several reasons. These scenarios provide quantitative data on both climate and socioeconomic variables over our assessment time horizon, are well documented in the scientific literature, have been widely used across a large range of impact studies, and were more current at the time of selection than other options.

The 2020 RPA Assessment relies on the approach used in the IPCC Fifth Assessment Report (AR5) (IPCC 2014) to provide global context and quantitative linkages between U.S. and global trends. Unlike the sequential approach for scenario development used in the IPCC Third and Fourth Assessment Reports, AR5 used a parallel process (Moss et al. 2010): four scenarios representing alternative climate futures (Representative Concentration Pathways or RCPs) were developed independently of five socioeconomic scenarios (Shared Socioeconomic Pathways or SSPs) (Nakićenović et al. 2014, O'Neill et al. 2014). The range of scenarios considered in the IPCC AR5 provided a broad spectrum of potential futures. We integrated RCP and SSP scenarios to ensure that the degree of atmospheric warming indicated by the RCP is consistent with the emissions generated by the socioeconomic activity depicted in the SSP storyline, and that the integrated scenarios do not indicate large departures from current natural resource policies.

The remainder of this chapter describes the process used to select and integrate two global climate and four global socioeconomic scenarios from AR5 into four RPA scenarios

Table 3-1. Characteristics of the four 2020 RPA Assessment scenarios.[a]

Characteristic	Scenario LM	Scenario HL	Scenario HM	Scenario HH
Global warming and U.S. socioeconomic growth	Lower warming and moderate U.S. growth	High warming and low U.S. growth	High warming and moderate U.S. growth	High warming and high U.S. growth
Global real GDP[b] growth, 2020–2070	Medium (4.9X)	Low (3.2X)	Medium (4.6X)	High (6.9X)
Global population growth, 2020–2070	Low[c] (1.2X)	High (1.6X)	Medium (1.4X)	Low (1.2X)
U.S. real GDP growth, 2020–2070	Medium (3.0X)	Low (1.9X)	Medium (2.8X)	High (4.7X)
U.S. population growth, 2020–2070	Medium (1.5X)	Low (1.0X)	Medium (1.4X)	High (1.9X)
Global emissions	Lower	High	High	High
Global scenario links	RCP 4.5-SSP1	RCP 8.5-SSP3	RCP 8.5-SSP2	RCP 8.5-SSP5

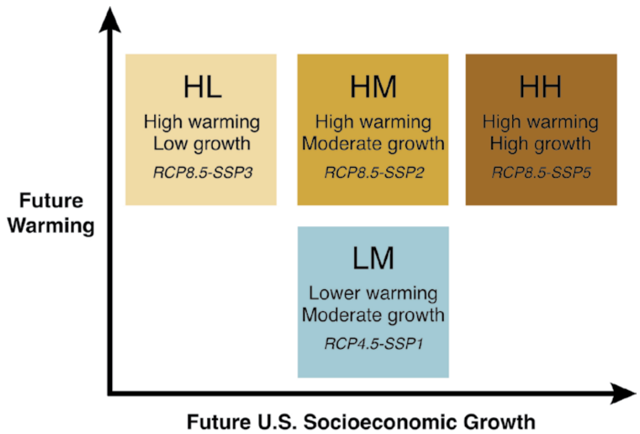
[a] *Numbers in parentheses are the factors of change in the projection period. For examples, U.S. real gross domestic product increases by a factor of 3.0 between 2020 and 2070 in Scenario LM.*

[b] *GDP = gross domestic product (based on estimates by the International Institute of Applied Systems Analysis 2019).*

[c] *Note: Low population involves initial increase with declines in the latter decades of the projection period.*

Source: Langner et al. 2020.

Figure 3-1. Characterization of the 2020 RPA Assessment scenarios in terms of future changes in atmospheric warming and U.S. socioeconomic growth. These characteristics are associated with the four underlying Representative Concentration Pathway (RCP) – Shared Socioeconomic Pathway (SSP) combinations.



Source: Langner et al. 2020.

(table 3-1, figure 3-1), and then downscale associated global climate and socioeconomic projections to a fine-scale resolution across the United States. Scenario "short names" are defined based on the climate scenario's global radiative forcing levels (first letter) and the socioeconomic scenario's U.S. growth characteristics (second letter), as described in the first line of table 3-1. The term "socioeconomic growth" is mainly focused on the rate of positive growth in aggregate economic output and in aggregate disposable personal income in the United States. The rate of population growth differs from the rate of economic growth in each scenario, although the two align in their general trajectories. Similar to the U.S. National Climate Assessment (USGCRP 2017) we label the RCP 4.5 climate scenario as "lower warming" and the RCP 8.5 climate scenario as "high warming." The four RPA scenarios are: lower warming-moderate U.S. growth (LM), high warming-low U.S. growth (HL), high warming-moderate U.S. growth (HM), and high warming-high U.S. growth (HH). The selected scenarios set the socioeconomic and biophysical bounds for evaluating resource futures in the 2020 RPA Assessment. A more extensive description of RPA scenario development is available in Langner et al. (2020).

Climate Scenarios for the 2020 RPA Assessment

In this section we describe the process used to select global climate scenarios and a manageable set of climate projections for the 2020 RPA Assessment. More details can be found in Joyce and Coulson (2020) and Langner et al. (2020).

Global Climate Scenarios

For the IPCC AR5, Representative Concentration Pathways (RCPs) based on radiative forcing represent global climate scenarios (Moss et al. 2010, USGCRP 2017). Radiative forcing is a change in energy flux of the atmosphere (warming or cooling) over time. Between 1750 and 2019, natural and anthropogenic factors have increased radiative forcing by 2.72 Watts/square meter (W m^{-2}), causing the atmosphere to warm during this period (IPCC 2021). RCPs were designed to explore possible climate futures over a wide range of emission levels and the consequences of future increases in radiative forcing by 2100. Components of radiative forcing used as inputs for climate modeling include emissions of greenhouse gases, air pollutants, and land use (van Vuuren et al. 2011). A large radiative force implies a larger change in the climate. Four RCPs were defined by different levels of future radiative forcing: a very low forcing level (RCP 2.6, or 2.6 W m^{-2}); two medium stabilization scenarios (RCP 4.5 and RCP 6.0); and one high forcing level (RCP 8.5) (IPCC 2014).

For the 2020 RPA Assessment, we chose to follow the Fourth National Climate Assessment approach for framing impacts of climate change by using RCP 4.5 and RCP 8.5 as the two bounding climate pathways for RPA projections (Joyce and Coulson 2020, Langner et al. 2020). From a scientific viewpoint, exploring all available alternative futures is desirable. But resource and time constraints, as well as communication challenges, required a narrowing of choices for the RPA Assessment. RCP 2.6 was not included in the RPA Assessment analyses because extensive mitigation policy is required to achieve this lower radiative forcing level, and the RPA Assessment focuses on futures with no significant change from current policy. We also did not consider RCP 6.0 because resource effects from that scenario are likely to fall between RCP 4.5- and RCP 8.5-based analyses. Using both a lower-end and a higher end scenario, RCPs 4.5 and 8.5 respectively, provides a wide range of long-term outcomes.

National Climate Projections

Resource and time constraints also affected the number of climate models and projections selected. Climate modeling institutions across the world have used the RCP data to undertake coordinated experiments with different global climate models. As a result, there are 20 or more climate projections per RCP available as part of the Coupled Model Intercomparison Project, Phase 5 (CMIP5) (https://esgf-node.llnl.gov/projects/cmip5/) (Hayhoe et al. 2017, Knutti and Sedlack 2013). To choose a set of climate models and associated downscaled projections for the 2020 RPA Assessment, we first identified the climate variables needed for the resource analyses and then developed criteria for selecting the climate models and the projections (Joyce and Coulson 2020, Langner et al. 2020).

Based on the resource analysis needs of the 2020 RPA Assessment, the downscaled dataset selected was MACAv2-METDATA (Abatzoglou 2013, Abatzoglou and Brown 2012). This dataset contained statistically downscaled projections from 20 different global climate models, each run under RCP 4.5 and RCP 8.5. The spatial resolution for this downscaled dataset was 4 km (2.5 miles), meeting the fine-scale needs for RPA Assessment resource analyses. Because the RPA Assessment focuses on the next 50 years (through 2070), we selected models that provided temperature and precipitation for this entire period, defining change as the difference between the future period (2041 to 2070) and the historical period (1971 to 2000).

Three criteria were used to screen individual climate models (Joyce and Coulson 2020). The first criterion was historical model performance to eliminate from further consideration those models consistently rated as poor performers (Rupp 2014, 2016, Rupp et al. 2013). The second criterion was that only one model from a modeling institution was selected to reduce the influence of modeling institution on the projections. The third criterion was to choose the same model for RCP 4.5 and RCP 8.5, if possible, to reduce model variability across the RCPs.

We selected five climate models that capture the full range of temperature and precipitation projections across the entire set of models. Ensembles that average projections across models, thereby reducing variability, have often been used to reduce the number of projections. We chose not to use an ensemble, because the individual model variability may be important when these projections are used as inputs in resource modeling efforts such as for water, forest condition, rangelands, and wildlife. We identified four projections that represented the least change and the greatest change in temperature (least warm, hottest) and the largest decrease and greatest increase in precipitation (driest, wettest) for the conterminous United States. Although these models each represent the magnitude of change for one climate variable, knowledge of what each model projects for the other climate variable (Joyce and Coulson 2020) is important for proper application of the information: models selected to represent the magnitude of change for one climate variable (such as temperature) may not project the mid-range value for the other climate variable (such as precipitation). A fifth projection was selected that was close to the mean change in temperature and precipitation of all model projections. We were able to select the same models for both RCP 4.5 and RCP 8.5 for all variables.

This set of five models provides a reasonable approximation of the overall projected temperature and precipitation space encompassed by the larger set of 20 models, but a greatly reduced total effort, thereby making the subsequent analysis feasible (table 3-2). Monthly downscaled projections for the conterminous United States were obtained and archived in the U.S. Department of Agriculture, Forest Service's Research Data Archive, along with the historical climate observations that were used in the MACA downscaling process (Coulson and Joyce 2020, Joyce et al. 2018); downscaled daily projections are available on request.

Although beyond the scope of the 2020 RPA Assessment, Joyce and Coulson (2020) also evaluated the utility of the RPA climate model selections for behavior at end of century (2070 to 2099) and for regions of the National Forest System (NFS). See the sidebar Using Scenarios and Projections in Resource Management Planning for a description of how planners might think about using climate projections. See Joyce and Coulson (2020) for more detailed information about the selection and utility of RPA climate model selections.

Socioeconomic Scenarios for the 2020 RPA Assessment

In this section we describe the process used to select global socioeconomic pathways and create nationally downscaled socioeconomic data for the 2020 RPA Assessment. More details on scenario selection can be found in Langner et al. (2020), and more information on the downscaling process can be found in Wear and Prestemon (2019a).

Global Socioeconomic Scenarios

Shared Socioeconomic Pathways (SSPs) were developed in parallel to the RCPs to provide scenarios of plausible societal development in support of the IPCC assessment process (O'Neill et al. 2014). They consist of distinct storylines that capture uncertainty about the future across

Table 3-2. Climate model projections selected to reflect different U.S. climate futures in the year 2070.

	Least warm	Hot	Dry	Wet	Middle
Climate model	MRI-CGCM3	HadGEM2-ES	IPSL-CM5A-MR	CNRM-CM5	NorESM1-M
Institution	Meteorological Research Institute, Japan	Met Office Hadley Centre, United Kingdom	Institut Pierre Simon Laplace, France	National Centre of Meteorological Research, France	Norwegian Climate Center, Norway

Source: Joyce and Coulson 2020.

Using Scenarios and Projections in Resource Management Planning

Climate change will continue to affect the natural resources and ecosystem services that are managed by Federal, State, and private landowners. Managers have a long experience with their local weather, climate, and resource conditions; the challenge is anticipating how future climate change will affect the resources. Just as historical observations can give a picture of past climate, monthly and annual climate projections can offer a plausible future climate, based on assumptions about atmospheric warming related to emissions, land use change, and our understanding of the Earth system. Working with a set of plausible future climate projections can facilitate identifying future risks, both in terms of future climate outcomes as well as the transitions that lead to those outcomes.

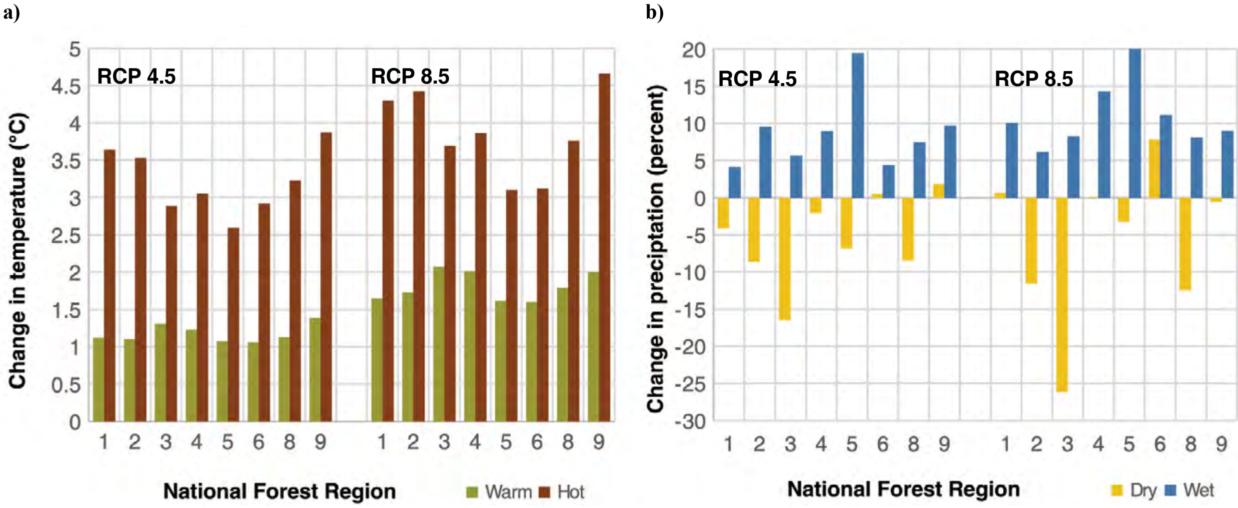
Land managers and planners might first ask how far in the future is information needed—5 years, 50 years, or 80 years? For example, because trees can live longer than 50 years and infrastructure planning often extends beyond the next decade, examining the more distant future climate might be important. Model selection for the RPA scenarios was based on behavior through 2070 but our analysis concluded that the same core models could be used to capture the range of climate futures for an end-of-century analysis (2070 to 2099). Managers and decisionmakers might also consider possible transitions from today's conditions to the alternative outcomes depicted by the RPA scenarios and climate projections. Many changes occur as systems encounter thresholds and transition from one state to another, sometimes with extreme consequences and needs for rapid, even large-scale interventions. Understanding and navigating these transitions can create additional opportunities for mitigation and adaptation.

Planners and managers might also ask which and how many plausible futures to examine. An overwhelming number of climate projections are available, and each projection offers insight into the future. The ensemble (or average of many projections) is often used to capture the trend; however, individual model variability may be important in managing risks to resources. RPA projections were selected with the objective of identifying a feasible set of projections that describe the range of future climates—hot, least warm, dry, wet, and middle—to represent the bounds of the most likely climate outcome based on our current knowledge. Examining this range of futures can allow planners and managers to assess potential future vulnerabilities and possible worst-case scenarios. Resource managers can also compare their past experiences with a plausible future. For example, if the recent climate has been hot, exploring the "hot" projection allows examination of the additional stress that could be placed on the resource in the future.

Figure 3-2. Relative comparisons of change by mid-century (2041 to 2070) from the historical period (1971 to 2000) between RPA climate model projections across National Forest System regions for (a) temperature and (b) precipitation under (left) RCP 4.5 and (right) RCP 8.5. Figures show that in all NFS regions: (a) the hot RPA projection (HadGEM2-ES) is always hotter than the least warm projection (MRI-CGCM3) and (b) the wet RPA projection (CNRM-CM5) is always wetter than the dry projection (IPSL-CM5A-MR).

a)

b)

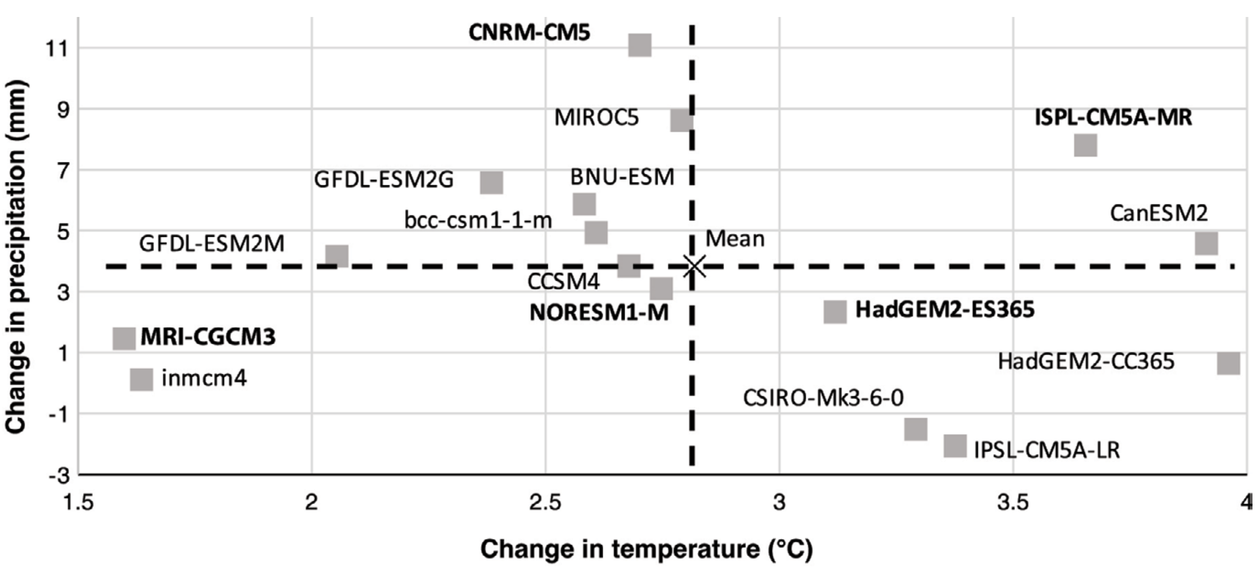


RCP = Representative Concentration Pathway.

RPA projections were selected based on results for the conterminous United States, but planners might instead be focused on a more specific spatial extent, such as a National Forest System (NFS) region (Joyce and Coulson 2020). Do the RPA projections represent the same climate futures at the regional scale? Regional climates vary greatly across the United States—for example, the dry Southwest and the wet Pacific Northwest. At the NFS regional scale, the relative comparisons are appropriate for all regions: the hot RPA projection is always hotter than the least warm projection and the wet projection is always wetter than the dry RPA projection in each region (figure 3-2). Consequently, projections used in this report have comparative value for NFS regions; however, alternative projections might be preferable for individual NFS regions. Joyce and Coulson (2020) analyzed all 20 MACAv2-METDATA climate models by NFS region to determine whether a different model might produce better absolute results for a given NFS region. In some situations, a different climate model was a better representative of the range within the region. For example, while the RPA wet model projects wetter conditions than the dry model in all NFS regions, the dry model projects wet conditions for NFS Region 6 (Pacific Northwest) while other climate models project a very dry future (figure 3-3). The relative comparisons between the wet and dry projections are appropriate for NFS Region 6, but planners and managers for this region may want to examine a different projection to specifically plan for a dry future. We direct planners and managers to the analysis in Joyce and Coulson (2020) to explore the relative ranking of climate models at the regional scale, but encourage use of the RPA climate model selections when possible as this also enables use of the associated RPA resource projections.

These climate projections, alongside socioeconomic projections and future land use projections, are used in the RPA Assessment chapters to project plausible future condition and availability of renewable resources. In addition to temperature and precipitation change, other climate variables are part of the climate dataset (such as potential evapotranspiration) and have been used in projecting the influence of future drought on resource availability. In addition to using climate projections directly as described here, managers and planners can examine the socioeconomic projections described later in this chapter, as well as the associated resource projections throughout the RPA Assessment to assess the plausible range of vulnerabilities and possible worst-case scenarios in future resource availability and condition. The projections provided throughout the 2020 RPA Assessment are based upon the same core scenarios and rely on the same five climate models—all selected to encompass the range of plausible socioeconomic and climatic futures. Resource projections can therefore also be interpreted and implemented as described above (e.g., examining future resource condition and availability specifically associated with lower or high atmospheric warming, different levels of future socioeconomic growth, and different climate futures).

Figure 3-3. Projected changes for NFS Region 6 (Pacific Northwest) in annual precipitation (percent) at mid-century (2041 to 2070) from the historical period (1971 to 2000) under RCP 8.5. While the RPA dry model (IPSL-CM5A-MR) projects a drier future than the RPA wet model (CNRM-CM5), the dry model does project an increase in precipitation at mid-century, and there are many models which project a decrease in annual precipitation in this region. Model names in bold are the national core RPA models for mid-century: least warm—MRI-CGCM3; hot—HadGEM2-ES; dry—IPSL-CM5A-MR; wet—CNRM-CM5; middle—NORESM1-M.



several variables: population, economic growth, technology, trade, and governance. Five SSPs were developed, with each described in terms of the challenges, costs, research and development investments, and degree of policy changes involved in mitigating or adapting to climate change. Four of the SSPs describe the range of high challenges (difficult, costly, and entailing large policy shifts) and low challenges for global adaptation and mitigation, while a fifth SSP defines an intermediate case. Although the SSPs capture a range of future levels of socioeconomic growth, no SSP envisions a future that entails sustained negative growth. The SSPs do not include climate feedbacks or specific policy options (O'Neill et al. 2014).

Three different modeling groups developed country-level projections of both population and income consistent with SSP global narratives. For the 2020 RPA Assessment, we relied on the economic projections provided by the International Institute for Applied Systems Analysis (Cuaresma 2017, IIASA 2018) because IIASA included more country-level projections that are important for modeling international trade flows as applied in RPA modeling of global wood products markets. To develop national socioeconomic projections linked to the global SSPs for use in the RPA Assessment, we focused on SSP variation in demographic and economic characteristics, which have been quantified at the country level (data available on the SSP public database at https://tntcat.iiasa.ac.at/SspDb/dsd?Action=htmlpage&page=welcome).

Global and U.S. trends do not necessarily follow the same trajectory across SSPs: global population trends and U.S. population trends diverge, while U.S. trends in GDP growth are more consistent with global trends (Langner et al. 2020). These patterns are tied to several interacting assumptions about economic growth, fertility and mortality, migration patterns, and the openness of the global economy. As with our climate pathway and projection selections, resource and time constraints limited the number of SSPs selected. After performing the downscaling analysis described in the next section, we selected four of the five SSPs to capture the magnitude of change in socioeconomic conditions across the entire set (Langner et al. 2020). We chose SSP3 and SSP5 because they bound the demographic and economic change (low and high change, respectively) for the United States and capture most of the range in global change as well. SSP1 and SSP2 follow similar trajectories for the United States and globally; however, the underlying narrative for these pathways offers opportunities to explore differences among resource- and sector-specific variables that could have different implications for natural resources. For example, the narrative for SSP1 is focused on low-emission energy sources, whereas SSP2 is more tightly linked to historical patterns of energy use. Therefore, we decided to retain both SSP1 and SSP2. We eliminated SSP4 because its trajectory falls between SSP3 and SSP2.

National Socioeconomic Projections

Considerable effort by the climate science community devoted to downscaling climate projections eliminated the need to develop our own downscaled climate data for the 2020 RPA Assessment. No similar effort had been devoted to socioeconomic scenarios—specifically to jointly downscaling the SSP-based population and economic projections. Projections of population and income that are downscaled using a consistent approach are critical inputs to various RPA modeling systems because they play a central role in determining natural resource demands and impacts across the United States; we therefore developed a methodology to downscale the country-level SSP data to a finer spatial scale (Langner et al. 2020, Wear and Prestemon 2019a). This approach was based on economic theory and is consistent with county-scale historical patterns of change (Wear and Prestemon 2019a). Although these projections capture recent historical trends in climate, they do not explicitly account for changing climate variables when projecting to 2070, resulting in considerable uncertainty, particularly in the latter years of the projections. Rising sea levels, extended droughts, and extreme heat could potentially alter not just the magnitude but also the direction of historical trends, which is not incorporated into existing projections. We hope to examine the possible implications of directional changes in historical trends through future research.

We applied the methodology to estimate county-level projections for all five SSPs (Wear and Prestemon 2019a). In these projections, the rate of personal income change nationwide (summed across all counties) was constrained to match the rate of GDP change nationwide as projected by IIASA (2018) for the United States for each of the SSPs. Under SSP3, population grows slowly to a peak in 2035 and then gradually declines to 2010 population levels by 2070, while income grows steadily at about 1 percent per year (from about $13 billion in 2010 to about $24 billion in 2070). Under SSP5, population expands by 86 percent, from 313 million to 581 million between 2010 and 2070, while real GDP grows at a rate of 2.5 percent per year between 2010 and 2070, more than quadrupling over this period. SSPs 1, 2, and 4 provide intermediate projections with population growing to between 390 million and 451 million people in 2070 and annual GDP growth rates of between 1.4 and 1.8 percent.

In terms of population, we project a shift in the Nation's population away from the Northeast and Midwest and toward the South and West, although the rates of such interregional population shifts vary across SSPs; the smallest shifts occur under the lowest population growth rate. Projections indicate that a large share of the current rural United States will experience either new or continued population losses or stable population across all scenarios while urban areas expand (see Wear and Prestemon

2019a for details). As described above, only downscaled socioeconomic projections for SSPs 1, 2, 3, and 5 were used to support resource projections in the 2020 RPA Assessment. The observed county-level population and personal income data from 2010 and projections over the 2015 to 2070 period used in the 2020 RPA Assessment are archived in the USDA Forest Service's Research Data Archive (Wear and Prestemon 2019b).

2020 RPA Scenarios

RPA scenarios were constructed by linking the RCPs (climate futures) with SSPs (socioeconomic futures). The RCPs and SSPs were developed to provide a scenario matrix architecture to assist in the development of common scenarios that can be used across different climate change research communities. While the RPA Assessment scenarios need to link to the general worldviews of the RCP and SSP futures, they also must provide a compelling range of futures for the United States and be available at the fine spatial scale needed to match the economic and ecological context of the RPA resource analyses.

As described above, RCPs 4.5 and 8.5 were selected as low and high bounding pathways to capture the range of plausible warming futures, and SSPs 1, 2, 3, and 5 were selected to capture the range of socioeconomic change; this resulted in eight possible RCP-SSP combinations for the 2020 RPA Assessment scenarios. When paired with the five climate projections, we were facing 40 potential future socioeconomic-climate outcomes for the United States—exceeding the analytical capacity of the Assessment. However, not all potential RCP-SSP combinations could be plausibly linked (Riahi et al. 2017). To link an RCP and SSP into an integrated scenario, the degree of atmospheric warming indicated by the RCP must be consistent with the emissions generated by the socioeconomic activity depicted in the SSP storyline. Because the RPA Assessment analyses are based on continuation of current policies, we selected RCP-SSP combinations that did not require assumptions that would indicate large departures from current policies for the RPA Assessment scenarios (Langner et al. 2020).

We paired RCPs and SSPs using the following logic. SSP1 is the only baseline scenario that resulted in radiative forcing close to the RCP 4.5 level and was judged to be the only SSP that could plausibly link with RCP 4.5 for RPA Assessment purposes. Combining any of the remaining SSPs with RCP 4.5 would require varying levels of technology or policy assumptions that are beyond the scope of RPA Assessment analyses except when the RPA framework is used specifically for policy analysis. SSP5 can be plausibly linked with RCP 8.5 for Assessment purposes. The remaining SSPs—SSP2 and SSP3—produced forcing levels between RCP 6.0 and RCP 8.5. Because we paired these SSPs with RCP 8.5-based climate projections, our results could overstate climate influence.

We acknowledge that many pairings might be plausible (assessing the mutual consistency of their assumptions is inexact); however, we selected four RCP-SSP combinations to underpin 2020 RPA Assessment analyses of resource effects without significant policy changes (table 3-1, figure 3-1). The four 2020 RPA Assessment scenarios encompass most of the projected range of climate change from the RCPs and projected quantitative and qualitative range of socioeconomic change from the SSPs, resulting in four distinct futures that vary across a multitude of characteristics (figure 3-4). The range of changes in global and U.S. characteristics is similar between the 2010 and 2020 RPA Assessment scenarios. For the United States, economic and population growth trends initially move in the same direction across scenarios (with population growth turning to shrinkage under SSP3 for the United States after 2040), whereas globally, economic and population growth diverge in three of the four scenarios. These quantitative trends and narratives provide a unifying framework that organizes the RPA Assessment natural resource sector analyses around a consistent set of possible world views.

Linking 2020 RPA Assessment Scenarios to Natural Resource Sectors

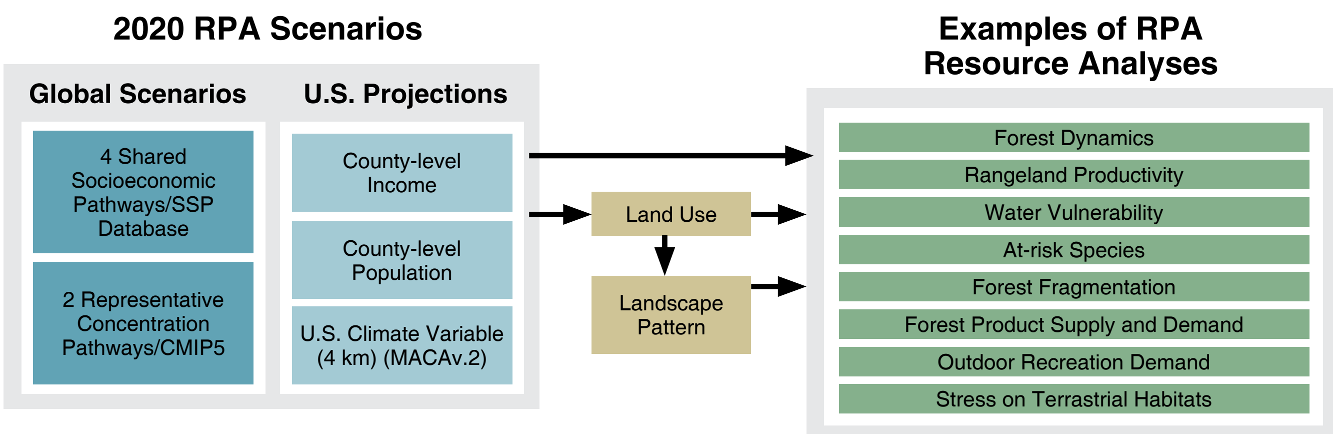
Defining the 2020 RPA Assessment scenarios is the beginning of the RPA analysis process. The RPA scientists then determine how to use the scenario data and assumptions in their resource sector analyses. Each analysis uses different combinations of the scenario variables and resource-specific variables to evaluate future resource outcomes. Examples of connections between components of the 2020 RPA Assessment scenarios and RPA Assessment resource analyses (figure 3-5) illustrate the numerous routes through which the scenario variables can influence resource analyses. In some cases, both socioeconomic and climate projections are direct inputs to resource analyses, including outdoor recreation demand, water vulnerability, and forest product supply and demand. In other cases, only the climate variables are direct inputs to the analyses, for example, in projections of rangeland productivity and stress on terrestrial habitats.

Land use and landscape pattern projections are often the intermediary between the scenarios and resource-specific effects (figure 3-5). The land use projections incorporate the U.S. climate and socioeconomic projections. In turn, the landscape pattern projections are based on the land use projections (Brooks et al. 2020). Land use projections are strongly influenced by population and economic drivers; changes are more rapid and more extensive in futures of higher populations or more rapid economic growth (or both). Analyses that rely only on the land use or landscape

Figure 3-4. Characteristics differentiating the 2020 RPA Assessment scenarios. These characteristics are associated with the four underlying Representative Concentration Pathway (RCP) – Shared Socioeconomic Pathway (SSP) combinations.

RPA Scenario (RCP-SSP)	Global Temperature Rise	U.S. Population Growth	U.S. Economic Growth Rate	Bioenergy Demand	Energy Sector Focus	Global Energy Usage	International Trade Openness
LM Lower warming Moderate growth *RCP4.5-SSP1*	Lower	Medium	Medium-High	High	Renewables	Low	Medium
HL High warming Low growth *RCP8.5-SSP3*	High	Low	Low	Low	Fossil fuels	Medium	Low
HM High warming Moderate growth *RCP8.5-SSP2*	High	Medium	Medium	Medium	Mixed	Medium	Medium
HH High warming High growth *RCP8.5-SSP5*	High	High	High	High	Fossil fuels	High	High

Figure 3-5. Pathway for incorporation of global scenarios into RPA resource analyses. Global scenario projections are downscaled across the U.S. and either incorporated directly into RPA resource analysis or indirectly (through land use/landscape pattern projections). RPA resource analyses are examples and not intended to be an exhaustive list.



Source: Langner et al. 2020.

patterns incorporate the scenario variables indirectly, instead of directly modeling the effects of climate, population, etc. More information about the land use and landscape pattern projections are available in the Land Resources Chapter.

Additionally, some resources factor individual scenario storylines into their model-based assumptions. In the case of forest products, for example, in addition to the direct incorporation of scenario variables, the FOrest Resource Outlook Model (FOROM) of global trade also incorporates differences across scenarios in trade openness, technology change rates, production and consumption increases in wood-based bioenergy, and forest growth rate changes globally and domestically (Johnston et al. 2021).

Langner et al. (2020) provides a broad overview of the four 2020 RPA Assessment scenarios, focusing on how the climate and socioeconomic projections and qualitative aspects of each scenario may affect natural resource conditions and trends. The individual RPA Assessment resource chapters provide quantitative modeling results and a tangible picture of the plausible future of these resources absent intervention.

Conclusions

The RPA scenarios and their underlying assumptions provide a common and coherent framework for developing projections of natural resource impacts in the RPA Assessment. Built from the IPCC global Representative Concentration Pathways and Shared Socioeconomic Pathways, these national, downscaled scenarios address the legislative mandate for RPA resource projections. Because the RPA scenarios and climate models were selected to capture the range of plausible future climate and socioeconomic variability, the future of global and domestic natural resources can differ substantially across the four scenarios and 20 scenario-climate futures. Projecting the range of plausible futures for our natural resources allows for a better understanding of how the underlying climate and socioeconomic drivers of change can alter natural resource conditions and create challenges across the United States.

COVID-19 Implications on RPA Scenarios

The SARS-CoV2 virus and associated COVID-19 illness were first identified at the end of 2019, and the World Health Organization declared a global COVID-19 pandemic on March 11, 2020. The COVID-19 disease resulted in widespread public health and economy-wide impacts. Governments around the world implemented strict lockdown regulations to contain the spread of the virus, which, along with fears of contracting the COVID-19 illness, shrank economic activity to lows not experienced in decades and global emissions to levels not experienced since the early 2000s. While the economic contraction was worse than the 2007 to 2009 financial crisis and associated deep recession, growth returned more quickly due to fiscal support in a few large economies and the arrival of vaccines (International Monetary Fund 2021). The U.S. recession was the shortest on record, at 2 months, and U.S. real GDP exceeded its pre-COVID level by the second quarter of 2021 (USDC Bureau of Economic Analysis 2021). Emissions also rebounded rapidly alongside economic activity; global emissions in December 2020 were 2 percent higher than in December 2019 (IEA 2021).

Other COVID-19 related disruptions appear to be longer lasting. U.S. metropolitan areas have seen dense urban core populations shift into the outer suburbs, primarily an acceleration of pre-pandemic trends and likely due to the proliferation of remote work (Patino et al. 2021). Visitation to public lands increased significantly during the pandemic, with campgrounds seeing a nearly 40-percent increase in average nightly reservations in 2020, and visitation to undeveloped general forest settings rising by more than 50 percent when compared with 2015 (see the Outdoor Recreation Chapter). Global supply chains—already stressed before the pandemic due to trade tensions, particularly between the United States and China—have seen significant disruptions and delays due to the collapse and subsequent increase in consumer demand, leading to higher consumer prices for many commodities and at least temporary inflation. The U.S. labor market has also experienced disruptions, beginning with significant unemployment during lockdown (defined by stay-at-home orders and mass quarantines) and followed by labor shortages in certain industries. The U.S. forest products sector experienced supply and demand dynamics to extents not historically registered, behaviors all linked to COVID-19 directly (illness-related mill staffing shortages) or indirectly (see Forest Products Chapter).

More than 2 years into the pandemic, it is not known if or how these disruptions will influence long-term trends. For example, the effects on Federal lands visitation from other significant events in recent decades (e.g., the September 11, 2001, terrorist attacks, the 2007 to 2009 Great Financial Crisis, and spikes in gasoline prices) have been transitory. Alternatively, Natural Resources Institute Finland (UNECE 2021, Viitanen et al. 2020) predicts permanent effects on forest products markets, for example the demand for tissue and hygiene paper products as well as some packaging materials is predicted to permanently shift upward, due to an increased demand for products that support greater hygiene and increased e-commerce, respectively.

The RPA scenarios were developed before the arrival of the global pandemic and associated global recession. The RPA scenario development and associated downscaling process described in this chapter is a multi-year process, and downscaled projections are necessary inputs to subsequent resource modeling efforts. A potential concern is that the scenario-based modeling of alternative futures employed in the RPA Assessment would have been different had the full implications of COVID-19 been known. We assert that the currently understood implications of COVID-19 would not alter our RPA scenario development to any considerable degree. As described in this chapter, the RPA scenarios originate with global scenarios produced by the IPCC. The IPCC has not released revised global scenarios because of the pandemic. Any changes to the RPA scenarios would therefore be disconnected from global projections and assumptions, resulting in obstacles and inconsistencies in our globally linked analyses (for example, our analyses of forest product markets). In addition, the RPA scenarios were selected to encompass the range of plausible socioeconomic and climate futures, incorporating low- and high-warming futures alongside a wide variety of socioeconomic futures and climate models that cover the boundaries of existing climate projections. These scenarios would only be irrelevant if effects of COVID-19 permanently force the U.S. socioeconomic or climate futures beyond these boundaries; early data and patterns from the past year suggest that this is unlikely. The pandemic is more likely to change the magnitude of important model parameters than to change the direction of their effects, meaning that we are more likely to see temporary changes to or permanent intensifications of existing trends than wholescale upheavals of longstanding patterns and relationships.

As the pandemic progresses and hopefully ends, data will continue to be collected about consequences of COVID-19 that could have implications for renewable resources in the United States. We will continue to monitor new data and hope to assess potential long-term impacts in our next Assessment. Early data is analyzed for several resources in this Assessment—see COVID-19 sidebars in the Disturbance Chapter, the Forest Products Chapter, and the Outdoor Recreation Chapter for analyses of the effects of early stages of the pandemic on these resources.

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Chapter 4

Land Resources

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The land resources of the United States have experienced significant changes since the 2010 Resources Planning Act (RPA) Assessment, and continual change is expected in most landscapes because of both natural and human actions. This chapter summarizes recent trends of land use and land cover across the conterminous United States and presents future projections to 2070 based on RPA scenarios. We begin by highlighting the key findings from a supporting RPA analysis of historical changes in the land base and evaluating how recent land cover changes affect landscape patterns including forest fragmentation. We then summarize land use projections under future scenarios and evaluate projected changes in impervious and tree covers and landscape patterns. Geographic regions reported in this chapter generally follow the RPA regions (as shown in figure 2-1 in the Introduction Chapter), except that the States of Alaska and Hawaii are not included. Later chapters provide more information about the condition and health of forests, rangeland, and other specific land resources.

Key Findings

- ❖ Developed lands continue to encroach on natural ecosystems and agricultural areas, with about half of new developed lands converting from forest or rangeland.
- ❖ Developed lands are projected to continue to expand in all scenarios, although less than projected in the 2010 RPA Assessment. The expansion of developed lands varies across regions and is projected to be larger under high socioeconomic growth scenarios and smaller under hotter climate futures.
- ❖ Forest land area increased slightly over the past decades, mostly at the expense of pasture and crop land areas. This trend is expected to shift to decreasing forest area under all scenarios, although at lower rates than projected by the 2010 Assessment.
- ❖ Forest cover fragmentation slowed over the past decade but continues overall and is expected to continue into the future for the western and southeastern subregions, while decreasing slightly in the north and central subregions.
- ❖ Changes in unfragmented forest land cover are more dynamic in private forests of the South, while changes in the West are slower and concentrated in public lands.
- ❖ Most forest lands remain in "natural" landscapes, but an increasing proportion is expected to be in "interface" landscapes near developed or agriculture use in the future.
- ❖ Economic and regional factors tend to be more important drivers of land use area changes than changes in climatic conditions.

Historical Land Use and Land Cover

- ❖ According to National Resources Inventory data, developed lands had the largest net increase of all land uses from 1982 to 2012—with forest and agriculture (crop and pasture) lands contributing about equally to new developed land—while crop lands had the largest decrease. Forest gains from other land uses (primarily from converted pasture) exceeded forest losses to other land uses (mostly to developed), resulting in a slight net increase in forest land area.
- ❖ Developed land area expanded at an increasing rate from 1982 to 1997, then continued to expand at a decreasing rate until 2012.
- ❖ Changes in the U.S. land base differ depending on whether land use or land cover is being examined. After 2000, changes in land use and land cover across the conterminous United States were broadly similar for agriculture and developed land, but less so for forest land. The differences in forest change between land use data and land cover data were mostly due to temporary losses of forest cover (canopy disturbances such as harvest or wildfire) that did not change the forest land use.

Maintaining productive forests and rangelands requires monitoring of those resources and analysis of change in relation to society's changing needs and expectations as well as a changing climate (see the sidebar Forest Carbon Land Base). Changes in U.S. forests and rangelands affect their associated resources, underscoring the importance of monitoring and examining trends in land use and land cover. Because the RPA Assessment is a multi-resource assessment where social, economic, and biological dimensions are all important, both land use and land cover perspectives are considered. This section summarizes the key findings from a recent RPA Assessment of land resources across the conterminous United States (Nelson et al. 2020) and describes the data used for the future projections of land resources later in this chapter. The RPA land base analyses use data from four primary sources: the U.S. Department of Agriculture, Forest Service Forest Inventory and Analysis Program (FIA) (land use in Burrill et al. 2018); the USDA Natural Resources Conservation Service National Resources Inventory (NRI) (non-Federal land use in USDA 2015); the National Land Cover Database (NLCD) (land cover in USGS 2019a, b, c, d); and the U.S. Census Bureau (USCB) (human demographics in U.S. Census Bureau 2017a, b). In general, gross change for a given category of land use or cover refers to area transitions to (gross loss) or from (gross gain) another category. Net change refers to the difference between the area in a category at different times. Net percent change is calculated as the ratio of net area change to the area at the first time.

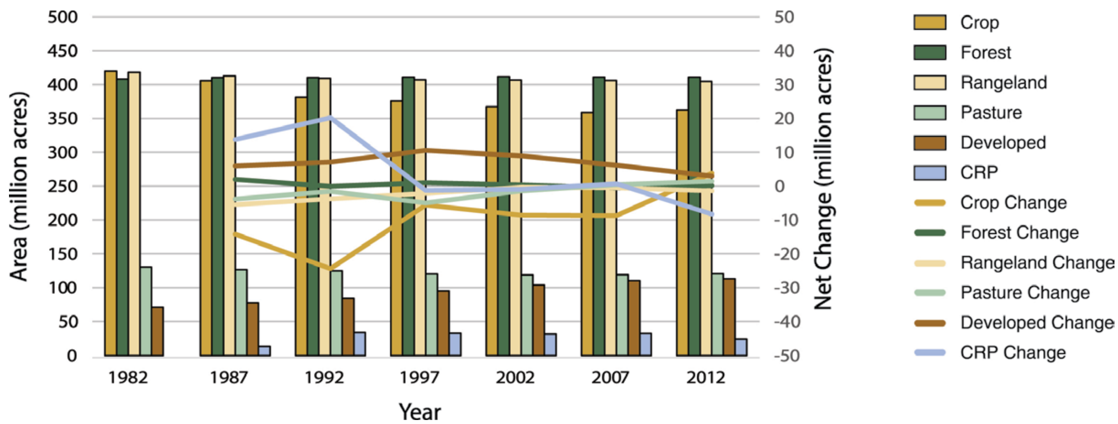
Land use refers to the social and economic intent for which land is used, while land cover refers to the vegetation, exposed land surfaces, water, and artificial structures covering the land surface at a given time (Coulston et al. 2014). Land use classes often incorporate both past use and intended future use, in addition to current conditions, while land cover classes relate to conditions only at a specific time (e.g., the instant at which satellite imagery is acquired). For example, substantial loss of tree canopy (e.g., due to wildfire, wind, or harvest) results in temporary loss of forest cover during the subsequent changes from bare ground to grass and shrub, but ultimately the area is again classified as forest cover when trees attain sufficient height and cover. However, the forest land use of that same disturbed area does not change because no permanent land use change occurred. Many inconsistencies between land classifications relate to differences in the temporal framework of definitions and observations. Therefore, the choice of one land classification system over another depends on the specific resource question being asked, the data available to address the question, and the timeframe of the analysis.

In this report we use two complementary USDA inventories (FIA and NRI) to represent current and projected future land use conditions. These inventories are based on statistical samples of plots, precluding their use for spatially explicit analyses such as landscape pattern assessment for which land cover data (NLCD) are better suited. Each of the following sections refers specifically to "land use" or "land cover" depending upon which data were used. While it is sometimes possible to compare estimates of land cover and estimates of land use, such comparisons often reveal only the definitional or temporal differences between data sources. In some cases, both types of data have been integrated to improve the interpretation of results.

National Resources Inventory on Non-Federal Land

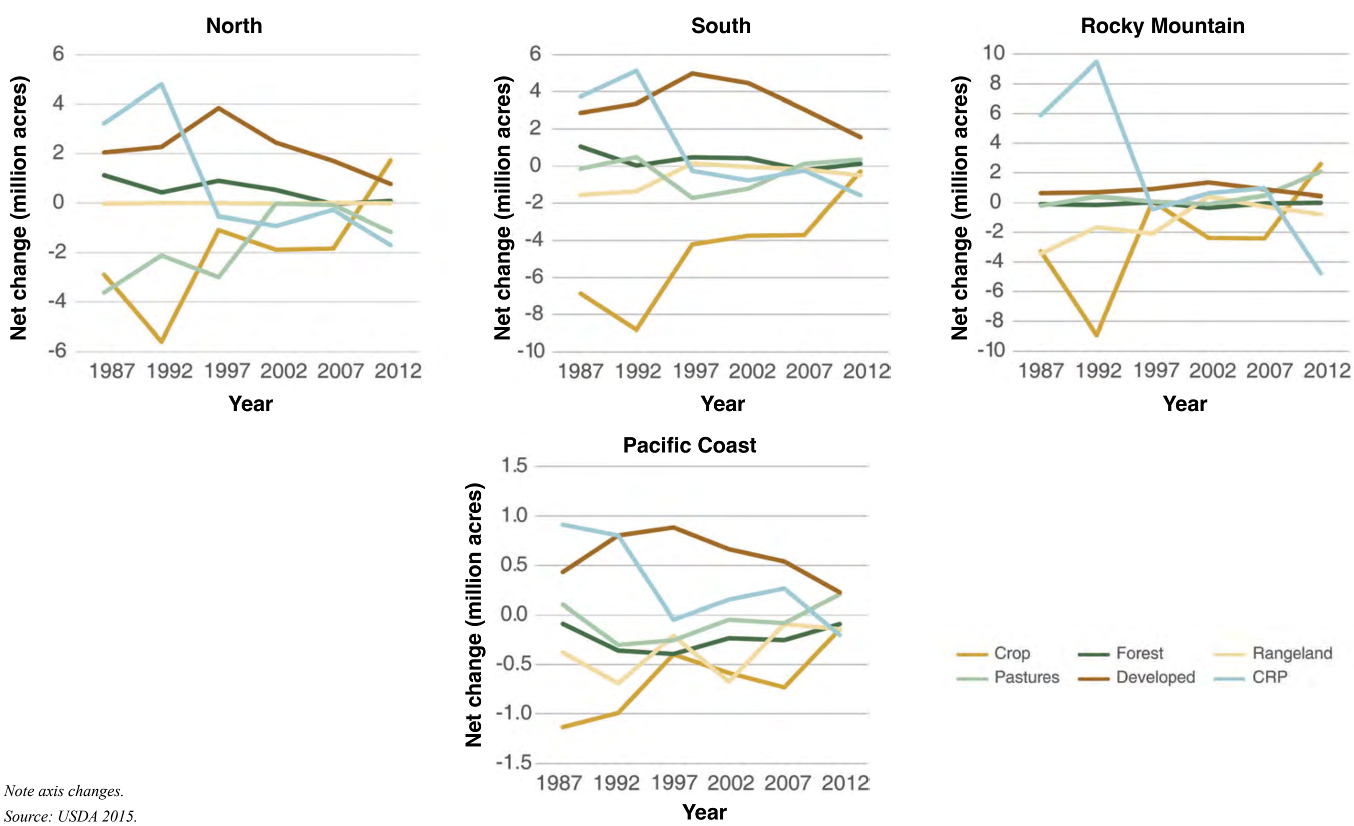
NRI estimates of land use status and trends are based on 5-year reports spanning a 30-year period (1982, 1987, 1992, 1997, 2002, 2007, 2012). The 2017 NRI Report was published after completion of RPA analyses of land use status and future projections. Results for NRI 2017 are generally similar to 2012 but are not included here. Forest land use comprised the largest share of non-Federal land in 2012 (411 million acres, 26.8 percent), followed closely by rangeland (405 million, 26.4 percent) (Nelson et al. 2020). Between 1982 and 2012, there were net losses of crop, pasture, and rangeland area, and net gains of forest, developed, and Conservation Reserve Program (CRP) area (figure 4-1). There was no CRP area in 1982 because CRP enrollments began in 1986. Crop land had the largest area decline (approximately 57 million acres), while developed land had the largest increase (approximately 42 million acres). While forest land area had only a slight increase during this period, there was significant gross change (i.e., forest area converted both to and from other uses). The largest loss of forest land was the approximately 18 million acres converted to developed land, and the largest gain in forest was the approximately 20 million acres converted from pasture. Net loss in rangeland was caused predominately by conversions to crop, developed, and pasture lands, but losses were partially offset by conversions to rangeland from crop, pasture, and forest lands. These cumulative changes result from periodic net changes which emphasize different types of transitions over time at the scale of both the conterminous United States (figure 4-1) and RPA regions (figure 4-2).

Figure 4-1. NRI area trends in land use classes (bars) and 5-year net change in land use classes (lines) in the conterminous United States from 1982 to 2012.



Source: USDA 2015. (Adapted from Figure 3 in Nelson et al. 2020.)

Figure 4-2. NRI trends in 5-year net area change in land use classes from 1987 to 2012 by RPA region.



Note axis changes.

Source: USDA 2015.

Forest Carbon Land Base

The forest land base of the United States offers many ecosystem services. One important service is the removal of carbon dioxide (CO_2) from the atmosphere. As part of the United States' commitment to the United Nations Framework Convention on Climate Change (UNFCCC), estimates of emissions and removals of CO_2 and other greenhouse gases are reported annually, not only for forest but across all land use categories and sectors of the economy in the National Inventory Report (NIR) (US EPA 2020). The land use definitions used in the NIR follow the Intergovernmental Panel on Climate Change (IPCC) guidelines for national greenhouse gas inventories (see Eggelston et al. 2006). These land use definitions differ from those used in this chapter. The purpose of this sidebar is to describe recent trends in the forest land base used for United States carbon reporting.

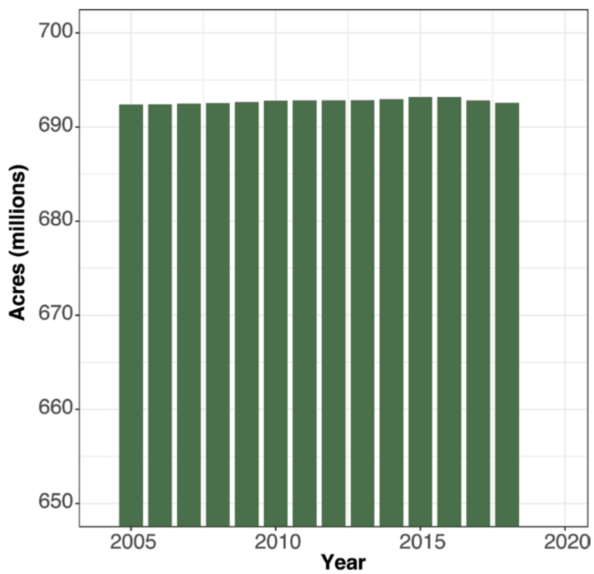
United States forests (including Alaska and Hawaii) and the harvested wood products obtained from them offset the equivalent of 11 percent of CO_2 emissions from other sectors each year (see the Forest Resources Chapter for carbon projections). Forest information is reported as part of the Land Use, Land Use Change, and Forestry chapter of the NIR, following IPCC good-practice guidelines. There are two important practices related to the reported forest land use information: only managed lands are considered (97 percent of all forest land is considered managed; Ogle et al. 2018), and land converted to forest is tracked separately from "forest remaining forest" for a period of 20 years after conversion (Eggelston et al. 2006). After that 20-year period, the converted land may be considered as forest remaining forest. Adhering to those practices results in estimates of the forest land base that differ from other estimates in this report.

The information contained in the NIR, along with projections of CO_2 emissions and reductions, inform the nationally determined contribution (NDC) for the United States under the Paris Agreement. NDCs for each country articulate efforts to reduce national emissions and adapt to the impacts of climate change. The United States accounts for emissions reductions in the land sector with 2005 as the base year. The data, methods, and models used to estimate emissions and removals are applied consistently over the entire UNFCCC reporting period (from 1990 until two years before the present), facilitating proper accounting. In 2023, the most recent estimates of land sector emissions and removals will be subtracted from the estimates in the base year 2005 to determine the contribution of the land sector and the land use categories within it to the U.S. NDC. This means that estimates of the forest land base and the carbon stocks and changes on that land base are of critical importance.

Since 1990, the area of forest remaining forest has been relatively stable at approximately 692 to 693 million acres. Losses that occurred through the 1990s were generally offset by gains in forest remaining forest from 2005 to 2016 (figure 4-3). In 2017 and 2018, there were losses in forest remaining forest of approximately 0.4 and 0.3 million acres respectively (figure 4-4). The dominant transitions into and out of forest involved the grassland, cropland, and settlement land uses. Since 1990, 79 million acres of grassland and 11 million acres of cropland have been converted to forest land. These gains were offset during that period by forest losses of 41 million acres to grassland, 8 million acres to cropland, and 35 million acres to settlement. The annual conversion rate of grassland to forest has sharply declined since 2013 from a peak of about 3 million acres per year to 2.45 million acres per year, while reciprocal conversion remained relatively stable at about 1.5 million acres per year (figure 4-4). The rate of forest conversion to settlement increased from 1990 to 2005 and has been relatively stable since then at approximately 1.4 million acres per year (figure 4-4).

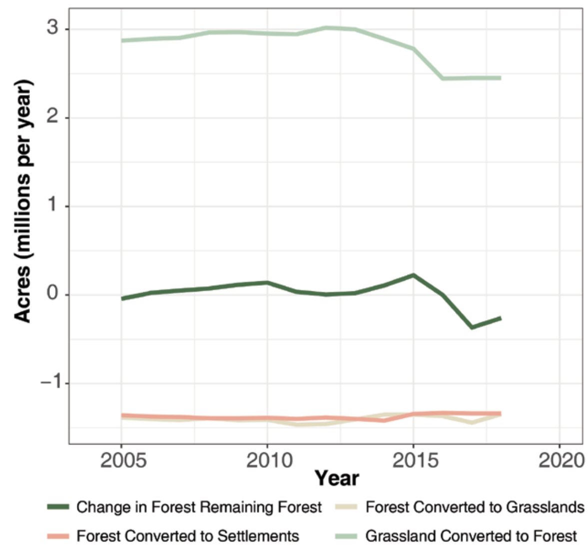
The amount of forest and trends in land use conversion have a direct impact on the amount of CO_2 the forests of the United States sequester and store (Domke et al. 2020a). Since the 1990s, the land use trends that support the NIR have changed (US EPA 2020). Future shifts in land use will influence the CO_2 sequestration and carbon storage capacity that forest land currently provides. The amount of forest area as well as disturbance dynamics, harvesting for fiber, and forest growth defines the sequestration potential of U.S. forests (Domke et al. 2020b). Understanding the range of potential future shifts in land use, disturbance, harvest, and growth can inform policy discussion on emission reduction targets (Coulston et al. 2015, Wear and Coulston 2019).

Figure 4-3. Area of U.S. "forest remaining forest" from 2005 to 2018.



Source: Domke et al. 2020a.

Figure 4-4. Key land use transitions affecting the area of "forest remaining forest" 2005 to 2018.



Source: Domke et al. 2020a.

Census Bureau Urban Area and Population

More than 80 percent of the U.S. population lived in urban areas in 2010, an increase from 75 percent in 1990 (Nelson et al. 2020). Census-defined urban area also expanded during that time, increasing from 2.1 percent (47 million acres) to 3.0 percent (68 million acres) of total land area, with larger increases occurring within the most urbanized counties. States with the largest urban area in 2010 were Texas (5.6 million acres), California (5.3 million acres), and Florida (4.7 million acres). States with the largest percentage of urban land in 2010 were New Jersey (39.8 percent), Rhode Island (38.7 percent), and Massachusetts (38.0 percent). The largest area of urban land growth from 1990 to 2010 occurred in Texas (1.9 million acres), Florida (1.8 million acres), and Georgia (1.4 million acres), while the largest percentage growth in urban land occurred in Nevada (128.6 percent), Delaware (91.4 percent), and North Carolina (87.8 percent). The expansion of urban area has driven the expansion of the wildland-urban interface (see the sidebar Wildland-Urban Interface).

National Land Cover Database

RPA analyses of forest cover include the NLCD woody wetlands class and the three NLCD upland forest classes. For general comparisons with the non-Federal statistics cited above, forest land cover comprised the largest share of non-Federal land in 2011 (416 million acres, 27.6 percent), followed by crop land (309 million, 20.5 percent) (Nelson et al. 2020). Between 2001 and 2011, there were net losses of crop, pasture, and forest lands, and net gains of shrub, grass, developed, and other (water, barren, herbaceous wetland) lands. Considering both non-Federal and Federal lands, forest comprised the largest share of land cover in the RPA North and South Regions in 2011, while shrub was the dominant land cover in the Rocky Mountain and Pacific Coast Regions (Nelson et al. 2020). Forest cover change from 2001 to 2011 was dominated by gains and losses from or to grass and shrub covers, for both Federal and non-Federal ownerships within all four RPA regions. Most of the net land cover changes from 2001 to 2011 occurred in non-Federal ownerships, which comprised more than three-fourths of the total area of the conterminous United States. Developed land had the largest percent net change (an increase) in all RPA regions, almost all on non-Federal land, while patterns of land cover transitions on Federal lands varied substantially among RPA regions.

Comparing Land Use and Land Cover Transitions

After 2000, changes in land use and land cover on non-Federal land in the conterminous United States were broadly similar for both agriculture and developed land, but less so for forest land. The differences in forest change between land use data (NRI) and land cover data (NLCD) were mostly due to temporary changes in forest cover (canopy disturbances) that did not change the forest land use. Because there is no rangeland class in NLCD, the NLCD shrub and grass classes are often used as surrogates for rangeland. However, portions of the NLCD shrub, grass, and barren cover classes are (regenerating) forest land use, while a portion of NLCD grass cover is pasture land use. The fact that those cover and use classes partially overlap prevents direct comparisons of land cover area and change with land use area and change (Nelson et al. 2020). The sidebar Protected Forest Area is an example of an analysis that is relatively insensitive to differences between land use and land cover.

The status and trends of FIA forest land area were recently updated in a supporting RPA report (Oswalt et al. 2019). Comparisons of FIA data with NRI and NLCD data during common periods showed that the average annual rates of FIA forest land use change between 2001 and 2011 were 0.26 percent from forest to nonforest and 0.34 percent from nonforest to forest for all ownerships across the RPA North and South Regions, resulting in a slight net gain in forest land use (Nelson et al. 2020). FIA data were insufficient to estimate change in the RPA Rocky Mountain and Pacific Coast Regions. According to NRI data, non-Federal lands experienced average annual rates of forest change between 2002 and 2012 of 0.18 percent from forest to nonforest and 0.19 percent from nonforest to forest, resulting in negligible net change in non-Federal forest land use. Thus, both land use datasets (FIA, NRI) reveal similar trends in forest land use area. In a general comparison, forest land cover between 2001 to 2011 experienced average annual rates of forest cover change across all ownerships of 0.46 percent from forest to nonforest and 0.17 percent from nonforest to forest, resulting in a net loss of NLCD forest cover (Nelson et al. 2020). For the RPA North and South Regions, the average annual net loss of forest cover was 0.28 percent. These land cover trends in the two eastern RPA regions differ slightly from land use trends, due mostly to differences in how forest canopy disturbances are classified (Nelson et al. 2020).

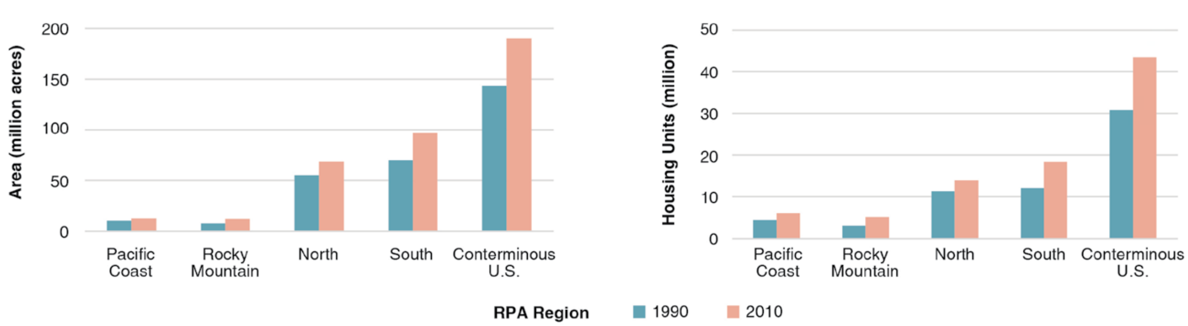
Wildland-Urban Interface

The wildland-urban interface (WUI), defined as the area where houses are in or near wildland vegetation, combines both land use (residential) and land cover (forest, grass, shrub) to identify an environment of unique interest to natural resource managers (Radeloff et al. 2005). Housing development in forested and other naturally vegetated ecosystems is of particular interest because housing development is increasing faster than population (Bradbury et al. 2014) and can have significant ecological effects (Pejchar et al. 2015). When native vegetation is lost and fragmented by houses and associated infrastructure, nonnative species are introduced, pollution increases, zoonotic diseases are transmitted, and wildfires become more common, challenging, and costly (Hansen et al. 2005, Bar-Massada et al. 2014, Syphard et al. 2017).

Tracking the extent of the WUI provides insights into ecological conditions and management concerns in residential areas with wildland vegetation (Zipperer et al. in press).

Radeloff et al. (2018) mapped WUI extent and change from 1990 to 2010 across the conterminous United States using decennial Census data (number of housing units) and land cover data (wildland vegetation coverage) to determine where housing is intermixed with, or adjacent to wildland vegetation. WUI environments were widespread in 2010, covering more than 190 million acres (10 percent of total area) and containing 43.4 million housing units (33 percent of all housing units) (figure 4-5). From 1990 to 2010, the WUI area grew by 46.8 million acres (33

Figure 4-5. Total area (left) and number of housing units (right) in the wildland-urban interface of the conterminous United States in 1990 and 2010.



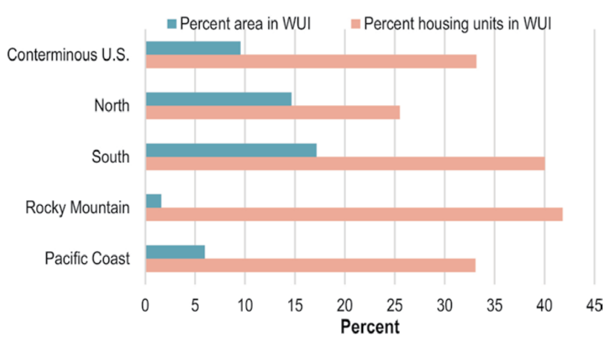
Source: Radeloff et al. 2017.

percent), an area larger than that of Washington State, and the number of housing units in the WUI increased by 41 percent. In 2010, the WUI contained 43 percent of the 29.2 million new housing units built between 1990 and 2010. There are striking regional differences in the percent of total area and total number of housing units in the WUI (figure 4-6) and growth rates (figure 4-7).

WUI extent, growth, and rates of increase are all of interest to land managers. Extent and growth indicate the need for natural resource managers, such as those who work to reduce wildfire risk, to engage in outreach to new WUI residents, while growth rates are a key concern to managers of changing forest and residential environments. The number of WUI homes and the amount of WUI area are consistently larger in the RPA North and South Regions, where forested areas have a long history of housing development. In those regions, the WUI is a relatively larger portion of total region area. The South Region is notable for extensive and prevalent WUI area, as well as relatively high rates of growth. In the western regions, smaller WUI areas experienced rapid growth from 1990 to 2010, particularly in the number of housing units. The Rocky Mountain Region had the smallest WUI area, but it contained 42 percent of all housing units in that region and experienced the fastest growth of both WUI area and housing units from 1990 to 2010. When compared to the eastern regions, the relatively higher western growth rates resulted from relatively smaller absolute gains.

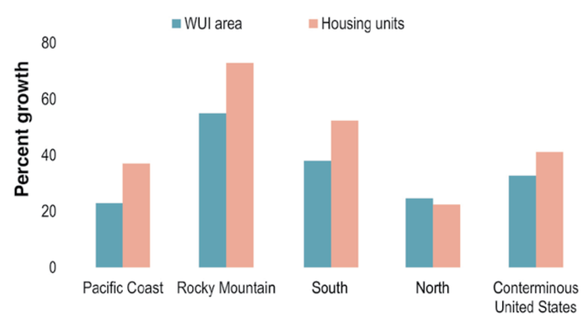
Forest land comprises a major share of the WUI area. The FIA forest land in 2013 (USDA Forest Service 2020) was evaluated in terms of its WUI status in a recent assessment of WUI research needs (Mockrin et al. in press). In 1990, that forest land occupied nearly 70 million acres (49 percent) of the total WUI area, and the WUI contained 10 percent of the nation’s forest land. Over the next two decades, the percent of total WUI area that was forest land did not change much, but WUI expansion increased the share of the nation’s total forest land area found in WUI environments. By 2010, forest land occupied 90 million acres (51 percent) of the total WUI area and the WUI contained 14 percent of total forest land. Across all years, approximately 85 percent of the forest land in the WUI was in the “low housing density intermix” WUI class, which represents the least developed WUI areas. The majority (80 percent) of the forest land in these WUI areas was privately-owned, typically individual- or family-owned forests, while 16 percent was in private corporate ownership. In 2010, just over one-quarter of the national total of 306 million acres of individual- or family-owned forest land area was in the WUI.

Figure 4-6. Percent of total area and percent of total housing units in the wildland-urban interface in 2010, by RPA region.



Source: Radeloff et al. 2017.

Figure 4-7. Percent growth in wildland-urban interface area and number of housing units from 1990 to 2010, by RPA region.



Source: Radeloff et al. 2017.

Protected Forest Area

Protected forests help to conserve the natural functioning of forests while preserving irreplaceable landscapes (Ervin 2003). The Protected Areas Database of the United States (PAD-US; Conservation Biology Institute 2016) maps the known protected areas (held in fee-simple ownership), along with the status of each protected area according to guidelines developed by the International Union for the Conservation of Nature (IUCN; Dudley and Stolton 2008). According to Nelson et al. (2020), 95 percent of the total protected forest area is held in either Federal or State ownership, of which 38 percent is in the RPA Rocky Mountain Region, 29 percent in the North Region, 17 percent in the Pacific Coast Region, and 16 percent in the South Region. For this report, protected forest area estimates in the conterminous United States were updated to the year 2016 for forest cover (USGS 2019d) and forest land use (Burrill et al. 2018). In addition to the seven IUCN protection categories, a de facto protection category included Federal- and State-owned area that has not yet been assigned to an IUCN category. Most public lands both satisfy the IUCN definition of the Sustainable Use category (VI) and approximate the Habitat Management areas category (IV) for some threats such as invasive plant occurrence (Riitters et al. 2018), justifying use of the de facto category for public lands not currently assigned.

Comprising over 30 percent of the total forest area (table 4-1), publicly owned and protected forest area may be the Nation's largest planned land use. Approximately 14 percent of total forest area occurred in a designated IUCN category, and an additional 18 to 20 percent had de facto protection. Wilderness areas contained the largest shares of protected forest area, while the smallest shares were contained in nature reserves, national parks, and natural monuments. While the area of protected forest depends on the definition of forest as land cover (NLCD) or land use (FIA), the shares of total forest area in each of the seven IUCN protection categories is similar for both cases.

Table 4-1. Protected forest cover and forest land use area in the conterminous United States, circa 2016.

Item	Forest area		Percent of total IUCN protected forest area	
	NLCD forest cover	FIA forest land use	NLCD forest cover	FIA forest land use
IUCN protection category[a]	million acres		percent	
Ia Nature reserve	1	1	1.2	1.3
Ib Wilderness area	25	33	33.5	34.2
II National park	7	8	8.8	8.4
III Natural monument	1	2	1.6	2.5
IV Habitat management	15	16	18.1	16.6
V Protected landscape	14	18	17.0	18.8
VI Sustainable use	16	17	19.7	18.2
All IUCN protection categories	79	96	100	100
De facto protection[b]	106	140		
No protection[c]	390	449		
Total forest area[d]	575	685		
Percent with IUCN protection	13.7%	14.0%		
Percent with de facto protection	18.5%	20.4%		

FIA = Forest Inventory and Analysis. IUCN = International Union for the Conservation of Nature. NLCD = National Land Cover Database.

[a] IUCN protection category definitions source: https://www.iucn.org/theme/protected-areas/about/protected-area-categories.

[b] Federal and State ownership not yet assigned to an IUCN category.

[c] Not in Federal or State ownership and not yet assigned to an IUCN category.

[d] Totals may differ slightly from elsewhere in this report. Entries may not sum to column totals because of rounding.

Excludes District of Columbia.

Sources: USGS 2019d; Burrill et al. 2018; Conservation Biology Institute 2016.

Historical Forest Fragmentation and Landscape Context

- ❖ Driven by a 2.6 percent net loss of forest cover area from 2001 to 2016, fragmentation increased in all RPA regions over a wide range of spatial scales. However, the rate of forest cover loss and fragmentation decreased after 2006 in all regions.
- ❖ In both 2001 and 2016, 88 percent of forest cover area was in landscapes dominated by "natural" land covers (forest, grass, shrub, water, wetland, or barren cover), while 31 percent was in "interface" landscapes containing at least 10 percent of developed or agriculture land cover.
- ❖ From 2001 to 2016, the loss of forest cover area was highest within landscapes dominated by developed land cover (9 percent), but the total forest area occurring in developed-dominated landscapes increased by 18 percent as those landscapes expanded to include additional forest area. The loss of forest cover area was lowest in agriculture-dominated landscapes (1 percent), but the total forest area in agriculture-dominated landscapes decreased by 5 percent as those landscapes contracted to exclude additional forest area.
- ❖ Most of the gross changes (loss and gain) of core (unfragmented) forest cover occurred on private land in the RPA South Region, while most of the net loss occurred on public land in the Pacific Coast and Rocky Mountain Regions.
- ❖ Most of the forest-nonforest cover edge in the vicinity of fragmented forest land in 2016 was associated with shrub or grass land in the Rocky Mountain and Pacific Coast Regions and with developed or agriculture land in the North and South Regions.

The preceding section described the land base in terms of the area of individual resource components such as forest and agriculture lands. Another component of the land base is the landscape, that is, the type and spatial arrangement of the resources that are contained in a given area. For example, a forested landscape contains mostly forest land area, while a forest-developed interface landscape contains substantial forest and developed land areas. Such landscape patterns influence the locations and types of forest changes that occur, as well as the ecological effects of those changes and the social values placed on them in different circumstances. Using land cover maps from 2001 to 2016, this section addresses several aspects of forest landscape patterns, including forest fragmentation and the anthropogenic context of forests. To improve interpretation of the findings, key results from the analysis are integrated with forest land use information from the Forest Inventory and Analysis (FIA) database circa 2016, and with forest canopy disturbance information (Schleeweis et al. 2020) from 2000 to 2010.

Land Cover Change

Overall changes in land cover area are a necessary baseline for evaluating landscape pattern changes over time. The previous section described the land cover area changes from 2001 to 2011 that were reported by Nelson et al. (2020). With the release of the 2016 National Land Cover Database (NLCD) which was used for this landscape pattern analysis, Homer et al. (2020) provided a detailed analysis of land cover area changes across the conterminous United States from 2001 to 2016. To supplement the information in Nelson et al. (2020), a brief update of land cover area changes sets a baseline for landscape pattern changes from 2001 to 2016.

The landscape patterns described in this section depend primarily on three generalized cover types: forest (including the NLCD upland forest and woody wetland classes), agriculture (including crop and pasture classes), and developed (which includes most of the impervious road surfaces as well as urban classes). From 2001 to 2016, there were net gains of developed cover area and net losses of forest cover area in all RPA regions, while the agriculture cover area increased in the western regions (Pacific Coast and Rocky Mountain) and decreased in the eastern regions (North and South; table 4-2). Unlike the two western regions, forest losses that occurred in the two eastern regions in the early 2000s were partially offset by later gains. Over all regions, the 5-year net gains in developed cover and losses in forest cover became smaller over time, and agriculture losses that occurred earlier in the timeframe were balanced by later gains such that the 15-year net change was relatively small.

Forest Cover Fragmentation

Forest fragmentation was assessed by measuring forest area density (FAD), which indicates "how much forest is surrounded by how much other forest," and is specifically the proportion of a neighborhood surrounding a given forest location that also has forest cover (Riitters et al. 2002). The interpretation of FAD is straightforward: if forests are not fragmented then FAD equals 1.0 for all forest locations and neighborhood sizes, and FAD decreases as fragmentation increases. Fragmentation is therefore relative to a completely forested condition, and deviations from that baseline arise from natural (and endemic) fragmentation as well as anthropogenic fragmentation. Riitters and Robertson (2021) summarized results across the conterminous United States using NLCD data for 2001, 2006, 2011, and 2016 (USGS 2019a, b, c, d), documenting increased fragmentation from 2001 to 2016 over a wide range of neighborhood sizes. This report highlights the status and trends of "interior" forest cover for a 38-acre neighborhood size, where a forest location is considered "interior" if the FAD value in its neighborhood is at least 0.9 (i.e., if the neighborhood is at least 90 percent forested; McIntyre and Hobbs 1999). Note that the same definition of interior forest was applied to forest land use projections in the later section on Projected Forest Fragmentation and Landscape Context but with a different neighborhood size.

The net change of interior forest area does not necessarily equal the net change of total forest area because interior forest change occurs at the neighborhood scale and total forest area change occurs at the pixel scale (Riitters and Wickham 2012). The interior status of a given location can change "directly" when that location itself changes, or "indirectly" when neighboring locations change. Thus, direct change refers to the gain or loss of forest at that location, while indirect change results from forest gains or losses in the neighborhood of persistent forest.

It is therefore useful to examine both forms of forest change at a larger geographic scale, such as on a per-county basis (figure 4-8). There was a net loss of interior forest area in 2,054 of 3,109 counties from 2001 to 2016. Of those, 1,042 counties exhibited losses of more than 5 percent and 334 counties had losses of more than 15 percent. In forest-dominated counties, interior forest losses exceeding 5 percent were frequent in the Pacific Coast and Rocky Mountain Regions but less common in the North and South Regions, where many counties exhibited net gains of interior forest area. Large percentage changes of interior forest area were common in relatively less-forested counties, but the relatively small area of forest in those counties had little influence on national statistics. The net loss of 2.6 percent of total forest area across the conterminous United States (table 4-2) translated to an overall net loss of 6.4 percent of interior forest area, but net loss rates varied from 3 to 13 percent among RPA regions (table 4-3). Most of the net changes to interior forest area occurred before 2006, after which the rate of net loss decreased in all regions, with indications of stabilization or net gains after 2006 in the two eastern regions.

The indications of stabilization or recovery of interior forest area do not imply there were no important changes during the later time periods—only that the gross gains offset gross losses. That does not account for differences in the locations of interior forest over time, which can influence the regional sustainability of interior-dependent ecological processes. In the RPA South Region, for example, the overall net loss of interior forest area from 2001 to 2016 (3 million acres; table 4-3) resulted from gross changes (direct and indirect) involving 42.1 million acres (table 4-4). The gross gain of 19.7 million acres of interior forest (direct and indirect)

Table 4-2. Total and periodic net area change in agriculture, developed, and forest land cover from 2001 to 2016, by RPA region. Statistics for 2001 to 2011 may differ from the RPA Land Base report (Nelson et al. 2020) because the previous editions of NLCD land cover maps were updated with the release of the 2016 edition.

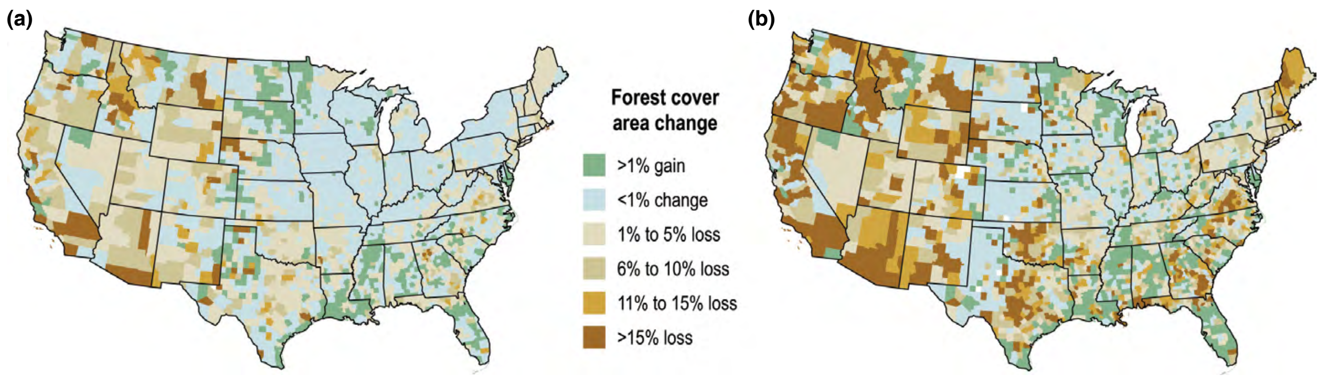
			Net change			Total net change
RPA region	**Land cover**	**Area in 2016**	**2001 to 2006**	**2006 to 2011**	**2011 to 2016**	**2001 to 2016**
		million acres	million acres	million acres	million acres	percent
Conterminous U.S.	Agriculture	450	-2.4	0.3	3.3	0.3
	Developed	106	3.4	2.2	1.5	7.2
	Forest	575	-12.0	-3.2	-0.2	-2.6
North	Agriculture	171	-0.8	-0.7	-0.2	-1.0
	Developed	38	0.9	0.6	0.3	5.2
	Forest	185	-2.2	--[a]	0.1	-1.1
South	Agriculture	128	-2.5	-0.9	0.5	-2.2
	Developed	42	1.7	1.1	0.8	9.7
	Forest	215	-4.5	0.1	1.8	-1.2
Rocky Mountain	Agriculture	128	1.0	1.9	2.8	4.6
	Developed	15	0.5	0.3	0.3	7.4
	Forest	111	-2.9	-2.2	-1.7	-5.7
Pacific Coast	Agriculture	22	-0.1	--	0.2	0.4
	Developed	11	0.2	0.1	0.1	4.6
	Forest	63	-2.5	-1.2	-0.5	-6.2

NLCD = National Land Cover Database.

[a] Value between -0.05 and 0.05.

Sources: USGS 2019a, b, c, d.

Figure 4-8. Per-county net percent change in (a) total forest cover area and (b) interior forest cover area (38-acre neighborhood size) from 2001 to 2016.



Source: USGS 2019a, d.

in the South Region during this time period implies that approximately one-fifth of that region's interior forest area in 2016 was in a different location compared to 2001. The indirect changes were relatively larger than direct changes, particularly in the North and South Regions, but less so in the Pacific Coast and Rocky Mountain Regions, suggesting that the spatial patterns of overall forest area change tended to be more dispersed in the eastern regions and more concentrated in the western regions.

To integrate forest cover and forest use data when evaluating fragmentation, measurements of FAD (forest cover) were combined with FIA field plot data (forest use in Burrill et al. 2018, Oswalt et al. 2019). This analysis used a set of plots representing 96 percent (659.3 million acres) of all FIA forest land (including woodland) in 2016; exotic and rare types of forest were excluded. Each plot location was attributed with its "core" forest status (yes or no) in 2001 and 2016, where core forest was defined as a location with FAD = 1.0 (i.e., the neighborhood is 100 percent forested) in the surrounding 11-acre neighborhood. As in previous RPA reports (e.g., USDA Forest Service 2016), this procedure differed from the analysis of "interior" forest by using a smaller neighborhood (11 acres) and a higher FAD threshold (100 percent) to obtain a better representation of fragmentation in the immediate vicinity of FIA forest plots.

In 2001, 266.7 million acres (40 percent) of the FIA 2016 forest area was classified as core forest. The loss and gain of core forest status (41.5 and 26.3 million acres, respectively) reduced the area of core forest to 251.5 million acres in 2016. In 2016, more than one-half of all core area in the conterminous United States was privately owned (140.9 million acres), and two-thirds of that area was in noncorporate private ownership (90.9 million acres). Public ownership accounted for 110.6 million acres of core area, with the Federal government owning three-fourths of that area (81.3 million acres). Consistent with the regional differences in private versus public forest land ownership (Oswalt et al. 2019), most of the western core area was publicly owned while most of the eastern core area was privately owned (figure 4-9). Most of the total gross gain and gross loss of core area occurred on privately owned land in the South Region (table 4-5). In both the North and South Regions, the losses on privately owned land substantially exceeded the gains. In contrast, two-thirds of the total net

Table 4-3. Total and periodic net change in interior forest cover area (38-acre neighborhood size) from 2001 to 2016, by RPA region.

	Interior forest area		Net change			Total net change	
RPA region	**2001**	**2016**	**2001 to 2006**	**2006 to 2011**	**2011 to 2016**	**2001 to 2016**	
	million acres	million acres	million acres	million acres	million acres	million acres	percent
Conterminous U.S.	295	276	-15.0	-3.3	-0.6	-19	-6.4
North	97	93	-3.7	--[a]	-0.2	-4	-4.0
South	100	97	-5.0	0.5	1.9	-3	-2.7
Rocky Mountain	62	54	-3.3	-2.5	-1.8	-8	-12.3
Pacific Coast	37	32	-2.9	-1.3	-0.5	-5	-12.8

[a] *Value between -0.05 and 0.05.*

Sources: USGS 2019a, b, c, d.

Table 4-4. Components of interior forest cover area (38-acre neighborhood) change from 2001 to 2016, by RPA region.

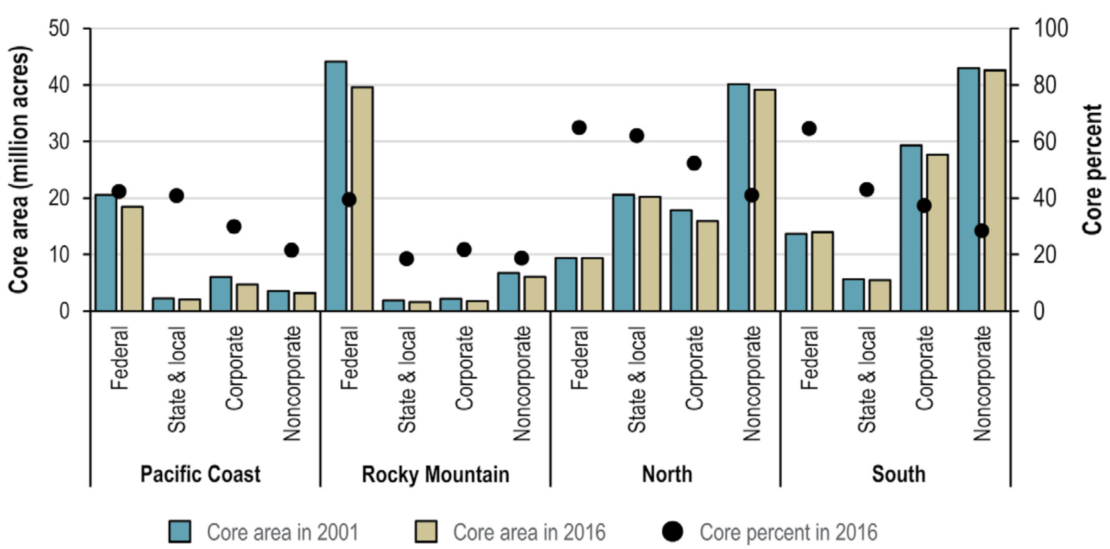
	Interior forest loss		Interior forest gain	
RPA region	Direct[a]	Indirect[b]	Direct[c]	Indirect[d]
	million acres	million acres	million acres	million acres
Conterminous U.S.	21.1	27.4	10.7	18.9
North	3.0	6.9	1.5	4.4
South	9.2	13.2	7.7	12.0
Rocky Mountain	5.0	3.7	0.3	0.9
Pacific Coast	3.9	3.5	1.1	1.6

[a] *A unit of interior forest was lost by conversion of that unit from forest to nonforest cover.*
[b] *A unit of interior forest was lost due to forest cover loss in the neighborhood of a persistent forest unit.*
[c] *A unit of interior forest was gained by conversion of that unit from nonforest to forest.*
[d] *A unit of interior forest was gained due to forest cover gain in the neighborhood of a persistent forest unit.*
Sources: USGS 2019a, d.

change of core area occurred in the Rocky Mountain and Pacific Coast Regions, typically on publicly owned lands. As a result, the conterminous United States total net change of core area was roughly the same for public and private lands.

To better understand the proximate drivers of core area loss, forest disturbance (canopy loss) attribution data from 2001 to 2010 (Schleeweis et al. 2020) was integrated with the land cover and FIA data. Each FIA plot location that changed from core to non-core status between 2001 and 2011 was attributed with one or more types of disturbance (removal, fire, and/or stress; see the Disturbances to Forests and Rangelands Chapter) that occurred in the surrounding 11-acre neighborhood. Disturbances in the neighborhood of FIA plots that changed from core to non-core status indicated that 87 percent of core area loss in the conterminous United States was associated with nearby canopy removal, while disturbances by fire or stress occurred near 21 percent of the core forest loss. (Note that multiple disturbances could have occurred near each plot.) Nearby disturbance by fire or stress was not common in the eastern forest type groups (figure 4-10); while fire or stress may occur relatively frequently in some of those eastern forest types, they are generally localized or of low enough severity not to remove the forest canopy, and therefore largely not appear in the eastern type groups. Among western forest type groups, nearby disturbance by fire was relatively common in all forest type groups except three that are typical of temperate rainforest (hemlock/Sitka spruce, redwood, alder/maple), and nearby disturbance by fire

Figure 4-9. The area of FIA forest land use in the conterminous United States with core forest cover status (11-acre neighborhood size) in 2001 and 2016, by RPA region and ownership category. The circles indicate the percentage of forest area that was core in 2016.



Sources: USGS (2019a, d); Burrill et al. (2018).

Table 4-5. Gross and net change of core forest cover status (11-acre neighborhood) for 2016 FIA forest land, by RPA region and ownership. Public ownership includes Federal and State and local. Private ownership includes corporate and noncorporate.

RPA region	Ownership	Loss	Gain	Net change
		million acres	million acres	million acres
Conterminous U.S.	Public	12.5	5.0	-7.4
	Private	29.0	21.3	-7.7
North	Public	2.3	2.0	-0.3
	Private	6.7	3.8	-2.9
South	Public	1.5	1.6	0.1
	Private	18.1	16.1	-2.0
Rocky Mountain	Public	5.5	0.6	-4.8
	Private	1.3	0.2	-1.2
Pacific Coast	Public	3.1	0.8	-2.3
	Private	2.9	1.2	-1.6

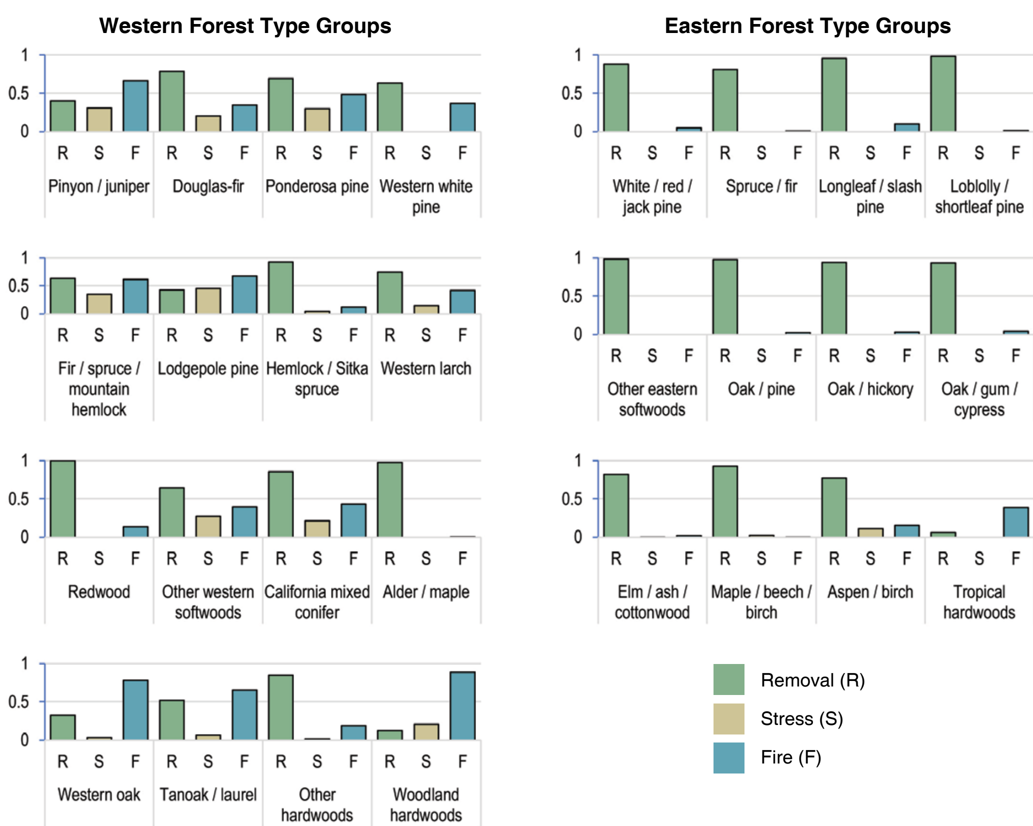
FIA = Forest Inventory and Analysis.

Sources: Burrill et al. 2018; USGS 2019a, d.

was more common than disturbance by removal in four forest type groups where timber harvesting is less common (pinyon/juniper, western oak, tanoak/laurel, woodland hardwoods) along with one forest type group that experienced extensive wildfires (lodgepole pine). Nearby stress was common in only 10 of the 28 forest type groups, mostly in the West. Because core area tends to occur in relatively remote areas where fire and stress are more common, the association of core area loss with those disturbance types was often higher than the overall exposure of all forest area to those disturbance types (see the Disturbances to Forests and Rangelands Chapter). For example, approximately 5 percent of all pinyon/juniper forest area was exposed to nearby stress from fire, but over half the loss of core area was associated with nearby fire.

An analysis to support interpretation of the potential impacts associated with fragmentation considered a larger 38-acre neighborhood and attributed each FIA plot location with the frequencies of the types of forest-nonforest "edges" in that neighborhood, as defined by the 2016 NLCD land cover map (Riitters et al. 2012). Five types of forest edge were identified: forest-developed, forest-agriculture, forest-shrub

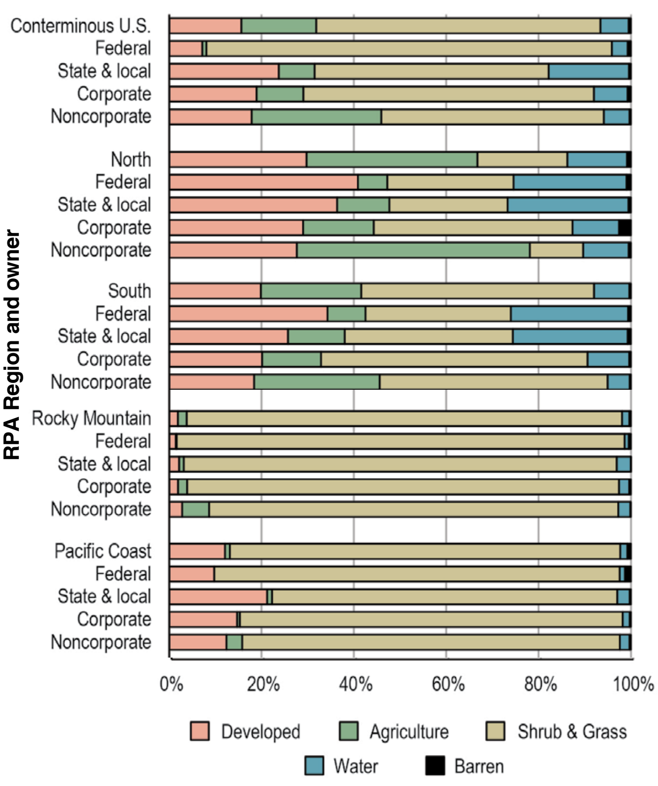
Figure 4-10. Proportion of FIA forest land area across the conterminous United States exhibiting a loss of core forest cover status—2001 to 2011. Loss associated with removal (R; green), stress (S; brown), or fire (F; blue) events within a 11-acre neighborhood, by forest type group for western forest type groups (left) and eastern forest type groups (right). The proportion of loss is on the vertical axis; the sum of proportions in a type group may be larger than 1.0 because more than one type of event can be associated with a given loss of core forest status.



Sources: USGS (2019a, c); Burrill et al. (2018).

& grass, forest-water, and forest-barren. The mean share of each type (Riitters et al. 2012) indicates their relative importance as edge where the forest is fragmented, which in turn can indicate the potential types of ecological impacts of fragmentation (e.g., Forman and Alexander 1998, Murcia 1995, Ricketts 2001). For example, nearby anthropogenic edge (farms, houses, roads, etc.) tends to increase fire ignitions (Radeloff et al. 2018) as well as occurrences of invasive forest plants (Riitters et al. 2018) (see also the Disturbances to Forests and Rangelands Chapter). Except for forest-developed edge in the Pacific Coast Region, almost all forest-nonforest edge in the two western regions is forest-shrub & grass edge (figure 4-11). Most of the forest-agriculture edge is contained in the two eastern regions, which also exhibit the largest percentages of forest-developed edge. Forest-agriculture edge is relatively more important near noncorporate private forest than public or corporate private forest. The relatively large shares of forest-developed edge in public ownerships are largely attributable to the presence of roads (a type of development) which traverse relatively less-fragmented forested landscapes (Riitters et al. 2012).

Figure 4-11. Mean shares of five types of forest cover edge within a 38-acre neighborhood of FIA forest land plots across the conterminous United States in 2016, by RPA region and ownership category.



Sources: USGS (2019d); Burrill et al. (2018).

While this analysis of forest cover fragmentation did not distinguish between natural and anthropogenic fragmentation, separate analyses of the same land cover data (Homer et al. 2020, Riitters et al. 2020) indicate that almost all forest cover losses and gains involved transitions between forest, shrub, and grass land covers. Furthermore, most forest cover gains and losses occurred in natural-dominated landscapes (see the Forest Landscape Context section below) and forest canopy losses were associated primarily with forest removal and secondarily with fire, stress, or land use conversion (see the Disturbances to Forests and Rangelands Chapter). Taken together, these findings are generally consistent with the interpretation that most forest cover loss results from pervasive forestry operations (Cohen et al. 2016, Curtis et al. 2018, Masek et al. 2008). Because losses due to forestry operations in the United States are typically followed by gains from forest regeneration, that interpretation is strengthened for the two eastern RPA regions by the balance between direct gains and losses of interior forest in each region (table 4-4). It is plausible that the relatively larger and continuing net loss of interior area in the western RPA regions (table 4-3) reflect slower regeneration following severe wildfire or stress (figure 4-10) especially on public lands (table 4-5).

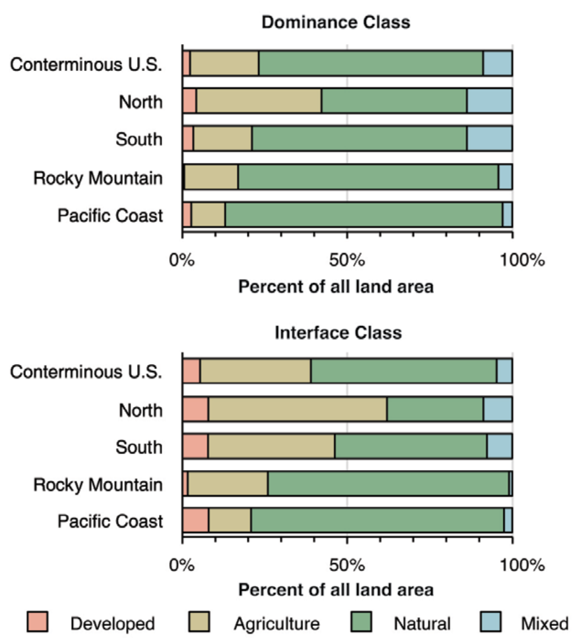
Forest Landscape Context

The anthropogenic context of land area in the conterminous United States was evaluated in terms of landscape dominance and interfaces that describe the relative importance of developed and agriculture land covers within a 162-acre neighborhood of a given location (Riitters et al. 2020). Landscape dominance identifies areas where developed, agriculture, or "natural" (i.e., all other) land covers are locally dominant (at least 60 percent of the neighborhood area), while the landscape interface identifies areas in which developed and/or agriculture land covers are a significant component of the local landscape (at least 10 percent of the neighborhood area). Using NLCD data from 2001 and 2016, developed land included the four NLCD developed classes (which incorporate most of the impervious road cover) and agriculture land included the pasture/hay and cultivated crop classes. All other NLCD cover classes were considered "natural" and the water class was excluded. Landscape dominance was classified as "developed," "agriculture," or "natural" if one of the three corresponding land cover types exceeded the 60 percent threshold value, and otherwise classified as "mixed." Similarly, landscape interface was classified as "developed," "agriculture," or "both" if the proportion of the corresponding land cover type(s) exceeded the 10 percent threshold value, and otherwise classified as "neither." The same classifications were applied in the later section on Projected Forest Fragmentation and Landscape Context, but with a different neighborhood size. In this section, landscape dominance and interface were evaluated for all land area and for forest cover area only, where the latter included the three NLCD upland forest classes and the woody wetlands class. Although the forest inventory plot data described above were not used for this analysis, the changing landscape context of FIA forest land use has been reported elsewhere (Riitters and Costanza 2019).

Most of the total land area was in the natural dominance class in 2016, but the proportion of area in each of the dominance classes varied among RPA regions (figure 4-12). The proportion of total area in developed- and agriculture-dominated landscapes was larger in the two eastern RPA regions than in the two western regions. In all regions, larger proportions of total area were contained in the developed and agriculture interface landscapes, with more than half of both the North and South Regions occurring in those landscape interfaces. Following the patterns of land cover change from 2001 to 2016 (table 4-2), there was a net gain of developed dominance and interface area in all RPA regions, and a net loss of agriculture dominance and interface area in all regions except the Rocky Mountain Region (figure 4-13). In the Rocky Mountain Region, the relatively large net losses of natural dominance and "neither" interface areas are due more to grassland conversion than forest conversion from 2001 to 2016 (Homer et al. 2020). Apart from agriculture-related changes in the Rocky Mountain Region, most of the net changes occurred in the two eastern regions.

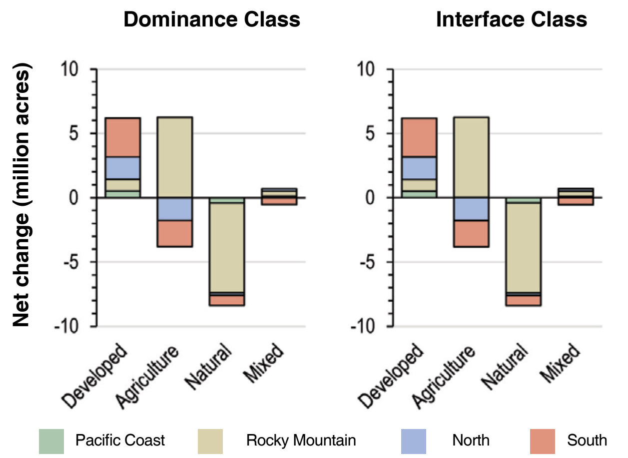
Analogous to the analysis of interior forest change, the components of forest cover change in relation to landscape

Figure 4-12. Share of total land area by dominance class (top) and interface class (bottom) in 2016, by RPA region. See text for definitions of dominance and interface classes.



Source: USGS (2019d).

Figure 4-13. Net change of total land area by dominance class (left) and interface class (right) from 2001 to 2016, by RPA region. Changes of land area to or from water are not included. See text for definitions of dominance and interface classes.



Source: USGS (2019a, d).

context include direct changes due to forest loss and gain in each type of landscape, and indirect changes due to expansion (or contraction) of each type of landscape to include (or exclude) the persistent forest area. In both 2001 and 2016, 88 percent of total forest cover area was in landscapes dominated by "natural" land covers (table 4-6), but 31 percent was in landscapes that contained a significant share (at least 10 percent) of developed or agriculture land cover (table 4-7). From 2001 to 2016, the forest area in developed dominance and interface landscapes increased by 0.4 and 1.4 million acres, respectively, while the forest area in agriculture dominance and interface landscapes decreased by 0.8 and 6.1 million acres, respectively. The changes in the agriculture and developed landscapes were driven primarily by indirect change. For example, the net rate of forest cover loss was highest within landscapes dominated by developed land cover

Table 4-6. Components of forest cover area change from 2001 to 2016 in the conterminous United States by landscape dominance class.

	Forest area		Net percent change		
Dominance class	**2016**	**Change**	**Total[a]**	**Direct[b]**	**Indirect[c]**
	million acres		percent		
Developed	2.6	0.4	17.7	-8.7	26.4
Agriculture	17.0	-0.8	-4.7	-1.0	-3.7
Natural	508.4	-13.7	-2.6	-2.7	0.1
Mixed	46.7	-1.3	-2.8	-1.8	-1.0
Total forest area	574.7	-15.5	-2.6	-2.6	--[d]

[a] *Percent change of area from 2001.*
[b] *Forest gain minus loss in a persistent dominance class.*
[c] *Dominance class gain minus loss of persistent forest.*
[d] *Not applicable.*
Sources: USGS 2019a, d.

Table 4-7. Components of forest cover area change from 2001 to 2016 in the conterminous United States by landscape interface class.

	Forest area		Net percent change		
Interface class	2016	Change	Total[a]	Direct[b]	Indirect[c]
	million acres		percent		
Developed	33.8	1.4	4.4	-3.7	8.1
Agriculture	121.9	-6.1	-4.8	-0.9	-3.8
Neither	397.8	-10.8	-2.6	-3.1	0.4
Both	21.1	--[d]	0.1	-2.3	2.5
Total forest area	574.7	-15.5	-2.6	-2.6	--[e]

[a] *Percent change of area from 2001.*
[b] *Forest gain minus loss in a persistent interface class.*
[c] *Interface class gain minus loss of persistent forest.*
[d] *Value between -0.05 and 0.05.*
[e] *Not applicable.*
Sources: USGS 2019a, d.

(9 percent), but the total amount of forest area occurring in those landscapes increased by 18 percent as the developed lands expanded to include additional forest area. The net rate of forest loss was lowest in agriculture-dominated landscapes (1 percent), but the total forest area in those landscapes decreased by 5 percent as agricultural lands contracted to exclude additional forest area. In contrast, the locations of natural-dominated and noninterface landscapes were relatively stable and the forest change within those landscapes was driven primarily by direct forest loss and gain.

Projected Land Use

- ❖ Developed land area is projected to increase in the future, while all non-developed land uses are projected to lose area. The most common source of new developed land is forest land.
- ❖ Forest land area is projected to decrease under all scenarios, although at lower rates than projected by the 2010 Assessment.
- ❖ Higher projected population and income growth lead to relatively less forest land, while hotter projected future climates lead to relatively more forest land.
- ❖ Projected future land use change is more sensitive to the variation in economic factors across RPA scenarios than to the variation among climate projections.

Land Use Change Model

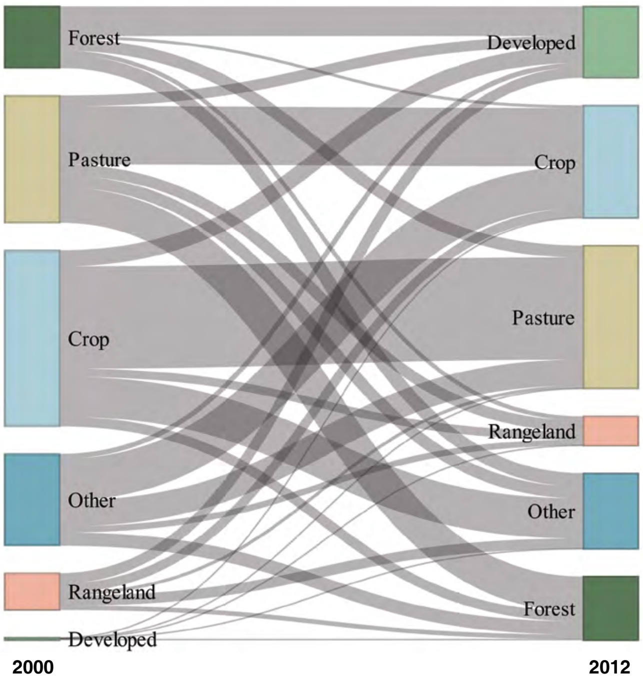
Land use change is a major driver of resource change. We projected land use change on private land for each county in the conterminous United States from 2020 to 2070 for five major land use classes: forest, developed, crop, pasture, and rangeland. The land use projections are based on the 20 RPA scenario-climate futures (four RPA scenarios and five climate projections; see the sidebar RPA Scenarios) and are therefore explicitly linked to projected climate change and socioeconomic change. Mihiar and Lewis (in review) provide details of the methods and results.

All land use change was assumed to occur on privately owned land within these land use classes; all other ownerships, as well as other NRI categories (Conservation Reserve Program, water, and other rural), were held constant throughout the projection period. Land development is assumed to be an irreversible change—developed land only gains area over time—because there were only trivial historical losses in developed area in the NRI data used to calibrate the projection models. The land use projections do not assume any significant future change in land use policy or regulations (i.e., projections are policy-neutral, based on historical land use relationships driven by future climate change as well as population and economic growth assumptions).

The future projections of land use were based on a subset of NRI data for private land only, spanning 2000 to 2012. During that time, the most active transitions occurred to/from crop and pasture lands (figure 4-14). Of the 6.7 million acres of crop land moving to other use, 67 percent of that land was placed in the Conservation Reserve Program (CRP). Likewise, 91 percent of new crop land from the other category originated from the CRP. The conversion trends of undeveloped land into developed land have changed significantly through time (figure 4-3). Approximately 1.2 million acres of undeveloped land transitioned into developed land annually in the 1980s; this amount increased to approximately 2.0 million acres per year between 1992 and 1997, but the rate of newly developed land declined thereafter (figure 4-3). Bigelow et al. (2022) found that the decline was consistent across urban and rural regions in the conterminous United States and resulted in 7.0 million acres of forest and agriculture land remaining undeveloped between 2000 and 2015. If developed land had continued to expand at the same rate observed before 2000, those 7.0 million acres of forest and agriculture use would have converted to a developed use.

The projections are based on land use transition probabilities, estimated from NRI plots with repeated observations during the years 2000 to 2012 (Mihiar and Lewis, in review). The modeling approach has three components: (a) developing empirical linkages between climate, population, income, and the value of land in production for the major U.S. land uses of agriculture (crop and pasture), forest, and developed; (b) estimating an empirical link between the net returns to each land use and the observed choice of land use across agriculture, forest, and developed conditional on the current land use allocation; and (c) using estimated transition probabilities to project future land use changes.

Figure 4-14. Gross land use change in the conterminous United States from 2000 to 2012. For land moving out of a particular land use in 2000 (bars on left), the width of the gray flows indicate the relative area moving into each new use in 2012 (bars on right).



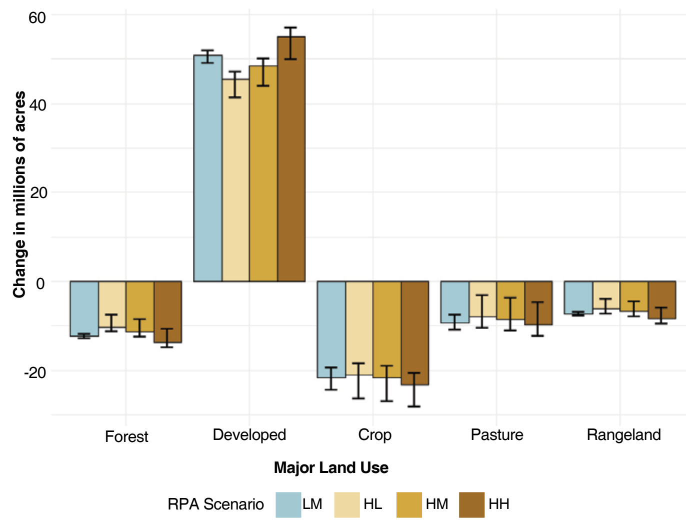
Source: USDA 2015.

Land Use Projections

Our analyses of the land use projections are stratified across several dimensions. We examine both gross and net land use change. Gross change describes all transitions of land between uses, while net change describes the change in land area after accounting for all transitions in and out of that land use. We also consider how the projections differ across the RPA North, South, Rocky Mountain, and Pacific Coast Regions. Finally, we explore the projections across the four RPA scenarios and five climate projections (see the sidebar RPA Scenarios). We examine the influence of atmospheric warming by comparing results from the lower warming-moderate growth RPA scenario (LM) to the high warming-moderate growth scenario (HM), and we examine the influence of socioeconomic growth by comparing the high warming-low growth RPA scenario (HL) to the high warming-high growth scenario (HH). In addition, the influence of future climate is examined by comparing results across the selected climate projections.

Projected trends in land use from 2020 to 2070 are consistent across RPA scenarios, indicating large net increases in developed land and moderate net declines in each of the non-developed land uses (figure 4-15). Projected declines are largest in crop use and smallest in rangeland use for each scenario. The HH scenario resulted in the largest net gain in developed land and largest net loss in forest land, while the HL scenario resulted in the smallest net gain in developed land and smallest net loss in forest land (table 4-9), suggesting that the land use change model (Mihiar and Lewis in review) is more sensitive to the variation in future economic variables (population and income) than in future atmospheric warming and climate variables (temperature and precipitation) across RPA scenario-climate futures.

Figure 4-15. Projected net land use changes from 2020 to 2070 across the conterminous United States, by RPA scenario. The range drawn within each bar represents difference in projection across climate projections.



LM = lower warming-moderate U.S. growth; HL = high warming-low U.S. growth; HM = high warming-moderate U.S. growth; HH = high warming-high U.S. growth.

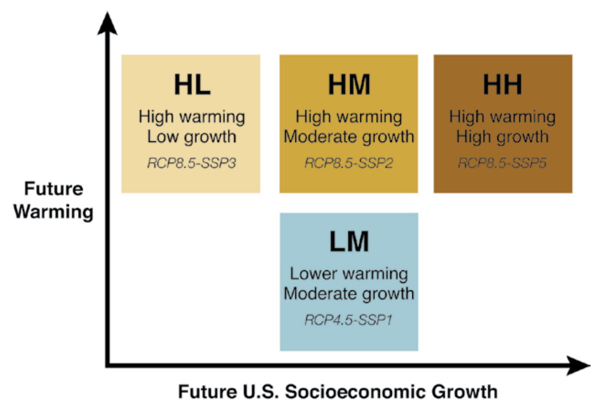
Land use projections reveal an expansion of developed land of 41.3 to 57.0 million acres across the RPA scenario-climate futures (table 4-9). However, those increases differ by RPA region (figure 4-18). The largest projected growth in developed land area is in the South Region, where approximately 18.4 (HL-hot) to 25.0 million acres (HH-wet) of new developed land is projected. The North Region has the second largest projected increase in developed land, approximately 10.6 (HL-hot) to 14.0 million acres (HH-least warm). The Rocky Mountain Region is projected to see developed land area grow between 6.4 million acres (HL-hot) and 8.9 million acres (HH-dry), and the Pacific Coast Region is projected to see developed land area grow by between 5.9 million acres (HL-hot) and 9.9 million acres (HH-least warm). These projected changes of developed land area are important to understand how future forested landscapes may evolve, because loss of forest land is projected to be the largest source of new developed land, accounting for an average of 46 percent of new developed land (table 4-10).

RPA Scenarios

The RPA Assessment uses a set of scenarios of coordinated future climate, population, and socioeconomic change to project resource availability and condition over the next 50 years. These scenarios provide a framework for objectively evaluating a plausible range of future resource outcomes.

The 2020 RPA Assessment draws from the global scenarios developed by the Intergovernmental Panel on Climate Change to examine the 2020 to 2070 time period (IPCC 2014). The RPA scenarios pair two alternative climate futures (Representative Concentration Pathways or RCPs) with four alternative socioeconomic futures (Shared Socioeconomic Pathways or SSPs) in the following combinations: RCP 4.5 and SSP1 (lower warming-moderate U.S. growth, LM), RCP 8.5 and SSP3 (high warming-low U.S. growth, HL), RCP 8.5 and SSP2 (high warming-moderate U.S. growth, HM), and RCP 8.5 and SSP5 (high warming-high U.S. growth, HH) (figure 4-16). The four 2020 RPA Assessment scenarios encompass most of the projected range of climate change from the RCPs and projected quantitative and qualitative range of socioeconomic change from the SSPs, resulting in four distinct futures that vary across a multitude of

Figure 4-16. Characterization of the 2020 RPA Assessment scenarios in terms of future changes in atmospheric warming and United States socioeconomic growth. These characteristics are associated with the four underlying Representative Concentration Pathway (RCP) – Shared Socioeconomic Pathway (SSP) combinations.



Source: Langner et al. (2020).

Figure 4-17. Characteristics differentiating the 2020 RPA Assessment scenarios. These characteristics are associated with the four underlying Representative Concentration Pathway (RCP) – Shared Socioeconomic Pathway (SSP) combinations.

RPA Scenario (RCP-SSP)	Global Temperature Rise	U.S. Population Growth	U.S. Economic Growth Rate	Bioenergy Demand	Energy Sector Focus	Global Energy Usage	International Trade Openness
LM Lower warming Moderate growth *RCP4.5-SSP1*	Lower	Medium	Medium-High	High	Renewables	Low	Medium
HL High warming Low growth *RCP8.5-SSP3*	High	Low	Low	Low	Fossil fuels	Medium	Low
HM High warming Moderate growth *RCP8.5-SSP2*	High	Medium	Medium	Medium	Mixed	Medium	Medium
HH High warming High growth *RCP8.5-SSP5*	High	High	High	High	Fossil fuels	High	High

characteristics (figure 4-17), and providing a unifying framework that organizes the RPA Assessment natural resource sector analyses around a consistent set of possible world views. The Scenarios Chapter describes how these scenarios were selected and paired; more details are provided in Langner et al. (2020).

The 2020 RPA Assessment pairs these four RPA scenarios with five different climate models that capture the wide range of projected future temperature and precipitation across the conterminous United States. An ensemble climate projection that averages across the multiple model projections is not used because of the importance of preserving individual model variability for resource modeling efforts. The five climate models selected by RPA represent least warm, hot, dry, wet, and middle-of-the-road climate futures for the conterminous United States (table 4-8); however, characteristics can vary at finer spatial scales. Although the same models were selected to develop climate projections for both lower and high-warming futures, distinct climate projections for each model are associated with RCP 4.5 and RCP 8.5. The Scenarios Chapter describes how these climate models were selected. Joyce and Coulson (2020) give a more extensive explanation.

Throughout the RPA Assessment, individual scenario-climate futures are referred to by pairing RPA scenarios with selected climate projections. For example, an analysis run under “HL-wet” assumes a future with high atmospheric warming and low U.S. population and economic growth (HL RPA scenario), as well as a wetter climate for the conterminous United States (wet climate projection).

Table 4-8. Five climate models selected to reflect the range of the full set of 20 climate models in the year 2070. Each model was run under RCP 4.5 and RCP 8.5, providing a range of different U.S. climate projections.

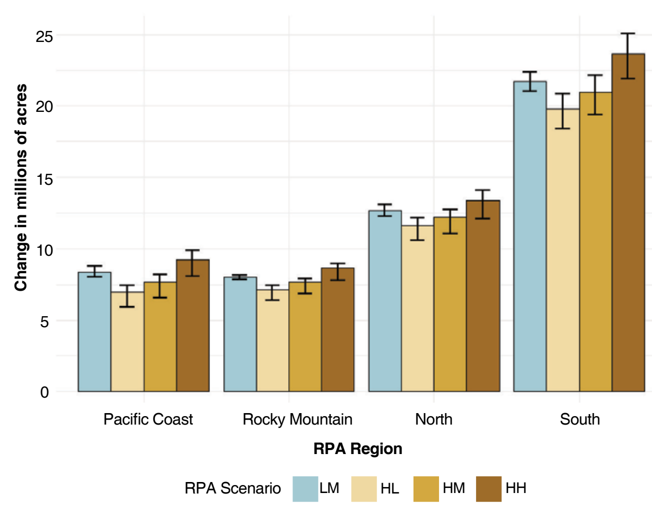
	Least warm	Hot	Dry	Wet	Middle
Climate model	MRI-CGCM3	HadGEM2-ES	IPSL-CM5A-MR	CNRM-CM5	NorESM1-M
Institution	Meteorological Research Institute, Japan	Met Office Hadley Centre, United Kingdom	Institut Pierre Simon Laplace, France	National Centre of Meteorological Research, France	Norwegian Climate Center, Norway

RCP = Representative Concentration Pathway.

Source: Joyce and Coulson 2020.

Over the 50-year period from 2020 to 2070, we project a total net forest land loss of between 7.6 and 15.0 million acres (table 4-9). When averaging results across RPA scenario-climate futures, approximately 91 percent of current forest land is projected to remain in forest use by 2070 (table 4-10). Most of the gross forest loss (19.8 to 26.0 million acres) is projected to convert to developed land (table 4-11), which is assumed to be a permanent change, followed by conversions to pasture, crop, and rangeland (table 4-11). When averaging results across RPA scenario-climate futures, we project about 25.3 million acres of new forest land will be added from conversions out of pasture land (17.4 million), crop land (2.4 million acres), and rangeland (5.5 million acres) (table 4-10). Transitions between forest and pasture lands are the most common and account for the largest area of gross forest change. Only conversions from forest to developed and pasture to forest show significant variation in projection across RPA scenario-climate futures (table 4-11). The remaining conversion types are not sensitive to scenarios or climate projections, varying by less than 1.0 million acres across scenarios and climate projections.

Figure 4-18. Projected net developed land use change from 2020 to 2070, by RPA region and RPA scenario. The range drawn within each bar represents difference in projection across climate projections.



LM = lower warming-moderate U.S. growth; HL = high warming-low U.S. growth; HM = high warming-moderate U.S. growth; HH = high warming-high U.S. growth.

Table 4-9. Projected net land use change from 2020 to 2070 by RPA scenario and climate projection.

	LM scenario					HM scenario				
	Climate projection					Climate projection				
	Least warm	Hot	Dry	Wet	Middle	Least warm	Hot	Dry	Wet	Middle
Land use	million acres (percent)					million acres (percent)				
Forest	-13.0 (-3.2%)	-11.9 (-2.9%)	-11.9 (-2.9%)	-12.5 (-3.0%)	-12.6 (-3.1%)	-12.5 (-3.0%)	-8.6 (-2.1%)	-11.8 (-2.9%)	-11.9 (-2.9%)	-12.1 (-3.0%)
Developed	51.8 (53.1%)	49.1 (50.4%)	50.7 (51.9%)	51.6 (52.8%)	50.7 (51.9%)	50.2 (51.3%)	43.9 (45.0%)	49.0 (50.2%)	50.1 (51.3%)	48.9 (50.1%)
Crop	-20.6 (-5.8%)	-20.4 (-5.7%)	-23.4 (-6.5%)	-24.4 (-6.8%)	-19.5 (-5.4%)	-19.2 (-5.3%)	-26.9 (-7.5%)	-19.7 (-5.5%)	-23.2 (-6.5%)	-19.3 (-5.4%)
Pasture	-10.6 (-8.9%)	-9.7 (-8.1%)	-7.8 (-6.5%)	-7.6 (-6.4%)	-10.9 (-9.7%)	-11.1 (-9.3%)	-3.7 (-3.1%)	-9.5 (-7.9%)	-8.0 (-6.7%)	-10.3 (-8.6%)
Rangeland	-7.6 (-1.9%)	-7.1 (-1.8%)	-7.6 (-1.9%)	-7.1 (-1.7%)	-7.8 (-1.9%)	-7.5 (-1.8%)	-4.6 (-1.1%)	-8.0 (-2.0%)	-6.9 (-1.7%)	-7.3 (-1.8%)

	HL scenario					HH scenario				
	Climate projection					Climate projection				
	Least warm	Hot	Dry	Wet	Middle	Least warm	Hot	Dry	Wet	Middle
Land use	million acres (percent)					million acres (percent)				
Forest	-11.3 (-2.8%)	-7.6 (-1.9%)	-10.7 (-2.6%)	-10.8 (-2.6%)	-11.0 (-2.7%)	-15.0 (-3.7%)	-10.8 (-2.6%)	-14.3 (-3.5%)	-14.5 (-3.5%)	-14.5 (-3.5%)
Developed	47.1 (48.3%)	41.3 (42.4%)	46.1 (47.3%)	47.0 (48.2%)	46.0 (47.2%)	57.0 (58.3%)	49.8 (51.1%)	55.6 (57%)	57.0 (58.3%)	55.3 (56.6%)
Crop	-18.4 (-5.1%)	-26.4 (-7.3%)	-19.0 (-5.3%)	-22.5 (-6.3%)	-18.6 (-5.2%)	-20.8 (-5.8%)	-28.3 (-7.9%)	-21.3 (-5.9%)	-24.9 (-6.9%)	-20.8 (-5.8%)
Pasture	-10.6 (-8.8%)	-3.3 (-2.7%)	-9.0 (-7.5%)	-7.5 (-6.2%)	-9.8 (-8.2%)	-12.3 (-10.3%)	-4.8 (-4.1%)	-10.6 (-8.9%)	-9.2 (-7.7%)	-11.4 (-9.5%)
Rangeland	-6.8 (-1.7%)	-4.0 (-1.0%)	-7.4 (-1.8%)	-6.3 (-1.6%)	-6.6 (-1.6%)	-9.0 (-2.2%)	-5.9 (-1.5%)	-9.5 (-2.3%)	-8.4 (-2.1%)	-8.7 (-2.2%)

LM = lower warming-moderate U.S. growth; HL = high warming-low U.S. growth; HM = high warming-moderate U.S. growth; HH = high warming-high U.S. growth.
Note: Differences with values calculated from table 4-11 are due to rounding.

Table 4-10. Projected gross land use change from 2020 to 2070, averaged over all RPA scenarios and climate projections.

		2070 land use (million acres)					
		Forest	Developed	Crop	Pasture	Rangeland	2020 total
2020 land use (million acres)	**Forest**	372.1	23.2	3.6	8.7	2.2	409.8
	Developed	-	97.7	-	-	-	97.7
	Crop	2.4	10.6	270.1	71.7	4.0	358.8
	Pasture	17.4	8.1	59.4	28.3	6.2	119.4
	Rangeland	5.5	8.8	3.9	1.5	382.5	402.2
	2070 total	**397.4**	**147.6**	**336.9**	**110.6**	**395.2**	**-**
	Mean 50-year net change	-12.4 (-3.0%)	50.7 (+51.9%)	-21.8 (-6.1%)	-9.2 (-7.7%)	-7.3 (-1.8%)	-

Note: The mean net changes shown here are not strictly comparable to values shown in tables 4-9 and 4-11.

Change of forest to developed land ranges from 19.8 million acres (HL-hot) to 26 million acres (HH-least warm) across RPA scenario-climate futures (table 4-11). Largely because of these losses to developed land, these RPA scenario-climate futures are also responsible for the overall smallest (34.4 million acres) and largest (40.5 million acres) gross losses of forest land. Gross gains of forest land are lowest under HH-middle (24.9 million acres) and highest under HM-hot (26.5 million acres), with most gains coming from pasture land across all scenario-climate futures.

The projections for crop to forest land transitions are relatively stable across RPA scenarios (table 4-11). However, under the higher warming RPA scenarios (i.e., HL, HM, and HH), the largest difference in gross change of crop to forest area is projected between the least warm and hot climate projections. We project approximately 0.5 million acres of additional forest area converting from crop land when comparing the least warm to the hot projections. We also project about 0.4 million acres of additional forest area converting from crop land under the HM scenario relative to the LM scenario, both using the hot climate projection. These results suggest that higher atmospheric warming results in more forest land and less crop land across the United States.

Pasture to forest land transitions account for the greatest amount of new forest land in the future, between 17.2 and 18.2 million acres, following a similar pattern to that of crop to forest land transitions (table 4-11). When comparing results using the hot climate projection, we project 1.0 million acres of additional forest from pasture land under the HM scenario relative to LM. When comparing results across climate projections under the HM scenario, we project 0.9 million additional acres converting to forest from pasture for the hot climate projection relative to the least warm projection. Our land use projections indicate that hotter future temperatures may lead to more forest land and less pasture land.

The projected reductions in forest land area, which occur on private lands under all RPA scenarios, differ by RPA region although losses are always highest under the HH-least warm scenario-climate future (figure 4-19). Projected forest land losses are largest in the South Region—between 4.6 million (HL-hot) and 9.2 million acres (HH-least warm).

Table 4-11. Projected gross forest land change from 2020 to 2070, by RPA scenario and climate projection.

	LM scenario					HM scenario				
	Climate projection					Climate projection				
	Least warm	Hot	Dry	Wet	Middle	Least warm	Hot	Dry	Wet	Middle
Gross forest loss	million acres					million acres				
Forest to developed	24.0	22.8	23.4	23.8	23.4	23.4	20.7	22.8	23.3	22.9
Forest to crop	3.6	3.6	3.5	3.5	3.6	3.6	3.6	3.6	3.5	3.6
Forest to pasture	8.7	8.7	8.7	8.7	8.7	8.7	8.8	8.7	8.7	8.7
Forest to rangeland	2.2	2.2	2.2	2.2	2.2	2.2	2.2	2.2	2.2	2.2
Gross forest gain										
Crop to forest	2.3	2.4	2.5	2.5	2.3	2.3	2.8	2.4	2.5	2.3
Pasture to forest	17.3	17.2	17.6	17.4	17.2	17.3	18.2	17.2	17.5	17.2
Rangeland to forest	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5

	HL scenario					HH scenario				
	Climate projection					Climate projection				
	Least warm	Hot	Dry	Wet	Middle	Least warm	Hot	Dry	Wet	Middle
Gross forest loss	million acres					million acres				
Forest to developed	22.3	19.8	21.7	22.2	21.8	26.0	22.9	25.2	25.8	25.2
Forest to crop	3.6	3.6	3.6	3.5	3.6	3.6	3.6	3.6	3.5	3.6
Forest to pasture	8.7	8.8	8.7	8.7	8.7	8.7	8.7	8.7	8.7	8.7
Forest to rangeland	2.2	2.2	2.2	2.2	2.2	2.2	2.2	2.2	2.2	2.2
Gross forest gain										
Crop to forest	2.3	2.7	2.4	2.5	2.3	2.3	2.7	2.4	2.4	2.3
Pasture to forest	17.4	18.2	17.2	17.5	17.2	17.3	18.2	17.1	17.4	17.1
Rangeland to forest	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5

LM = lower warming-moderate U.S. growth; HL = high warming-low U.S. growth; HM = high warming-moderate U.S. growth; HH = high warming-high U.S. growth.

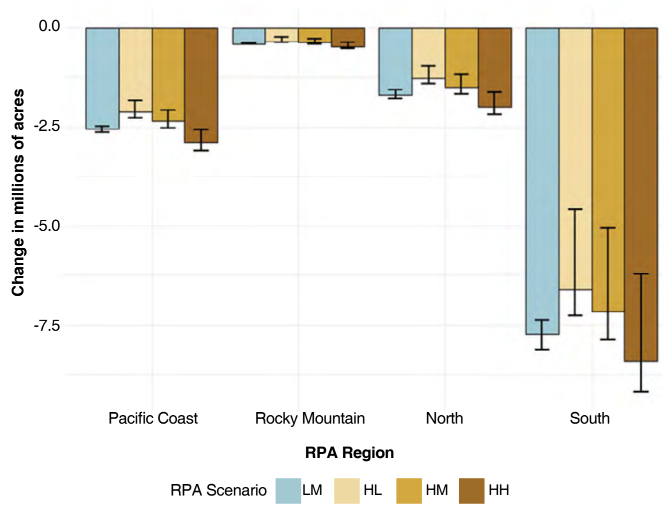
Notes: There are no transitions from developed to forest land. The sum of the rounded gross changes shown here may differ from the net changes shown in table 4-9.

The Pacific Coast Region is projected to lose between 2.5 million (LM-wet) and 3.1 million (HH-least warm) acres of forest land area, and the North Region is projected to lose between 1.6 million (LM-dry) and 2.2 million (HH-least warm) acres. The Rocky Mountain Region is projected to lose less than 0.5 million acres under all RPA scenario-climate futures. The large projected losses in the South Region can be explained by both the large initial base of forest area and the large projected gains in developed land area, mostly deriving from forest land. The small projected forest losses in the Rocky Mountain Region are explained by its much smaller initial base of forest area, and by the projection that rangeland is the dominant source of new developed land in this region.

To examine the impact of future atmospheric warming on future land use change, we compared the lower warming LM and high warming HM RPA scenarios (table 4-9), where warming varies across scenarios but economic growth is similar. The average net increase in developed land area is 52.0 percent across the five climate projections under the LM scenario, while the corresponding average is 49.6 percent under the HM scenario, a difference of 2.4 percent. The difference between the LM and HM scenarios suggests that a future with higher atmospheric warming avoids a moderate amount of new development to the benefit of non-developed land uses. Slight differences in socioeconomic projections between LM and HM may also play a role in the differing outcomes for land development found in our projections. However, an analysis where socioeconomic projections were held constant also found lower development rates associated with a higher warming future (Mihiar and Lewis in review). Avoided-development under the HM scenario primarily affects forest land, resulting in approximately 1.2 million acres of additional forest by 2070. The higher warming future also benefits pasture land, with projections for the HM scenario resulting in 0.8 million acres more pasture land than the LM scenario.

To examine the impact of economic growth on future land use change, we compared the low growth HL and high growth HH RPA scenarios (table 4-9), where economic growth varies across scenarios, but atmospheric warming remains constant. The influence of economic growth, represented by population and income projections, on new developed land far surpasses the influence of future warming described above when comparing the LM and HM scenarios. The average net expansion of developed land area (across the five climate projections) is 46.7 percent under the HL scenario, while the corresponding average is 56.3 percent under the HH scenario—a difference of 9.4 percent. Forest land is projected to be 3.5 million acres lower under the HH scenario than the HL scenario, and crop and pasture lands are also projected to be lower

Figure 4-19. Projected forest land net change from 2020 to 2070, by RPA region and RPA scenario. The range drawn within each bar represents difference in projection across climate projections.



LM = lower warming-moderate U.S. growth; HL = high warming-low U.S. growth; HM = high warming-moderate U.S. growth; HH = high warming-high U.S. growth.

under the HH scenario (by 2.2 million and 1.6 million acres, respectively). Our results suggest that scenarios assuming higher atmospheric warming reduce the projected expansion of developed land area, while scenarios assuming higher growth in population and income have the opposite impact. This result is supported by an extensive analysis of the impact of climate on land use change conducted by Mihiar and Lewis (in review).

This analysis projected 50-year net land use changes that are significantly different from the projected 50-year net changes reported in the 2010 RPA Assessment. In particular, the 2010 RPA Assessment projected an average increase in developed land area between 39 and 69 million acres from 2010 to 2060, while we project an increase in development ranging from 43.9 to 57.0 million acres from 2020 to 2070. Similarly, the 2010 RPA Assessment projected a 50-year average loss in forest land ranging from 16 to 34 million acres by 2060, whereas we project a 50-year loss in forest area ranging from 10.7 to 15.0 million acres by 2070. The difference in projected developed land area change is likely due to the declining annual rate of new developed land which began around the year 2000 (figure 4-3). The 2010 RPA Assessment projections were based on NRI data from 1987 to 1997 and did not reflect the declining annual rate after 2000.

Projected Tree and Impervious Cover Change

❖ Projections of tree and impervious cover were generally consistent among three representative scenarios which all indicated an increase in impervious cover and a slight increase in tree cover nationally.

Tree and impervious cover change alongside changes in land use. Tree cover is one of the simplest proxies for assessing the amount of forest and its associated benefits, for example moderating climate, reducing building energy use and atmospheric carbon dioxide (CO_2), providing wood products, improving air and water quality, mitigating rainfall runoff and flooding, providing wildlife habitat, enhancing human health and social well-being, and lowering noise impacts (Nowak and Dwyer 2007). Air pollution removal by conterminous United States trees and forests in 2010 was estimated at 19.2 million tons, with health effects valued at $6.8 billion (Nowak et al. 2014). These pollutants are: carbon monoxide (CO); nitrogen dioxide (NO_2); ozone (O_3); lead (Pb); sulfur dioxide (SO_2) and particulate matter (PM), which includes particulate matter less than 10 microns (PM_{10}) and particulate matter less than 2.5 microns ($PM_{2.5}$) in aerodynamic diameter. A critical question related to forest sustainability is how tree cover is likely to change given projected land use changes. By estimating the potential change in tree cover across the conterminous United States, forest management plans can be developed to provide desired levels of tree cover and forest benefits for current and future generations.

Impervious surfaces (such as roads and buildings) change alongside land and tree cover change. Impervious surfaces provide essential services to society, but they can also negatively impact the environment through increased air temperatures and heat islands (Heisler and Brazel 2010, Oke 1989). These environmental changes consequently affect building energy use, human comfort and health, ozone production, and pollutant emissions. In addition, impervious surfaces significantly affect urban hydrology (e.g., stream flow, water quality) (National Research Council 2008, US EPA 1983).

The projected land use changes in the 20 RPA scenario-climate futures (see the sidebar RPA Scenarios, above) were used to estimate changes in tree and impervious cover between 2020 and 2070. The baseline amount of 2020 tree and impervious cover in each land cover class of every county in the conterminous United States was calculated using the 2016 USDA Forest Service Tree Canopy Cover (TCC) dataset (USDA Forest Service 2019) and the NLCD 2016 Percent Developed Imperviousness (PDI) dataset (MRLC 2021). Because the 2001 NLCD tree canopy cover data underestimates tree cover (Nowak and Greenfield 2010), we applied similar photointerpretation (PI) methods to 4,000 random points across the conterminous United States to estimate tree and impervious cover within RPA land use classes and compare them with TCC estimates. There was no statistically significant difference between PDI and PI values for impervious cover; however, the TCC data underestimated PI tree cover by an average of 10.8 percent (table 4-12). An adjustment factor (table 4-12) was used to adjust tree cover for each TCC pixel estimate. Adjusted tree cover, hereafter referred to as tree cover, was then calculated for each RPA land cover class in each county of the conterminous United States.

For projections, the tree canopy cover estimated from the 2016 data was used as the 2020 base tree cover estimate. For each subsequent decade from 2030 to 2070, the projected area of each land use class was multiplied by the county-specific percent tree and impervious cover of the corresponding land cover class to estimate the tree and impervious cover in each county. If a county was missing a land cover class in 2020, the cover values from a neighboring county were used. This process assumed that the average tree and impervious covers in 2020 for each land cover class at the county level remain constant through time, with the land use class area changing through time (Nowak et al. 1996).

Three of the 20 RPA scenario-climate futures were selected for mapping and analysis of projected cover changes:

- **Average scenario (HM-wet).** The national average tree cover increase was closest to the average change among all RPA scenario-climate futures.
- **Maximum scenario (HL-hot).** The scenario had the highest average increase in tree cover.

Table 4-12. Comparison of USDA Forest Service tree canopy cover and photo-interpreted percent tree canopy cover estimates by RPA land use class.

Land use class	2016 TCC	2016 PI	Difference[a]	Adjustment factor[b]
Forest	58.9	75.4	-16.5	0.401
Developed	16.1	31.6	-15.5	0.185
Crop	2.2	8.0	-5.8	0.059
Pasture	14.2	25.6	-11.4	0.132
Other	2.6	10.9	-8.3	0.085
Water	0.4	5.6	-5.2	0.052
All classes	21.8	32.7	-10.8	na

AF = adjustment factor; NLCD = National Land Cover Database; PI = photo-interpreted; TCC = tree canopy cover.

[a] Difference in percent tree cover (TCC minus PI). All differences are significant at alpha = 0.05.

[b] Adjustment factor used to adjust TCC tree cover estimates; AF = -difference / (100 - NLCD tree cover).

- **Minimum scenario (HH-middle).** The scenario had the lowest average increase in tree cover.

Projected changes in tree and impervious cover were summarized by State, RPA region, and ecoregion (i.e., forest, desert, grassland) (Nature Conservancy 2018).

Projected Tree Cover Change

While the national average tree cover did not change much among the three scenarios, there were regionally consistent differences in tree cover change (figure 4-20). The overall projected national increase in tree cover between 2020 and 2070 in the average scenario was 0.02 percent. Areas projected to have tree cover increases were in central Florida, California, Texas, and Oklahoma; eastern Washington, Colorado, and Arkansas; southern Minnesota, Wisconsin, and Michigan; northern Missouri; western New York, Ohio, Kentucky, and Tennessee; and Illinois and Indiana. Tree cover loss was projected in New England; much of the Southeastern United States; northern Minnesota, Wisconsin, Idaho, and Louisiana; southern Missouri; eastern Texas, Oklahoma, and Kansas; and western Arkansas, Washington, and Oregon (figure 4-20).

Counties that had the largest projected increases in tree cover were typically in the RPA South Region. The counties with the largest decreases in tree cover were all city-based counties in Virginia (table 4-13), which are all much smaller than the typical U.S. county and tend to build out with the developed land use within their boundaries by 2070. Overall, the States with the largest projected increases in tree cover were Delaware (+0.9 percent), Indiana (+0.9 percent), and Illinois (+0.7 percent); greatest reductions in tree cover

Figure 4-20. Tree cover change for three RPA scenarios from 2020 to 2070.

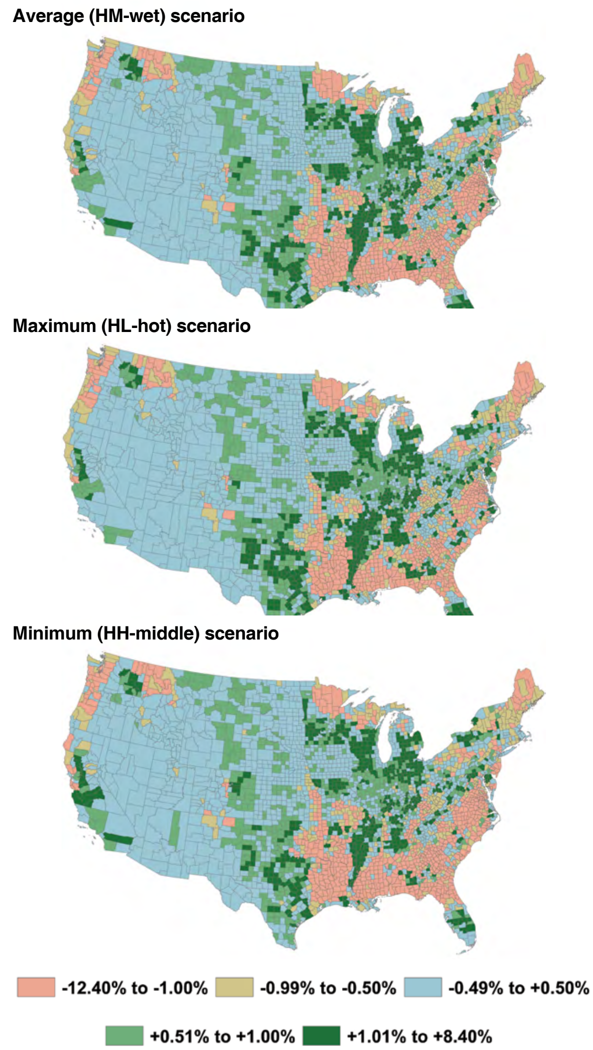


Table 4-13. Top five counties in the conterminous United States with the greatest projected increases and decreases in tree cover from 2020 to 2070 for the average, maximum, and minimum scenarios.

Average scenario HM-wet		Maximum scenario HL-hot		Minimum scenario HH-middle	
County	Change (percent)	County	Change (percent)	County	Change (percent)
		Projected increases			
Tunica, MS	+6.3	Desha, AR	+8.4	Tunica, MS	+5.8
Quitman, MS	+6.0	Tunica, MS	+7.3	Quitman, MS	+5.5
Desha, AR	+5.7	Arkansas, AR	+7.2	Jefferson, WV	+5.3
Dyer, TN	+5.7	Monroe, AR	+6.9	Dyer, TN	+5.2
Cross, AR	+5.2	Cross, AR	+6.8	Boone, AR	+4.8
		Projected decreases			
Petersburg city, VA	-7.6	Petersburg city, VA	-7.9	Danville city, VA	-8.6
Danville city, VA	-8.6	Danville city, VA	-8.8	Newton, TX	-9.4
Emporia city, VA	-11.1	Emporia city, VA	-11.0	Emporia city, VA	-10.8
Franklin city, VA	-12.0	Franklin city, VA	-12.0	Franklin city, VA	-11.6
Buena Vista city, VA	-12.4	Buena Vista city, VA	-12.3	Buena Vista city, VA	-12.1

HM = high warming-moderate U.S. growth; HL = high warming-low U.S. growth; HH = high warming-high U.S. growth.

were in Georgia (-1.3 percent), Maine (-1.1 percent), and Virginia (-1.1 percent). The North (+0.15 percent) and Rocky Mountain (+0.14 percent) Regions exhibited overall increases in projected tree cover while the Pacific Coast (-0.3 percent) and South (-0.24 percent) Regions exhibited decreases in projected tree cover (table 4-14). The grassland (+0.44 percent) and desert (+0.21 percent) ecoregions had projected increases in tree cover while the forest ecoregion (-0.30 percent) exhibited projected decreases in tree cover (table 4-15).

Table 4-14. Tree cover in 2020 by RPA region (percent of total area) and projected changes in tree cover in 2070 for the average, maximum, and minimum scenarios.

RPA region	2020	2070 for scenario:			Change for scenario:		
		Average HM-wet	Maximum HL-hot	Minimum HH-middle	Average HM-wet	Maximum HL-hot	Minimum HH-middle
	%	%	%	%	%	%	%
North	39.7	39.9	39.9	39.8	0.15	0.17	0.10
South	45.9	45.7	46.0	45.5	-0.24	0.05	-0.41
Rocky Mountain	17.9	18.0	18.0	18.0	0.14	0.13	0.14
Pacific Coast	34.0	33.9	34.0	33.9	-0.03	-0.02	-0.03
Conterminous U.S.	32.7	32.7	32.8	32.6	0.02	0.10	-0.04

HM = high warming-moderate U.S. growth; HL = high warming-low U.S. growth; HH = high warming-high U.S. growth.

Table 4-15. Tree cover in 2020 by ecoregion (percent of total area) and projected changes in tree cover in 2070 for the average, maximum, and minimum scenarios. Ecoregions are sorted by decreasing percent change for the average scenario.

Ecoregion	2020	2070 for scenario:			Change for scenario:		
		Average HM-wet	Maximum HL-hot	Minimum HH-middle	Average HM-wet	Maximum HL-hot	Minimum HH-middle
	%	%	%	%	%	%	%
Grassland	15.1	15.5	15.6	15.5	0.44	0.47	0.42
Desert	15.0	15.2	15.2	15.2	0.21	0.19	0.23
Forest	49.0	48.7	48.9	48.6	-0.30	-0.14	-0.40
Conterminous U.S.	32.7	32.7	32.8	32.6	0.02	0.10	-0.04

HM = high warming-moderate U.S. growth; HL = high warming-low U.S. growth; HH = high warming-high U.S. growth.

Projected Impervious Cover Change

While the average tree canopy cover did not change much, with some areas gaining tree cover and other areas losing tree cover, impervious cover was projected to increase throughout most of the conterminous United States from 2020 to 2070 (figure 4-21). The overall projected increase in impervious cover in the average scenario was 0.46 percent, 23 times greater than the net percent increase in tree cover (0.02 percent). Areas that exhibited the greatest projected increases in impervious cover were in the more densely populated regions of the United States.

Counties that had the largest projected increases of impervious cover were in California and Virginia (table 4-16). Less than 1 percent of counties were projected to have a decrease in impervious cover and the average decrease was negligible in those counties. Overall, the States with the largest projected increases in impervious cover were Delaware (+1.9 percent), California (+1.2 percent), and New Jersey (+1.0 percent). The Pacific Coast Region exhibited the largest overall increase in projected impervious cover (+0.87 percent), followed by the South (+0.62 percent), North (+0.50 percent), and Rocky Mountain (+0.18 percent) Regions (table 4-17). The forest ecoregion had the largest projected increase in impervious cover (+0.61 percent), followed by the grassland (+0.30 percent) and desert (+0.26 percent) ecoregions (table 4-18).

Discussion

The projections of tree and impervious cover across the conterminous United States were generally consistent among the average, maximum, and minimum scenarios. All scenarios showed an increase in impervious cover and

Table 4-16. Top five counties in the conterminous United States in terms of greatest projected increases and decreases in impervious cover from 2020 to 2070 for the average, maximum, and minimum scenarios.

Average scenario HM-wet		Maximum scenario HL-hot		Minimum scenario HH-middle	
County	**Change (percent)**	**County**	**Change (percent)**	**County**	**Change (percent)**
Projected increases					
Santa Clara, CA	+14.2	Santa Clara, CA	+10.6	Stanislaus, CA	+19.7
Stanislaus, CA	+13.8	Franklin city, VA	+10.2	Santa Clara, CA	+18.7
Franklin city, VA	+9.9	Stanislaus, CA	+9.1	Franklin city, VA	+9.6
Buena Vista city, VA	+9.1	Buena Vista city, VA	+9.0	Bowie, TX	+9.2
Emporia city, VA	+8.1	Emporia city, VA	+8.2	Buena Vista city, VA	+8.7
Projected decreases					
Daniels, MT	-0.0015	Judith Basin, MT	-0.0015	Daniels, MT	-0.0015
Hall, TX	-0.0022	Greeley, NE	-0.0023	Greeley, NE	-0.0018
Sheridan, KS	-0.0023	Sheridan, KS	-0.0024	Hall, TX	-0.0019
Greeley, NE	-0.0024	Hall, TX	-0.0032	Sheridan, KS	-0.0023
Floyd, IA	-0.0051	Floyd, IA	-0.0051	Floyd, IA	-0.0046

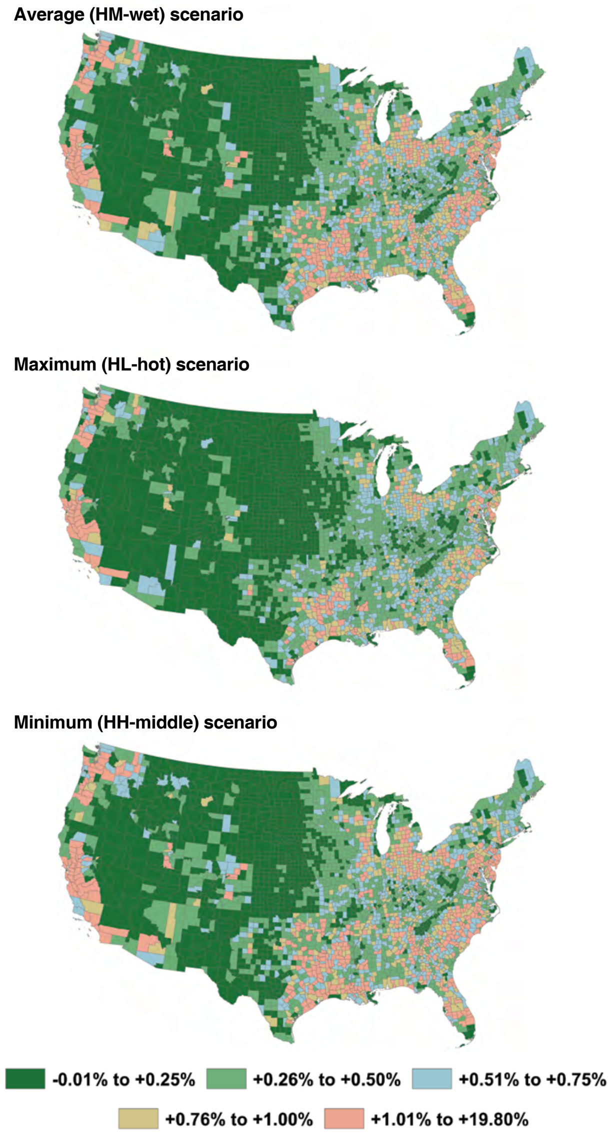
HM = high warming-moderate U.S. growth; HL = high warming-low U.S. growth; HH = high warming-high U.S. growth.

Table 4-17. Impervious cover in 2020 by RPA region (percent of total area) and projected changes in impervious cover in 2070 for the average, maximum, and minimum scenarios.

RPA region	2020	2070 for scenario:			Change for scenario:		
		Average HM-wet	Maximum HL-hot	Minimum HH-middle	Average HM-wet	Maximum HL-hot	Minimum HH-middle
	%	%	%	%	%	%	%
North	2.2	2.7	2.6	2.7	0.50	0.41	0.52
South	1.8	2.4	2.3	2.4	0.62	0.52	0.67
Rocky Mountain	0.5	0.6	0.6	0.7	0.18	0.15	0.20
Pacific Coast	1.6	2.5	2.3	2.8	0.87	0.69	1.16
Conterminous U.S.	1.4	1.8	1.7	1.9	0.46	0.37	0.51

HM = high warming-moderate U.S. growth; HL = high warming-low U.S. growth; HH = high warming-high U.S. growth.

Figure 4-21. Impervious cover change for three RPA scenarios from 2020 to 2070.



a little net growth in tree cover nationally. The scenarios also exhibited generally consistent regional variation of changes in tree and impervious cover. Impervious cover was projected to increase by an average of 0.46 percent (from 1.4 to 1.8 percent of the land base), which is a 34 percent relative increase in impervious cover. The projected increase in impervious cover was consistent with recent trends of increasing impervious cover in urban areas nationally (Nowak and Greenfield 2018) and within urban areas globally (Nowak and Greenfield 2020).

While it is likely that impervious cover will increase due to expanding human populations and associated land development, the outcome for tree cover is less certain because many interacting factors affect tree cover, including land use change, climate change, forest policies and management activities, and natural disturbances. Furthermore, these factors are themselves influenced by the natural environment and human policies and activities. Thus, the projected changes in tree cover based on projected land use changes may not be realized, depending on how those factors alter tree cover. While total tree cover area is not projected to change much, it is likely to shift among regions, with some areas gaining and others losing tree cover. By understanding these potential changes and the reasons for these changes, forest management plans can be devised to sustain healthy forests that promote human health and well-being for current and future generations.

Table 4-18. Impervious cover in 2020 by ecoregion (percent of total area) and projected changes in impervious cover in 2070 for the average, maximum, and minimum scenarios. Ecoregions are sorted by decreasing percent change for the average scenario.

Ecoregion	2020	2070 for scenario:			Change for scenario:		
		Average HM-wet	Maximum HL-hot	Minimum HH-middle	Average HM-wet	Maximum HL-hot	Minimum HH-middle
	%	%	%	%	%	%	%
Grassland	1.8	2.4	2.3	2.5	0.61	0.51	0.69
Desert	1.0	1.3	1.2	1.3	0.30	0.24	0.32
Forest	0.6	0.8	0.8	0.9	0.26	0.20	0.31
Conterminous U.S.	1.4	1.8	1.7	1.9	0.46	0.37	0.51

HM = high warming-moderate U.S. growth; HL = high warming-low U.S. growth; HH = high warming-high U.S. growth.

Projected Land Use Patterns

- ❖ Future changes to spatial patterns of land use, such as landscape dominance and natural interface area, are strongly related to projected changes in general land use area.
- ❖ New development is projected to occur near existing development, almost doubling the area of developed-dominant land.
- ❖ Projected new development increases the area of the developed-natural interface and shifts land from the agricultural-natural interface to the joint developed-agricultural-natural interface.
- ❖ Projected land use pattern changes are consistent across all 20 RPA scenario-climate futures. The RPA scenarios had a greater impact than the climate projections on future landscapes near man-made land uses, but both drivers had about the same degree of impact in less-modified landscapes.
- ❖ While overall forest land use area was projected to decrease, the share of more-contiguous forest was projected to increase in the RPA South Central, Northeast, and North Central Subregions.

Future land use changes are likely to result in landscape pattern changes, but additional analyses were needed to project changes in landscape patterns from the county-level land use projections described in the section Land Use Projections. In this section, the county-level land use projections were downscaled (disaggregated) into spatially explicit land use maps at 90 m spatial resolution (approximately 2 acres per pixel), and the future landscape patterns were measured on those maps. The downscaling applied a demand-allocation simulation method (Brooks et al. 2020) to a 2020 land use base map for the conterminous United States. For each of the 20 RPA scenario-climate futures (four RPA scenarios, five climate projections), future land use maps were simulated at decadal intervals until 2070. The simulations were repeated 20 times for each scenario-climate future, each time assuming a different degree of spatial randomness of land use changes (Brooks et al. 2020). We then measured landscape patterns on each of the 2,000 simulated future maps (20 scenario-climate futures x 5 decades x 20 simulations). Following the naming conventions of the land use projections, "developed" includes the NRI developed class, "agriculture" includes the crop and pasture classes, and "natural" includes forest and other non-developed and non-agricultural NRI classes. The simulated spatial changes were applied only on privately owned land area (Conservation Biology Institute 2016), but for consistency with overall land area totals, the public land (Federal, State, and local government) and Tribal ownerships were included in the landscape pattern analysis. This section focuses on cumulative simulated changes from 2020 to 2070 to evaluate climatic, socioeconomic, and regional differences in future landscape patterns.

The future landscape pattern around each pixel was described by one of four dominance classes and one of four interface classes (see the section Historical Forest Fragmentation and Landscape Context) within a 162-acre neighborhood. In addition, future forest fragmentation was assessed by classifying future forest pixels into "interior" and "non-interior" forest, where interior forest is defined as a forest pixel at the center of a 162-acre neighborhood that is at least 90-percent forested (Riitters and Robertson 2021). Despite using the same general methods, we do not recommend strict comparisons of landscape patterns in this section and in the section Historical Forest Fragmentation and Landscape Context due to scale differences and qualitative differences between land use and land cover.

The county-level land use projections for all scenarios indicate increases in developed land area, drawing primarily from forested and other natural lands. The future changes of landscape patterns reflect those trends, as modified by several simulated degrees of randomness which placed future land use changes either near or far from existing area of the same land use (Brooks et al. 2020). Driven by the land use projections, we expect overall increases in the area of developed-dominated landscapes and developed interfaces, and a decrease of interior forest area. Where forest and agriculture land uses are both converted to developed area, the landscapes become more heterogeneous with the local blending of developed, agriculture, and natural land.

We summarize the overall results for the conterminous United States across all simulations, followed by comparisons among subsets of simulations defined by RPA scenarios and climate projections (see the sidebar RPA Scenarios). One RPA scenario and one climate projection were selected as "base cases" and the remaining models and scenarios were compared in terms of deviations from the base cases. The base cases, chosen to reflect "middle-ground" situations, were the HM RPA scenario and the middle climate projection. All comparisons were made using median outcomes across all simulations within a given set of scenarios and/or climate projections. Projected changes among classes were summarized in terms of net changes.

National Results

Across all RPA scenarios, climate projections, and simulations, the projected trends in landscape dominance generally followed the corresponding county-level trends. Developed-dominated land area was projected to increase by a median of 47.3 million acres (95 percent) from 2020 to 2070 (table 4-19). This area was balanced primarily

Table 4-19. Projected changes in landscape dominance from 2020 to 2070 across all RPA scenarios, climate projections, and simulations. Note that the median values do not necessarily sum to zero.

Dominance class	Median change	Range of change	Relative median change
	million acres	million acres	percent
Developed	+47.3	(+32.6, +56.8)	+95.1
Agriculture	-29.4	(-35.0, -25.4)	-7.03
Natural	-19.0	(-24.3, -9.6)	-1.49
Mixed	-0.03	(-3.2, +9.6)	-0.02

by median decreases of 29.4 million acres (7 percent) of agriculture-dominated land and by 19.0 million acres (1 percent) of natural-dominated land. The land area in the "mixed" dominance class (where no one land use covers more than 60 percent of the surrounding area) was projected to increase slightly across all models and scenarios (<0.1 million acres, <0.1 percent). Figure 4-22 illustrates the distribution of simulated changes for all simulations of the RPA scenario-climate futures.

With one exception, the projected RPA regional trends in dominance class area (table 4-20) generally conformed to historical trends in land cover dominance (figure 4-13). The exception was that the historical increase in agriculture-dominated land from 2001 to 2016 in the Rocky Mountain Region was not projected to continue. While differences between land cover and use may account for some of this trajectory change in landscape dominance, the projections were consistent with the county-level land use projection models, which indicated a future decrease of agriculture land area in that region.

We also assessed projected trends in the median areas of interface classes (figure 4-23, table 4-21). Across all simulations, the median share in the developed interface class was projected to increase by 49.9 million acres (76 percent) from 2020 to 2070, comparable to the projected increase of area in developed-dominated land. Like dominance, this increase was drawn from the agriculture interface area which had a projected decrease of 45.6

Figure 4-22. Projected net area changes of four landscape dominance classes across the conterminous United States from 2020 to 2070. The bars represent the median values across all RPA scenarios, climate projections, and simulations. The violin plots indicate the distribution of simulated values, with the violin height representing the full range of values and the width representing their relative frequency.

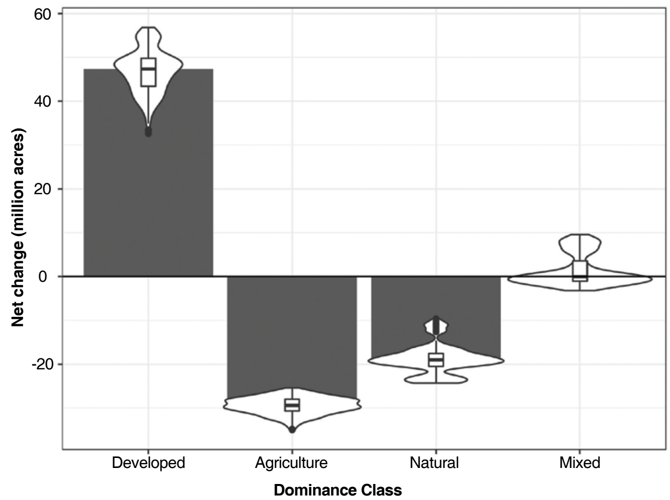


Figure 4-23. Projected net area changes of four landscape interface classes across the conterminous United States from 2020 to 2070. The bars represent the median values across all RPA scenarios, climate projections, and simulations. The violin plots indicate the distribution of simulated values, with the violin height representing the full range of values and the width representing their relative frequency.

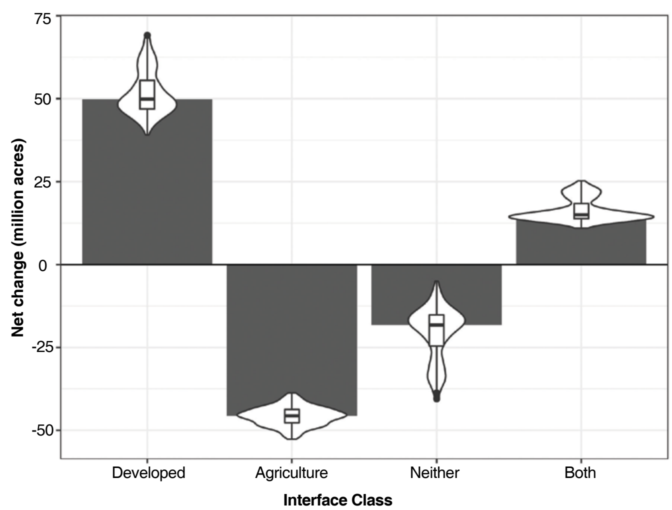


Table 4-20. Projected median change in landscape dominance area from 2020 to 2070 across all RPA scenarios, climate projections, and simulations, by RPA region. Values in parentheses indicate the range.

	Landscape dominance class (million acres)			
RPA region	**Developed**	**Agriculture**	**Natural**	**Mixed**
North	+12.4 (8.69, 14.7)	-11.4 (-12.9, -9.72)	-0.74 (-1.47, -0.09)	-0.66 (-1.29, +2.14)
South	+21.5 (16.1, 26.0)	-10.7 (-14.3, 8.63)	-8.97 (-11.2, -4.72)	-2.51 (-3.89, -1.99)
Rocky Mountain	+5.89 (2.99, 7.60)	-4.25 (-4.85, -3.68)	-3.48 (-5.04, -0.76)	+1.82 (0.94, 3.22)
Pacific Coast	+7.51 (4.89, 9.37)	-3.05 (-3.87, -2.41)	-5.76 (-7.36, -3.89)	+1.33 (0.952, 2.29)

Table 4-21. Projected changes in interface class area from 2020 to 2070 across all RPA scenarios, climate projections, and simulations. Note that the median values do not necessarily sum to zero.

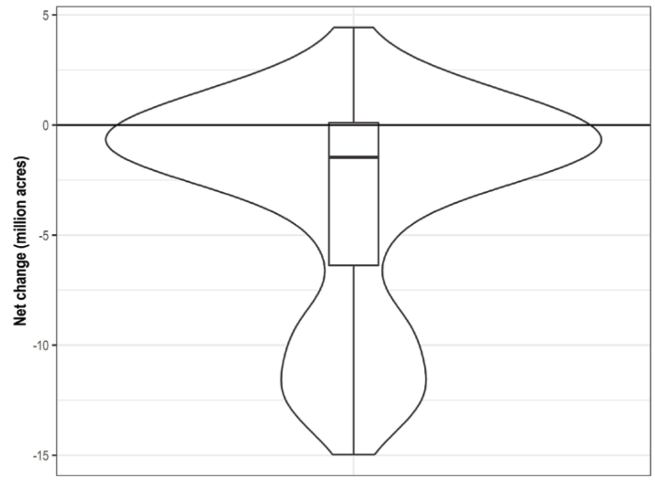
Interface class	Median change	Range of change	Relative median change
	million acres	million acres	percent
Developed	+49.9	(+39.1, +69.2)	+76.1
Agriculture	-45.6	(-52.6, -38.7)	-8.04
Neither	-18.2	(-40.5, -5.05)	-1.69
Both	+15.0	(+11.0, +25.2)	+19.6

million acres (8 percent), and non-interface area which was projected to decrease by 18.2 million acres (2 percent). The "both" interface area (where both developed and agriculture interface with natural landscapes) was projected to increase by 15.0 million acres (20 percent), which contrasts with the relatively stable share of land in the corresponding mixed dominance class. This difference is accounted for by noting that the projected decrease in agriculture interface area exceeds that of the agriculture-dominated area by more than 15 million acres. Put another way, while lands with agricultural context are generally being converted to lands with a more developed context, a considerable part of this conversion (the 15 million acres) is from non-interface land with more than 90-percent agriculture in the neighborhood to land that has at least 60-percent agriculture (i.e., remains agriculture-dominant) but now includes at least 10-percent developed land as well (i.e., becomes "both" interface).

While the values reported here are net changes across all simulations, maps of gross change (not shown here) suggest that conversion of natural land to agriculture land occurs near existing development, and that new developed land tends to be connected to existing development. Support for this interpretation is in the "long tails" in the violin plots (figure 4-23), where simulations with extremely large areas of developed interface have correspondingly small areas of non-interface land.

We assessed projected trends of interior forest area to evaluate the effects of land use change on forest fragmentation from 2020 to 2070. Over all simulations, the median projected interior forest area change was a decrease of 1.5 million acres (figure 4-24). That loss is equivalent to approximately 12 percent of the projected net forest area loss during that time (table 4-9). However, variation across the RPA scenarios and climate projections was such that over a quarter of the simulations exhibited a projected increase in interior forest, suggesting that the direction and the degree of interior area change depends on both future climate and socioeconomic trends.

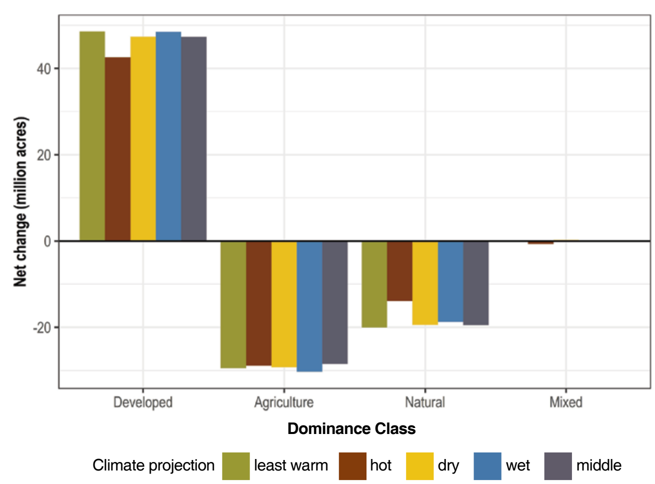
Figure 4-24. Distribution of projected changes in interior forest area from 2020 to 2070, across all RPA scenarios, climate projections, and simulations. The violin height represents the full range of values, and the width represents their relative frequency.



Climate Projection Results

To compare the main effects of the different climate projections on projected landscape patterns, we aggregated projected changes across all RPA scenarios and simulations separately within each climate projection and compared the median results of each projection with those of the middle climate projection base case. Figure 4-25 shows the effects of the different climate projection on projected future landscape dominance patterns. Impacts on each dominance class were consistent across all climate projections; however,

Figure 4-25. The effect of climate projection on landscape dominance, displayed as median projected change from 2020 to 2070.



the hot projection produced the most divergent results. In particular, the hot projection inhibited the general increase in developed-dominated land area (4.3 million fewer acres gained than the middle projection of 47.3 million acres gained), with a corresponding inhibition in the reduction of natural-dominated land (5.8 million fewer acres lost than the middle projection of 19.5 million acres lost). The difference between the hot and least warm climate projections was larger than the difference between the dry and wet projection. The wet projection resulted in the largest acceleration to reductions to agriculture-dominated land (1.8 million acres more lost than the middle projection of 28.5 million acres lost), with the balance spread across developed and natural dominant lands.

Figure 4-26 shows the effects of the different climate projections on future interface classes. As with landscape dominance, all climate projections result in the same direction of change: increasing developed interface and interface between both developed and agriculture with the natural landscape ("both"), with decreasing agriculture and neither-interface. The hot climate projection again generally projects the most divergent results, including an inhibited increase to developed interface land and a corresponding inhibited decrease to the neither interface. Also similar to their effects on landscape dominance, the difference between the hot and least warm climate projections was larger than the difference between the dry and wet projections. The hot projection reduced the projected developed interface net gain by 3.2 million acres, consistent with the effect on developed-dominated land. The wet projection resulted in the most accelerated decrease in agriculture interface land (similar to that projection's effect on agriculture dominated land): agriculture interface class area was projected to decrease by 2.2 million acres beyond the middle projection, with the balance spread across the other interface classes.

Figure 4-26. The effect of climate projection on natural interface, displayed as median projected change from 2020 to 2070.

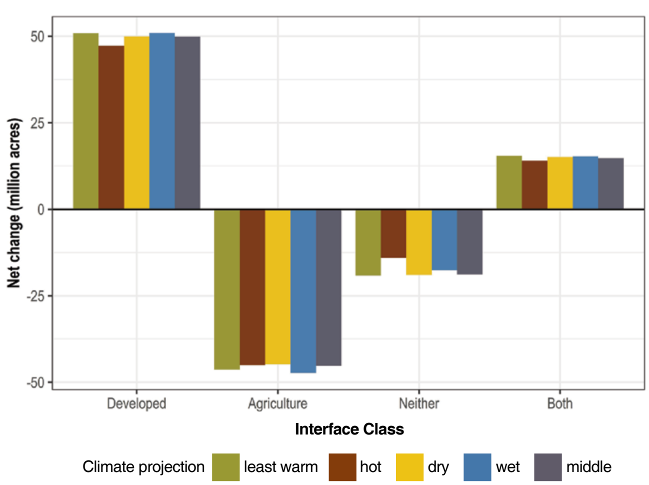


Figure 4-27. The effect of climate projection on interior forest, displayed as median projected change from 2020 to 2070.

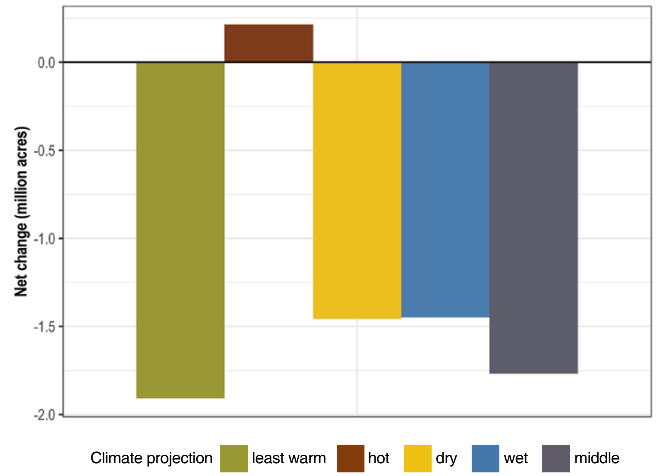


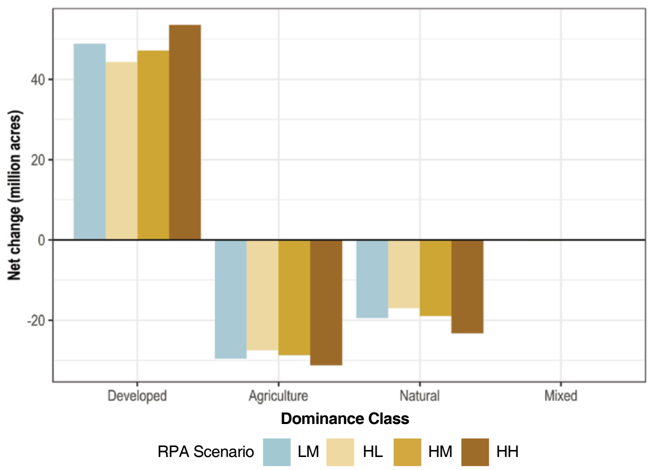
Figure 4-27 shows the effect of the different climate projections on projected future interior forest area. As with dominance and interface classes, the hot climate projection produced the most divergent results, yielding in this case a median projected increase to interior forest area. This result contrasts with a decrease of 1.8 million acres projected by the middle climate projection, as well as decreases of 1.5 million acres under the dry and wet projections, and 1.9 million acres under the least warm projection. Under the hot projection, the relatively slower increase of developed land results in relatively more remaining natural land, including interior forest. This suggests that under the hot projection, developed land is drawing from a mixture of non-interior forest and agricultural lands.

RPA Scenario Results

To compare the effects of the different RPA scenarios on projected landscape patterns for the conterminous United States, we aggregated projected changes across all climate projections and simulations separately within each RPA scenario (figure 4-14), and then contrasted the median results for each scenario with the base case (HM RPA scenario).

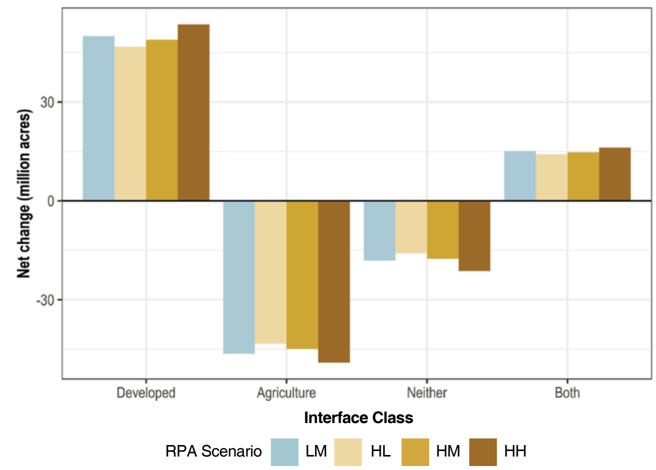
Figure 4-28 shows the effect of the RPA scenario on projected landscape dominance. The differences between high and low growth (HH and HL, respectively) had a greater effect on landscape dominance than the contrast between lower and high atmospheric warming (LM and HM, respectively). High growth was projected to increase developed-dominated land by 9.3 million acres more than the low growth scenario and 6.4 million acres above the HM base scenario. This additional

Figure 4-28. The effect of RPA scenario on landscape dominance, displayed as median projected change from 2020 to 2070.



LM = lower warming-moderate U.S. growth; HL = high warming-low U.S. growth; HM = high warming-moderate U.S. growth; HH = high warming-high U.S. growth.

Figure 4-29. The effect of RPA scenario on natural interface, displayed as median projected change from 2020 to 2070.



LM = lower warming-moderate U.S. growth; HL = high warming-low U.S. growth; HM = high warming-moderate U.S. growth; HH = high warming-high U.S. growth.

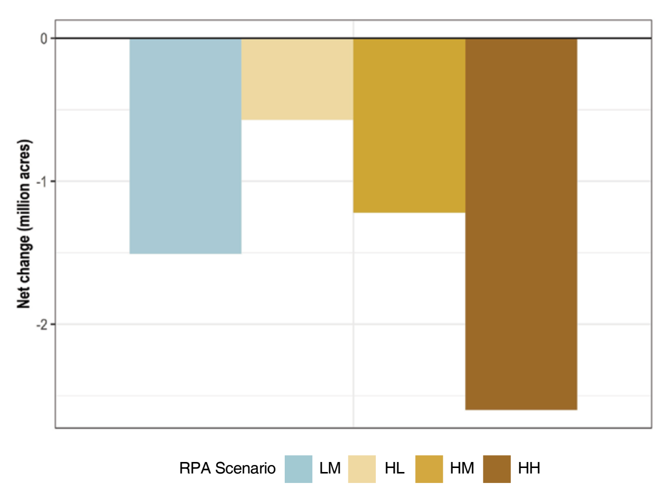
development came from agricultural and natural lands, resulting in lower projected areas for those dominance classes. The reduced projected developed-dominant land projected under the low growth scenario results in more agricultural- and natural-dominant areas. Trends for the LM scenario tended to mirror those for the HH scenario, albeit with a reduced magnitude of change relative to the HM base scenario.

Figure 4-29 shows the effect of the RPA scenario on projected interface class area. General patterns conformed to those for landscape dominance, with the main difference being an increased shift from the agriculture interface into the "both" interface class as compared to agriculture- and mixed-dominated land, respectively. This effect was more pronounced under the HH scenario, suggesting that the driver of the increased "both" interface area over the agriculture interface is economic growth (with more growth leading to more interface area containing both developed and agriculture land).

Figure 4-30 shows the effect of the RPA scenario on projected interior forest area. While the loss of interior forest area under HL is less than in other scenarios, the median interior forest area is projected to decrease across all scenarios. The loss of interior forest area from 2020 to 2070 under the HH scenario, 2.6 million acres, is over four times greater than the loss under the HL scenario (0.6 million acres). As with landscape dominance and interface classes, comparing projected results associated with the different economic growth levels (SSP) of the scenarios resulted in larger differences than the different warming levels (RCP).

Comparing the relative sensitivity of the results to RPA scenarios and climate projections, we found the former to be a stronger driver of differences in landscape dominance (compare figures 4-25 and 4-28) and landscape interface (compare figures 4-26 and 4-29) near artificially created land uses. In contrast, both drivers of change resulted in about the same degree of variation in less-modified landscapes. Taking landscape dominance as an example, the range of developed-dominated land area in 2070 is 9.2 million acres across RPA scenarios and 5.9 million acres across climate projections. For agriculture-dominated land area, the range is 3.7 million acres across RPA scenarios and 1.8 million acres across climate projections. The range for natural-dominated land area differed very little between RPA scenarios (6.3 million acres) and climate projections (6.2 million acres). While the

Figure 4-30. The effect of RPA scenario on interior forest, displayed as median projected change from 2020 to 2070.



LM = lower warming-moderate U.S. growth; HL = high warming-low U.S. growth; HM = high warming-moderate U.S. growth; HH = high warming-high U.S. growth.

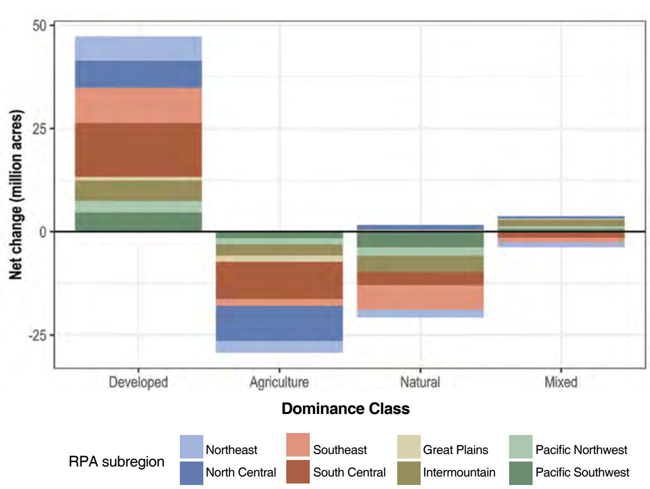
opposite result was obtained for the mixed dominance class, the magnitudes of those ranges are small in comparison to the other dominance classes (0.4 million acres for RPA scenarios versus 0.9 million acres for climate projections). Like natural-dominated land area, there is slightly more variation among climate projections than among RPA scenarios for non-interface land area and interior forest area because those conditions generally occur in less-modified landscapes.

Regional Results

Projected changes were expected to vary geographically because of regional differences in biophysical constraints on land use and in initial socioeconomic conditions. Those differences imply that regional differences are inseparable from climate projection and RPA scenario differences, which prevents identifying projection or scenario differences at the regional level. Thus, we estimated regional changes in terms of median outcomes across all simulations, by RPA subregion (figure 2-1).

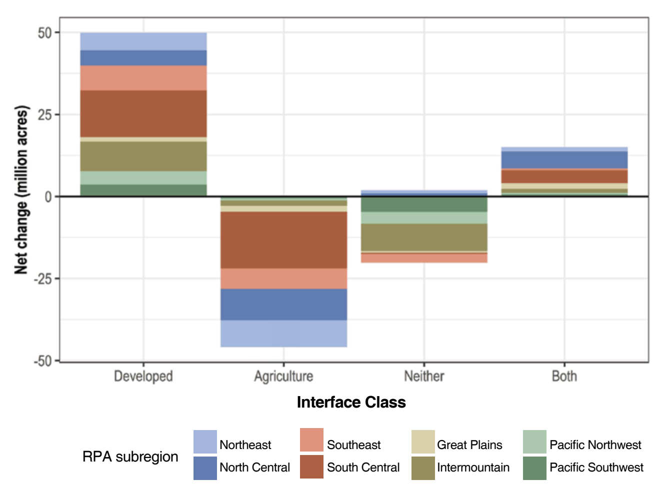
The area of developed-dominated land was projected to increase in all subregions, but the offsetting changes to other dominance classes varied among subregions (figure 4-31). Agriculture-dominated area was projected to decrease in all subregions, while natural-dominated land area was projected to decrease in all subregions except the North Central and Great Plains Subregions. The area of the mixed dominance class is projected to decrease in the eastern subregions and increase in the western subregions. The projections are generally similar to historical land cover dominance results (see the section Historical Forest Fragmentation and Landscape Context), with the exception that the historical increase of agriculture-dominated area in the Rocky Mountain Region was not projected to continue.

Figure 4-31. Projected net area change of four landscape dominance classes from 2020 to 2070, by RPA subregion. The bars represent median subregional net changes across all RPA scenarios, climate projections, and simulations.



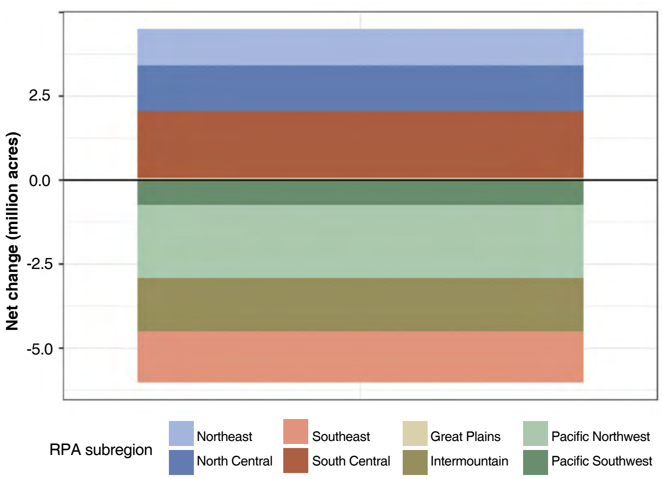
Projected trends of interface class areas were generally similar to those of landscape dominance, except for the “both” interface class as compared to mixed-dominated class (figure 4-32): the median “both” interface area increased for all subregions, whereas the Northeast, Southeast, and South Central Subregions all saw decreases to mixed-dominated land area. For changes in both dominance and interface classes, subregional differences in initial conditions (i.e., the original area of each class) largely explained subregional differences of the change (analysis not shown here). The projected changes in interface classes were generally similar to historical changes based on land cover, with the same exception to historical trends in the Rocky Mountain Region.

Figure 4-32. Projected net area change of four landscape interface classes from 2020 to 2070, by RPA subregion. The bars represent median subregional net changes across all RPA scenarios, climate projections, and simulations.



Projected changes of interior forest area were driven by the net loss of total forest area and by the locations of forest gains and losses in relation to the locations of the extant forest. Despite the overall projected loss of total forest area, the projected net change in interior forest from 2020 to 2070 varied by subregion (figure 4-33). The Southeast Subregion and the western subregions were projected to experience a decrease of interior forest area, with the largest area decrease in the Pacific Northwest Subregion. Interior forest area was projected to increase in the northern and eastern subregions, particularly in the South Central and North Central Subregions. That these subregional increases were projected despite concordant overall forest loss suggests a consolidation of contiguous forest in those subregions.

Figure 4-33. Projected net change of interior forest area from 2020 to 2070, by RPA subregion. Values shown are the medians across all RPA scenarios, climate projections, and simulations.



While these median projections are impacted by both climate and socioeconomic factors, as previously shown for the overall conterminous United States, we found no instance where such variation changed the direction of the projected subregional trends.

Management Implications

Historical patterns of land use and land cover changes are likely to continue under any future scenario, albeit at different rates than projected for the 2010 RPA Assessment. Apart from the projected increase in urban land use area, mostly deriving from land in forest and agriculture uses, the primary implication is related to the specific locations of new urban or developed land. Will future urban growth continue to expand upon the existing urban areas as our projections indicate? Or will other socioeconomic drivers such as resource scarcity or pandemics lead to a concentration within existing urban areas or to a more dispersed pattern of development? Urban densification would place additional pressures on urban forests, while the conversion of rural land would create new "urban interface" landscapes where land managers, both private and public, could face novel pressures in some areas. As more stakeholders with potentially new expectations enter conversations about land management, more emphasis could be placed on "all-lands" or "partnership" management approaches that encourage public engagement.

Our analyses of land use change considered only the value of timber commodities in valuing forest land and did not directly value other forest ecosystem services such as carbon storage, water quantity, or wildlife habitat. These values are discussed in the Forest Resources, Water Resources, and Biodiversity Chapters but were not explicitly included in our land use models. Placing additional value on those services would tend to increase the relative economic return to forest compared to other land uses that do not supply those services, which in turn would tend to increase the area of forest remaining forest.

Our current models suggest that socioeconomic drivers of land use and cover change play a more significant role than climate drivers. If so, then management actions taken in response to actual or expected climate change in a specific circumstance are unlikely to alter the fundamental economic drivers of forest land use change, unless the actual changes are so unusual or widespread that economic considerations play a smaller role in future choices of land use and cover. At the same time, climate change has the potential to become the most important driver of long-term land use changes. Our future projection models are based on historical land use and economic data from a time when climate change was arguably less important than it may become in the future. Even intense but localized disturbances such hurricanes and large wildfires have not fundamentally altered land use, nor the major drivers of land use change at regional scales. This is not to say that climate change had less import in prior decades, only that our future projections are based on data from that period. It is therefore not surprising that economic factors dominate climate factors in our future projections of the nation's land resources. However, in the past several years there is evidence of large-scale climate-related events such as prolonged extreme drought in the Western States which could be harbingers of fundamental changes in the capacity to support some land uses over large areas. Another example is sea level rise, which has the potential to change land use dynamics over large coastal regions. With the advent of such climate-related phenomena, some areas may no longer have the capacity to support traditional land uses indefinitely, which could shift those land uses and the associated provision of ecological services to other geographic areas. While it may never be possible to adequately project all the local changes in climate, land use, and land cover that could occur, model improvements would help to better address the range of potential future impacts on the land base at both local and regional scales.

Conclusions

This chapter summarized recent trends of land use and land cover and presented future projections to 2070 based on RPA scenarios. Historical analysis of FIA data indicated that the total forest and woodland area in the conterminous United States has been relatively stable for several decades. The NRI data for only non-Federal forest land indicated a slight gain of forest area from 1982 to 2012, mostly from previously agricultural land uses. In contrast, the total area with forest cover, across all land uses, declined by approximately 3 percent from 2001 to 2016. The difference was explained in part by the loss of forest cover in areas not used as forest, and in part by the temporary loss of forest cover in areas used as forest.

While the total forest area has been relatively stable, the forest and land resources of the United States are highly dynamic over time and space. Because the spatial arrangement of the forest changes over time, the consequent changes in fragmentation and landscape context are often much larger than suggested by net area change alone. Shorter term changes such as the use of agriculture land for pasture or cultivated crops and the transitional cover of forest land use with forest, grass, or shrub covers are driven largely by economic returns to agriculture and forest management but also by temporary forest disturbances. Such changes are pervasive on privately owned land, relatively less common on public lands, and cumulatively affect a much larger total area than is indicated by net area changes over time. Over the long term, the most important lasting land use change has been and will likely continue to be the conversion of rural lands to urbanized lands, driven by increasing U.S. population and relative economic returns to development in comparison with returns to either agriculture or forest operations.

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Chapter 5

Disturbances to Forests and Rangelands

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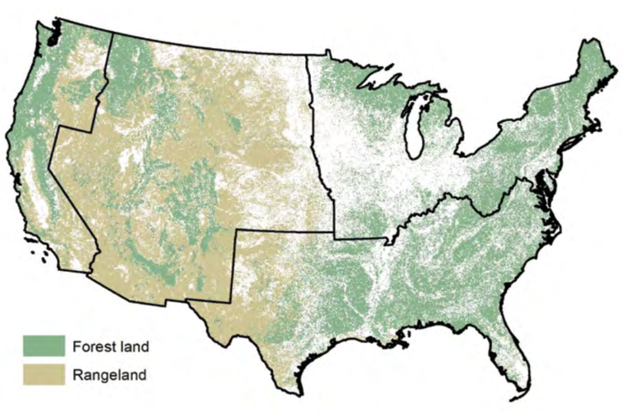
Disturbances including fire, insect and disease outbreaks, and drought are ubiquitous in forests and rangelands, and many disturbance events are parts of the natural dynamics of forest and rangeland ecosystems. This chapter is a new addition to the Resources Planning Act (RPA) Assessment and summarizes disturbance trends in the recent past and projected future trends within forests and rangelands across the conterminous United States. We assess status and trends of abiotic and biotic disturbance agents, including fire, drought, insects and disease, and nonnative invasive plants. Along with those agents, we summarize some forest management actions—prescribed burning and removals—that can be classified as disturbances because they alter environmental conditions and lead to changes in forest structure or community composition (White and Jentsch 2001), even though they can lead to forest resilience in the long term. The chapter is organized into sections focused on individual disturbance agents, most of which are summarized for forests and rangelands, with the exceptions of insect and disease agents and removals which are summarized only for forests. At the end of the chapter, we present a look at recent exposure of forests to multiple disturbances: removal, stress, and fire. Quantitative summaries emphasize *exposure* to disturbances: that is, trends or changes in the extent, severity, frequency, or duration of a disturbance from historical conditions, or expected future change from recent trends (Glick et al. 2011, Thorne et al. 2018). Where possible, we examine disturbance exposure alongside information about the sensitivity and adaptive capacity of forests and rangelands to disturbances and changing disturbance regimes. We conclude with general management considerations for incorporating information on changing disturbance regimes into planning and actions that can increase resilience of forest and rangeland ecosystems to global change.

Key Findings

- The annual area of fire in forests and rangelands has increased since 1984, and the average annual area burned from 2000 to 2017 was more than double the pre-2000 average.
- The two western RPA regions have generally had higher exposure to fire and drought than the eastern regions, as well as the greatest rates of tree mortality caused by insects and diseases. In contrast, forests in the RPA South Region have experienced the highest rates of removals.
- The highest rates of invasion by nonnative plants occur near agricultural or developed land uses, primarily in forests in the RPA South Region and portions of the North Region, as well as rangelands in the Pacific Coast Region.
- Fire-caused tree mortality in forests is expected to increase by 2070. The highest rates of fire mortality are expected if climate follows the hot or dry climate futures under any of the high warming RPA scenarios.
- Drought exposure for forests and rangelands is expected to increase by 2070, and forest and rangeland ecosystems in the Southwest are expected to experience the most substantial increases.

A disturbance can be defined as an event that changes environmental conditions within an ecosystem. Disturbances combine with other biotic, abiotic, and biophysical factors to affect forests, rangelands, and the services and resources derived from those ecosystems (Kelly et al. 2020, Seidl et al. 2016). As climate, other biophysical factors, and management regimes change, disturbance regimes are being altered (Bowman et al. 2020, Donovan et al. 2017, Pureswaran et al. 2018, Sommerfeld et al. 2018), with the possibility of some disturbance types becoming more frequent, severe, or longer in duration (Cook et al. 2015, Dale et al. 2001, Seidl et al. 2017). At the same time, some disturbance types have become less frequent in certain ecosystems (for example, Nowacki and Abrams 2014, Steel et al. 2015). These alterations to disturbance regimes have the potential to drive changes in the distribution, structure, species composition, or function of forest and rangeland ecosystems, putting those ecosystems at risk and presenting challenges for management (Anderson-Teixeira et al. 2013, Clark et al. 2016, Coop et al. 2020, Vose et al. 2018). There is mounting evidence that management actions such as thinning or prescribed fire may play key roles in mitigating or ameliorating the impacts of disturbances like drought in some ecosystems (Bradford and Bell 2017, Knapp et al. 2021, Krofcheck et al. 2018, Vose et al. 2019). Identifying trends in, and attributing causes of disturbances on forests and rangelands enables examination of effects on forest and rangeland resources and can inform regional and national management and policy. In this chapter we summarize trends within the conterminous United States (except where otherwise stated) and within RPA regions (figure 5-1). The time periods for summaries of recent past trends vary by disturbance agent, but most include data beginning in at least the 1990s, while future projections are for the period 2020 to 2070.

Figure 5-1. Distribution of forest land and rangeland in the four RPA regions.



Sources: The distribution of forest land is from Brooks et al. forest land use map (see Land Resources Chapter); the distribution of rangeland is from Reeves and Mitchell (2011).

Fire in Forests and Rangelands

- ❖ The annual area of large fires has increased in both forests and rangelands over the 1984 to 2017 period. The average annual area burned by large wildfires since 2000 is more than double the pre-2000 average.
- ❖ In forests, prescribed fires conducted for management have been most prevalent in the South Region.
- ❖ Increases in the volume of trees killed by fire in forests are expected by 2070, with the greatest increases associated with the hot and dry climate futures under the higher warming scenarios.
- ❖ In forests, increases in the annual area of moderate-severity fires are expected in all RPA regions by 2070 under all RPA scenarios. In the Pacific Coast and South Regions, the area of high-severity fires is also expected to increase, while in the Rocky Mountain and North Regions, the area of high-severity fires is projected to either increase or decrease, depending on the warming scenario.
- ❖ Extreme droughts lead to increased wildfire activity in rangelands where annual vegetation production is consistently high. Where average productivity is low but interannual variability in productivity is high, increased wildfire activity occurs following wet periods.

Forests

Fire is a dominant disturbance agent in many types of forests in terms of area affected, the extent of tree damage and mortality, and resulting effects on forest resources and ecosystem services (Pausas and Keeley 2019, Thom and Seidl 2016). At the same time, fire is a natural and integral feature of forest ecosystems, many of which are adapted to particular regimes of fire frequency, intensity, severity, and seasonality (Greenberg and Collins 2021). Beginning in the first half of the 20th century and until the 1950s, the average annual area of forest burned by all fires in the United States decreased, although year-to-year variability in burned area remained (Littell et al. 2009, Parisien et al. 2016, van Wagtendonk 2007). This decrease in average burned area disrupted natural fire regimes in many parts of the country, leading to accumulation of potential fire fuels and leaving some forest ecosystems vulnerable to larger and more severe future fires (Abatzoglou et al. 2017, Calkin et al. 2015, Parisien et al. 2016). The expansion in many forested regions of the wildland-urban interface (WUI), where human development and natural lands meet or intermix, has increased chances of human-caused fire ignitions and resulted in greater economic impacts (e.g., property damage and loss) and loss of human life (Calkin et al. 2014, Radeloff et al. 2018) (see the Land Resources Chapter). A warming climate is expected to magnify wildfire activity, including more extreme wildfire events as droughts become more likely (Abatzoglou and Williams 2016, Barbero et al. 2015, Littell et al. 2016).

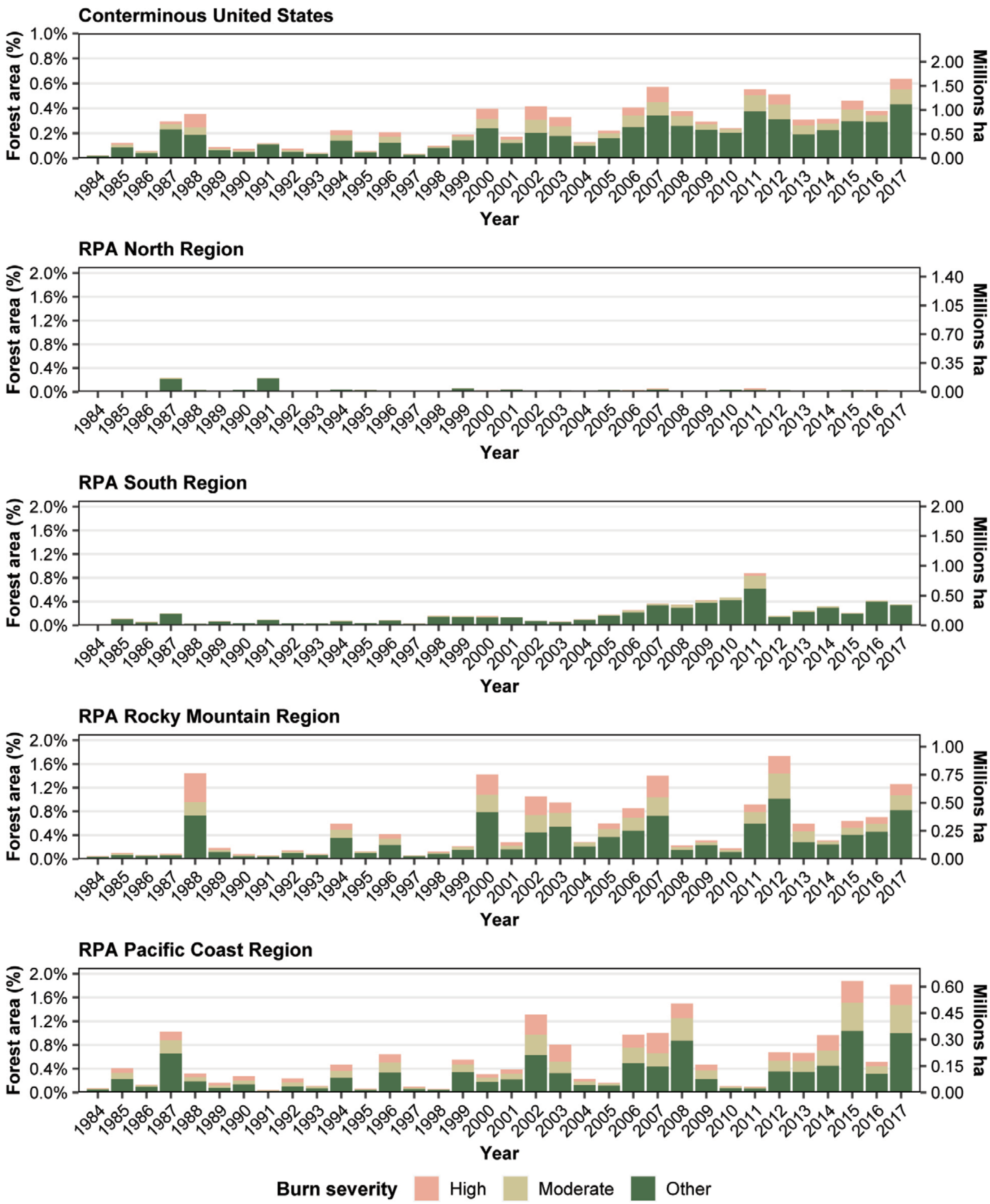
Trends in total forest area burned by large fires (defined as fires at least 405 ha in size in the Western United States and 202 ha in the East) and burn severity show notable differences over time and by region (figure 5-2). Across the conterminous United States, the annual forest area burned by large fires has shown an increasing trend. Between 1984 and 2000, burned forest area in the United States averaged 334,000 ha per year (about 0.13 percent of total forest area). Since 2000, the burned forest area averaged 965,000 ha per year (about 0.37 percent of total forest area), representing a 189-percent increase, or nearly triple the pre-2000 average. This same trend is seen at the regional scale, except for the RPA North Region, but burned area also varies widely for each region from year to year. Over the entire time period, the greatest area of large fires occurred in the two western RPA regions (Pacific Coast and Rocky Mountain). Since 2000, burned area averaged 259,000 ha per year in the Pacific Coast and 403,000 ha per year in the Rocky Mountain Region, representing increases of 165 percent and 219 percent over the pre-2000 average, respectively. Those two regions also had the greatest areas of moderate- and high-severity fires in all years. The RPA South Region experienced a 271-percent increase, to an average of 286,000 ha per year burned since 2000—a larger proportional increase than the two western regions—however moderate- and high-severity fires were rare. In contrast, there has been relatively little large-fire activity on forest lands in the North Region during the period of record. Many of the fires in the North Region are relatively small prescribed fires conducted by management agencies and thus not included here (see the following paragraphs). On average, the area of high-severity fires has increased across the United States since 2000, with 141,000 ha of high-severity fires burning annually since 2000, compared with 48,000 ha annually prior to 2000. The share of the total area of large fires classified as high severity remained approximately unchanged between the two periods, averaging 14.4 percent prior to 2000 and 14.6 percent since 2000. This increase in area but not in proportion of the total corroborates other assessments (e.g., Vose et al. 2018).

Since 2017, the United States, and especially the Rocky Mountain and Pacific Coast Regions, have set several records for areas burned. In 2020, more than 4.1 million ha burned on all lands (not just forest) in the United States—the largest burned area in a single year, and most of that area occurred in the Rocky Mountain and Pacific Coast Regions (Hoover and Hanson 2021). The large burned area in 2020 has been linked to dry atmospheric conditions and a higher vapor pressure deficit, which led to drier fuels that could ignite more easily; climate change was a substantial contributor to those conditions (Higuera and Abatzoglou 2020).

While the large fires summarized above can include some prescribed fires, many prescribed fires are smaller in extent than the cutoff for large fires, and are thus largely excluded from the analysis of large fires (Nowell et al. 2018). In addition, prescribed fires conducted by State agencies are explicitly excluded from the large-fire dataset (Picotte et al. 2020). Prescribed fire is the practice of using fire for management purposes, including maintaining or restoring ecological conditions, helping forests adapt to changing biophysical and climatic conditions, and reducing the risk of wildfires in fire-prone forests (Hunter and Robles 2020, Krofcheck et al. 2018, Ryan et al. 2013). In some forest ecosystems, it is therefore the absence of fire, rather than prescribed fire, that disrupts an ecosystem's dynamics and can be considered a "disturbance" to the ecosystem (e.g., Fill et al. 2015). Because prescribed fires are important to the dynamics of forests across the country, we summarize prescribed fire use by region to complement the summary of large-fire areas.

Nationally consistent, comprehensive data on the locations and severities of prescribed fires in forests are difficult to obtain (Nowell et al. 2018; but see Hawbaker et al. 2017, 2020). However, results from a recent State survey on prescribed burning activities show that approximately 3.68 million ha of prescribed fires were conducted in 2017 for forestry objectives nationwide (Melvin 2018). The treated area increased slightly from 3.37 million ha in the original 2011 survey conducted, and continued to increase in 2018 and 2019 (Melvin 2021). Most of the 2017 area (2.35 million ha, 64 percent of the total) occurred in the RPA South Region (Melvin 2018), supporting other recent studies that highlighted the general importance and widespread nature of prescribed burning in forests in the Southeastern United States (Mitchell et al. 2014, Nowell et al. 2018). See the sidebar COVID-19 as a Constraint on Prescribed Burning in the Southeastern United States for discussion of some recent challenges in applying prescribed fire in the Southeast. Importantly, the areas reportedly treated by prescribed fire exceed the area of forest affected by large wildfires in any single year of the wildfire data summarized here, for the country as a whole and for the South Region.

Figure 5-2. Percent and area of forest burned by large fires (at least 405 ha in the Western United States and 202 ha in the Eastern United States) over time by burn severity category. The “other” category combines the severity categories of underburned to low severity, low severity, and increased post-fire greenness/vegetation response.



ha = hectares.

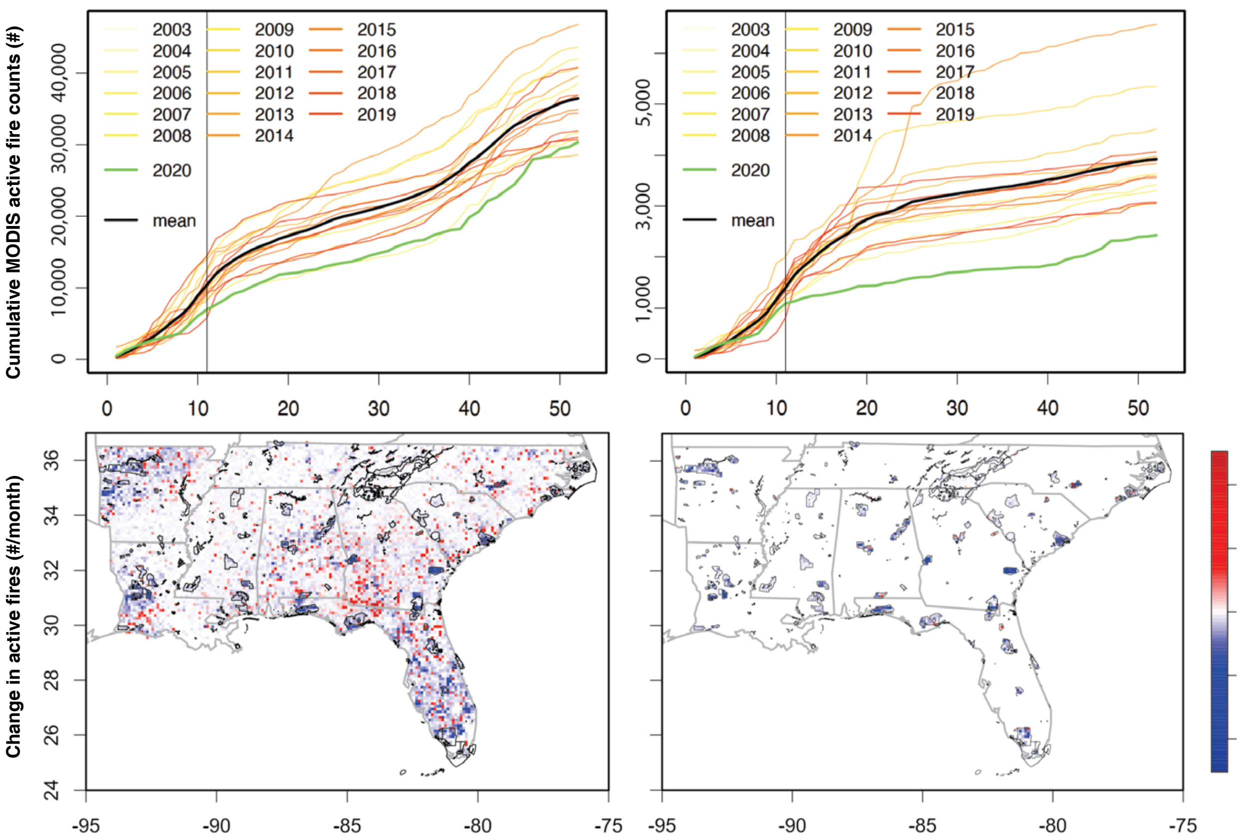
Source: Monitoring Trends in Burn Severity (MTBS, Eidenshink et al. 2007, Picotte et al. 2020).

COVID-19 as a Constraint on Prescribed Burning in the Southeastern United States

Prescribed fire is an essential management tool for many land management objectives and across a wide diversity of Southeastern ecosystems. There are diverse impediments to applying fire in the Southeast, including smoke management, limited resources, and public approval (Kobziar et al. 2015). Beginning in March 2020, the COVID-19 pandemic led to stay-at-home and shutdown orders across the world. Almost immediately, hypotheses emerged on how COVID-19 would affect all components of the Earth system (Diffenbaugh et al. 2020). To begin to determine the effects of COVID-19 on managed fire in the Southeast, we examined the record of active fires—that is, fires that were detected when NASA satellites passed overhead.

A decline in active fires was immediately observed as Federal and State agencies and private landowners adapted to work-from-home orders (Figure 5-3, Poulter et al. 2021). Following an exceptionally wet February, active fires increased for the first half of March, but then declined abruptly in mid-March and for the remainder of 2020. In some cases, land managers halted prescribed fire programs to avoid creating smoke conditions that might exacerbate health problems. In other cases, fire crews were unable to work because of COVID-19 safety regulations, or because of staff shortages as crew members were infected (Cahan 2020). In summer and fall 2020, a notable shift in the seasonal timing of prescribed fire application on all lands

Figure 5-3. Active fires detected by satellites in the Southeastern United States. The top two panels show cumulative weekly active fire counts by year (2003 to 2020) for all lands (left) and Federal lands only (right). The bottom two panels show the change in the number of active fires in April 2020 compared with the 18-year average for all lands (left) and Federal lands only (right), with fewer fires than average in blue and more fires than average in red. In the top panels, the vertical black line indicates March 15, the approximate date of COVID-19 stay-at-home orders in 2020. In the bottom panels, black outlines indicate Federal lands, which are those owned by the U.S. Departments of Interior, Defense, or Agriculture. Active fires are defined as places where a fire was burning when a satellite passed overhead.



Source: MODIS instrument on the NASA AQUA and TERRA satellites.

occurred in response to COVID-19, with increases in late-year burning to compensate for lost burned-acreage during the spring. By the end of 2020, the number of active fires was 21 percent below the 20-year average for all private and public lands, and 41 percent below the 20-year average for federally owned lands. This large reduction and seasonal shift in active fire detected in the satellite record was confirmed to come from a reduction in managed fires based on the Integrated Interagency Fuels Treatment Database (IIFT, https://iftdss.firenet.gov/).

The reduction in managed fires in 2020 follows a decline in early 2019 when the Federal government was shut down. Thus, the challenges in conducting burning due to COVID-19 added to an already expanding backlog of prescribed fire acreage in the Southeast as COVID-19 continued into 2021. In the near term, ecosystems and plant and animal species that are linked to frequent fire (including federally listed species) may suffer from the reduced habitat quality caused by reduced fire extent. Wildfire hazard reduction efforts on these lands have also been stalled, potentially exacerbating future wildfire threats. Moving forward, managers face the challenge of "catching up" on the backlog while confronting the need to maintain species, broader ecosystem processes, and fire hazard reduction targets across the region.

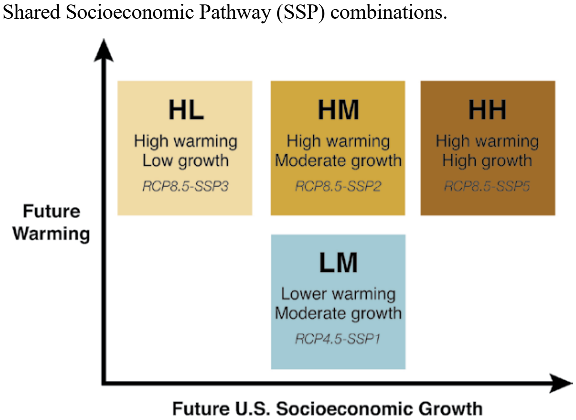
Future trends in volumes of tree mortality from wildfires were summarized from RPA Forest Dynamics Model results (see the Forest Resources Chapter) for the RPA scenarios (see the sidebar RPA Scenarios). The Forest Dynamics Model projects the future forest inventory, including volumes and areas of forest by RPA region and forest type group, forward in time for the 20 RPA scenario-climate futures (four RPA scenarios, five climate projections). A submodel projects the future fire occurrence and tree mortality resulting from fire based on Forest Inventory and Analysis (FIA) data and links to other submodels that modify forest characteristics over time, including basal area, down woody material that can act as fuels, stand age, species composition, and harvest probability. Because of the limited ability of FIA field crews to detect low-severity fires, fires that do not lead to tree mortality are omitted from the Forest Dynamics Model. Thus, the projections can be used to examine changes in annual mortality volume from fire and changes in areas burned by moderate- and high-severity fires, but they do not provide estimates of total burned areas. More information about the Forest Dynamics Model can be found in the Forest Resources Chapter and in Coulston et al. (in preparation).

RPA Scenarios

The RPA Assessment uses a set of scenarios of coordinated future climate, population, and socioeconomic change to project resource availability and condition over the next 50 years. These scenarios provide a framework for objectively evaluating a plausible range of future resource outcomes.

The 2020 RPA Assessment draws from the global scenarios developed by the Intergovernmental Panel on Climate Change to examine the 2020 to 2070 time period (IPCC 2014). The RPA scenarios pair two alternative climate futures (Representative Concentration Pathways or RCPs) with four alternative socioeconomic futures (Shared Socioeconomic Pathways or SSPs) in the following combinations: RCP 4.5 and SSP1 (lower warming-moderate U.S. growth, LM), RCP 8.5 and SSP3 (high warming-low U.S. growth, HL), RCP 8.5 and SSP2 (high warming-moderate U.S. growth, HM), and RCP 8.5 and SSP5 (high warming-high U.S. growth, HH) (figure 5-4). The four 2020 RPA Assessment scenarios encompass the projected range of climate change from the RCPs and projected quantitative and qualitative range of socioeconomic change from the SSPs, resulting in four distinct futures that vary across a multitude of characteristics (figure 5-5), and providing a unifying framework that organizes the RPA Assessment natural

Figure 5-4. Characterization of the 2020 RPA Assessment scenarios in terms of future changes in atmospheric warming and U.S. socioeconomic growth. These characteristics are associated with the four underlying Representative Concentration Pathway (RCP) – Shared Socioeconomic Pathway (SSP) combinations.



Source: Langner et al. 2020.

Figure 5-5. Characteristics differentiating the 2020 RPA Assessment scenarios. These characteristics are associated with the four underlying Representative Concentration Pathway (RCP) – Shared Socioeconomic Pathway (SSP) combinations.

RPA Scenario (RCP-SSP)	Global Temperature Rise	U.S. Population Growth	U.S. Economic Growth Rate	Bioenergy Demand	Energy Sector Focus	Global Energy Usage	International Trade Openness
LM Lower warming Moderate growth *RCP4.5-SSP1*	Lower	Medium	Medium-High	High	Renewables	Low	Medium
HL High warming Low growth *RCP8.5-SSP3*	High	Low	Low	Low	Fossil fuels	Medium	Low
HM High warming Moderate growth *RCP8.5-SSP2*	High	Medium	Medium	Medium	Mixed	Medium	Medium
HH High warming High growth *RCP8.5-SSP5*	High	High	High	High	Fossil fuels	High	High

resource sector analyses around a consistent set of possible world views. The Scenarios Chapter describes how these scenarios were selected and paired; more details are provided in Langner et al. (2020).

The 2020 RPA Assessment pairs these four RPA scenarios with five different climate models that capture the wide range of projected future temperature and precipitation across the conterminous United States. An ensemble climate projection that averages across the multiple model projections is not used because of the importance of preserving individual model variability for resource modeling efforts. The five climate models selected by RPA represent least warm, hot, dry, wet, and middle-of-the-road climate futures for the conterminous United States (table 5-1); however, characteristics can vary at finer spatial scales. Although the same models were selected to develop climate projections for both lower and high-warming futures, there are distinct climate projections for each model associated with RCP 4.5 and RCP 8.5. The Scenarios Chapter describes how these climate models were selected. Joyce and Coulson (2020) give a more extensive explanation.

Throughout the RPA Assessment, individual scenario-climate futures are referred to by pairing RPA scenarios with selected climate projections. For example, an analysis run under “HL-wet” assumes a future with high atmospheric warming and low U.S. population and economic growth (HL RPA scenario), as well as a wetter climate for the conterminous United States (wet climate projection).

Table 5-1. Five climate models selected to reflect the range of the full set of 20 climate models in the year 2070. Each model was run under RCP 4.5 and RCP 8.5, providing a range of different U.S. climate projections.

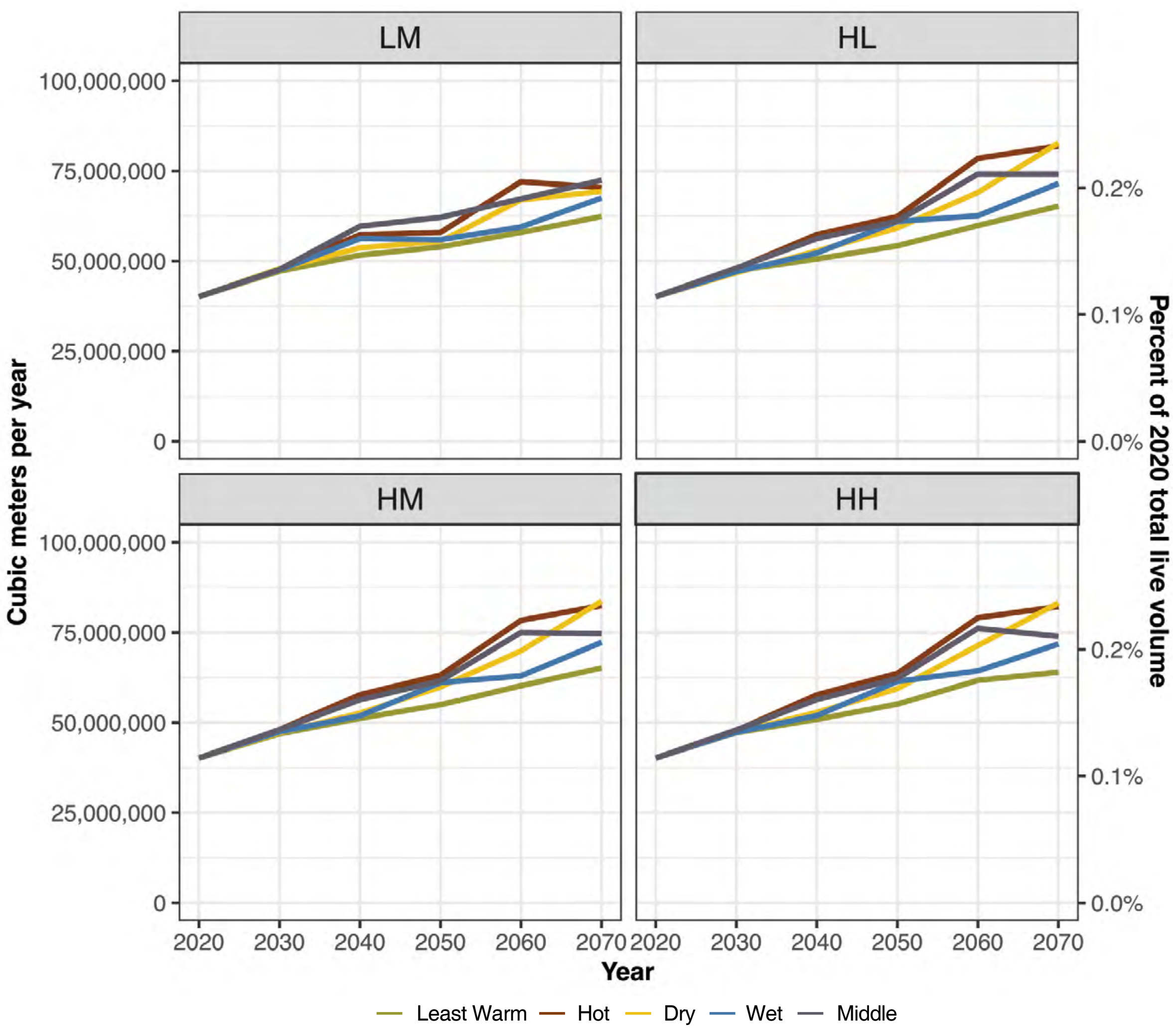
	Least warm	Hot	Dry	Wet	Middle
Climate model	MRI-CGCM3	HadGEM2-ES	IPSL-CM5A-MR	CNRM-CM5	NorESM1-M
Institution	Meteorological Research Institute, Japan	Met Office Hadley Centre, United Kingdom	Institut Pierre Simon Laplace, France	National Centre of Meteorological Research, France	Norwegian Climate Center, Norway

RCP = Representative Concentration Pathway.

Source: Joyce and Coulson 2020.

Annual fire mortality volume is projected to increase over time across the United States and in each RPA region under all 20 scenario-climate futures (figure 5-6)—from 40 million cubic meters in 2020 (0.10 percent of total live volume in all forests) to between 62 million cubic meters under LM-least warm (the LM scenario and least warm climate model) and 84 million cubic meters under HM-dry (the HM scenario and dry climate model) in 2070, representing an increase of between 55 and 108 percent relative to 2020 values. The result that all futures project the same directional change indicates relatively low uncertainty in the impact of future climate and socioeconomic change on fire mortality volume. Generally, the greatest increases in fire mortality volume by 2070 were projected for plausible futures that included the dry or hot climate projections under the three high-warming RPA scenarios (HL, HM, and HH). The smallest increases were projected for the least warm climate projection regardless of the RPA scenario. These projections generally agree with studies that point to expected increases in fire occurrence over much of the country, especially as climate becomes warmer and drier (Gao et al. 2021, Littell et al. 2016). While a substantial increase in fire mortality volume was projected, the combined average annual volume of removals for timber harvest in Florida, Georgia, North Carolina, and South Carolina totaled just over 86 million cubic meters in 2016 (Oswalt et al. 2019), slightly exceeding the most extreme fire mortality volume projection for the conterminous United States in 2070 (84 million cubic meters).

Figure 5-6. Projected annual fire mortality volume over time for all RPA scenarios. Results summarize output from Forest Dynamics Model simulations (see the Forest Resources Chapter for more details on the model). In each panel, the dark lines represent the median outcome of 100 simulations, and the shaded area represents the inter-quartile range of those simulations. The right-hand vertical axis shows the values in terms of percent of total live volume in 2020. Both vertical axes apply to all four panels. Because the total live volume of forests is expected to increase over time (see the Forest Resources Chapter), the volume killed by fire represents a lower proportion of the total volume in 2070 than is displayed.

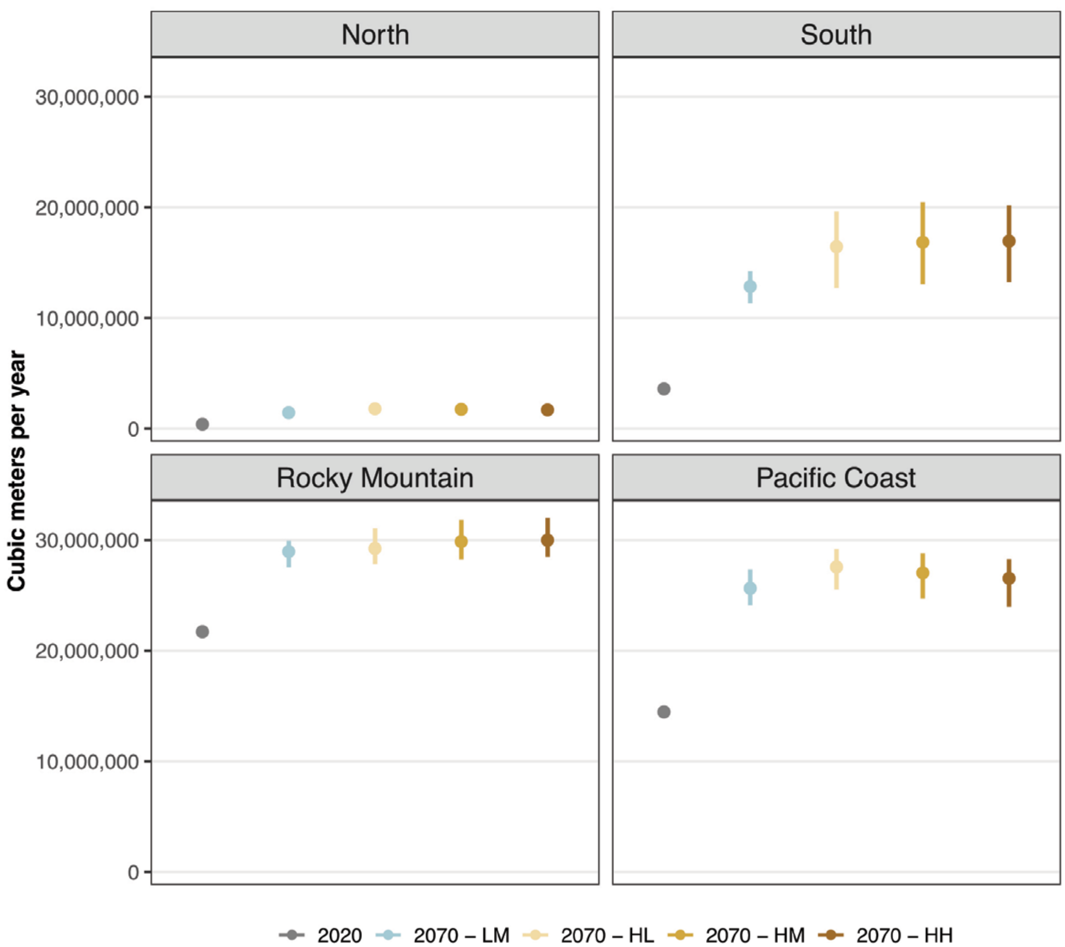


LM = lower warming-moderate U.S. growth; HL = high warming-low U.S. growth; HM = high warming-moderate U.S. growth; HH = high warming-high U.S. growth.

The expected trends in annual fire mortality volume within RPA regions mirror the nationwide trend, with increases projected in all regions. The relative magnitudes of increase differ by region, and the projected changes in forest and fire dynamics that result in increased volume differ slightly by region. In the Rocky Mountain Region, fire mortality volume is expected to increase between 20 and 55 percent, from 22 million cubic m in 2020 to between 26 and 34 million cubic m by 2070 (table 5-2, figure 5-7). In the Pacific Coast Region, annual fire mortality volume in 2020 was lower than in the Rocky Mountain Region, but is expected to increase to a level either slightly below or comparable to the Rocky Mountain Region by 2070—from approximately 14 million cubic m in 2020 to between 24 and 29 million cubic m in 2070, representing a 63- to 100-percent increase. In the South, while fire mortality volume is lower overall than in the two western regions currently and throughout the future period, an increase of 184 to 505 percent, to between 10 and 22 million cubic m, is projected by 2070. In the North Region, where there is very little fire activity, annual fire mortality volume is expected to increase as well, but remain lower than all three other regions. Increases to between 1.2 and 2.0 million cubic m are projected by 2070.

A projected increase in annual tree volume killed by fire in a region can be due to an increase in the area burned by fire, an increase in the proportion of live volume in burned forest stands that is killed by fire, or a combination of both factors. In the Rocky Mountain Region, the annual area of moderate-severity fires (between 30- and 70-percent mortality by volume) is expected to more than double from 2020 to 2070 (108- to 179-percent increase) (table 5-2), while projections

Figure 5-7. Annual fire mortality volume for RPA regions in 2020 and projected in 2070 for all RPA scenarios. Results summarize output from Forest Dynamics Model simulations (see the Forest Resources Chapter for more details on the model). For the values in 2070, dots represent the mean of the five RPA climate projections under each RPA scenario, while vertical bars indicate the range of values across those climate projections.



LM = lower warming-moderate U.S. growth; HL = high warming-low U.S. growth; HM = high warming-moderate U.S. growth; HH = high warming-high U.S. growth.

Table 5-2. Projected changes from 2020 to 2070 (value and percent change) in overall annual fire mortality volume, fire mortality volume as a percent of total volume in burned locations, and annual areas of moderate- and high-severity fires for each RPA region. Moderate-severity fires are defined as those that kill 30 to 70 percent of volume, while high-severity fires killed at least 70 percent of volume. The first column under each variable indicates the absolute change, and the second column indicates the percent change by 2070 over 2020 values.

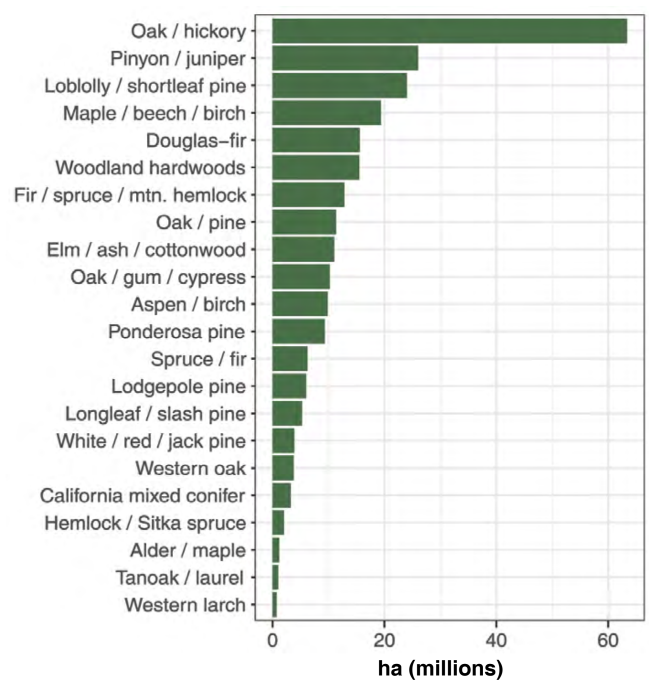
	Change in fire mortality volume		Change in area of moderate-severity fires		Change in area of high-severity fires		As percent of volume in burned locations	
	million m^3	percent	ha	percent	ha	percent	percentage points	percent
North	0.83-1.6	196-385	6,000-11,000	483-884	-1,300-4,800	-16-62	-3.4- -2.5	-19- -14
South	6.6-18.2	184-505	12,000-54,000	72-330	19,000-70,000	70-256	0.4-3.5	2-17
Rocky Mountain	4.4-12.0	20-55	46,000-76,000	108-179	-3,300-34,000	-2-24	-10.0- -7.1	-16- -12
Pacific Coast	9.1-14.4	63-100	40,000-53,000	141-185	36,000-49,000	69-95	2.9-3.9	6-8

ha = hectares; m^3 = cubic meters.

of high-severity fires (at least 70 percent mortality by volume) show either decreases or small increases in annual areas. In other words, under all scenarios, the annual area of moderate-severity fires in the Rocky Mountain Region is projected to increase more than the area of high-severity fires between 2020 and 2070. The overall average annual proportion of live volume killed by fire in locations that burned is expected to decrease 12 to 16 percent over that time in the region (table 5-2). In the Pacific Coast and South Regions, the projected annual areas of both moderate- and high-severity fires increase by 2070, along with the average proportion of volume killed (table 5-2). While few studies have examined projected trends in fire severity, most research has suggested the potential for higher fire severity as climate changes, including portions of the Western United States (Halofsky et al. 2020, Van Mantgem et al. 2016), and increases in the number of extreme fire events in portions of the South (Terando et al. 2017). That aligns with our results for the Pacific Coast and South, but our 2070 projection of either an increase or a decrease in area of high-severity fires for the Rocky Mountain Region highlights the uncertainty associated with projecting fire severity. Parks et al. (2016) modeled future fire severity for the Western States and projected the potential for lower fire severity for most of the West, including the Rocky Mountains, if vegetation changes occur that result in reduced fuels. However, future changes to fuel levels are highly uncertain and depend on many factors, including climate, forest productivity, management, and fire history.

Each RPA region is heterogeneous and contains forests characterized by more frequent, low-severity fires, as well as those characterized by less frequent, moderate- or high-severity fires (Greenberg and Collins 2021, Schoennagel et al. 2004). Understanding the projected dynamics of fire within each type of forest (figure 5-8) can provide insights into the potential effects of future fire on those forests. Most forest type groups are expected to have greater fire mortality volumes by 2070 compared with 2020, although the magnitude of increase is expected to vary by forest type group (figures 5-9, 5-10). Several of the western type groups that have high or moderate annual fire mortality volumes in 2020 are expected to experience large increases under all RPA scenarios, including Douglas-fir, ponderosa pine, woodland hardwoods, and pinyon/juniper, and the annual area of high-severity fires is also expected to increase in those groups (figure 5-9). The latter three of those groups each occur, at least in part, in relatively dry portions of the South Central and Southwestern United States, where dry conditions are expected to become more common in the future (see the section Drought in Forests

Figure 5-8. Area of forest for each forest type group in the FIA database, circa 2013. All analysis in this chapter that was based on FIA data excluded nonstocked, exotic, and tropical groups, and two others that were limited in extent: the western white pine and redwood type groups.

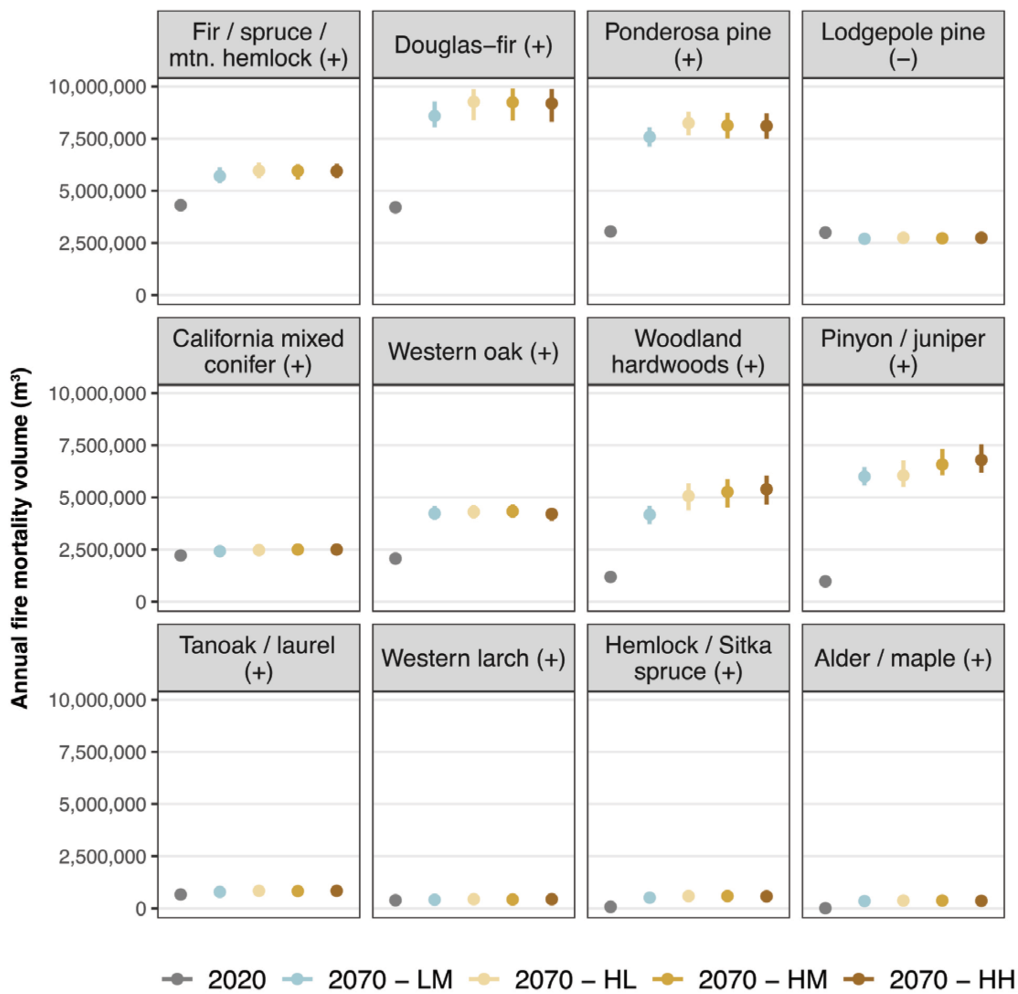


FIA = Forest Inventory and Analysis; ha = hectares.

and Rangelands). Much or all of the extents of those type groups are characterized by relatively low live volumes and frequent, low-severity fire regimes that kill few trees, but in many places those fire regimes have shifted toward higher-severity fires (Greenberg and Collins 2021). An increase in the area of high-severity fires could therefore further threaten those forest ecosystems. Douglas-fir forests are historically characterized by less frequent, higher severity fires, and the expected increase in fire mortality volume, along with increasing area of high-severity fires, could imply more frequent severe fires in that forest type. Lodgepole pine is one notable forest type group with lower projected fire mortality volume in 2070 than in 2020. The average annual area of high-severity fires in the lodgepole pine type group is also projected to decrease (figure 5-9), accounting for much of the decline in fire mortality volume.

Forest type groups found predominantly in the East are expected to see relatively modest changes in fire tree mortality volume (figure 5-10). One exception is the oak/hickory forest type group, whose fire mortality volume is projected to at least double by 2070 and whose annual

Figure 5-9. Annual fire mortality volume for western forest type groups in 2020 and projected in 2070 for all RPA scenarios. Results summarize output from RPA Forest Dynamics Model simulations (see the Forest Resources Chapter for more details on the model). For the values in 2070, dots represent the mean of the five RPA climate projections under each RPA scenario, while vertical bars indicate the range of values across those climate projections. Forest type groups are arranged according to their 2020 observed annual fire mortality volume (highest at the top left to lowest at the bottom right). Pluses and minuses in parentheses after each forest type group name indicate an increase (+) or decrease (-) in annual area of high-severity fire projected by 2070, defined as fires that result in at least 70 percent of live volume killed, or whether an increase was projected for some futures and a decrease was projected for others (-/+).

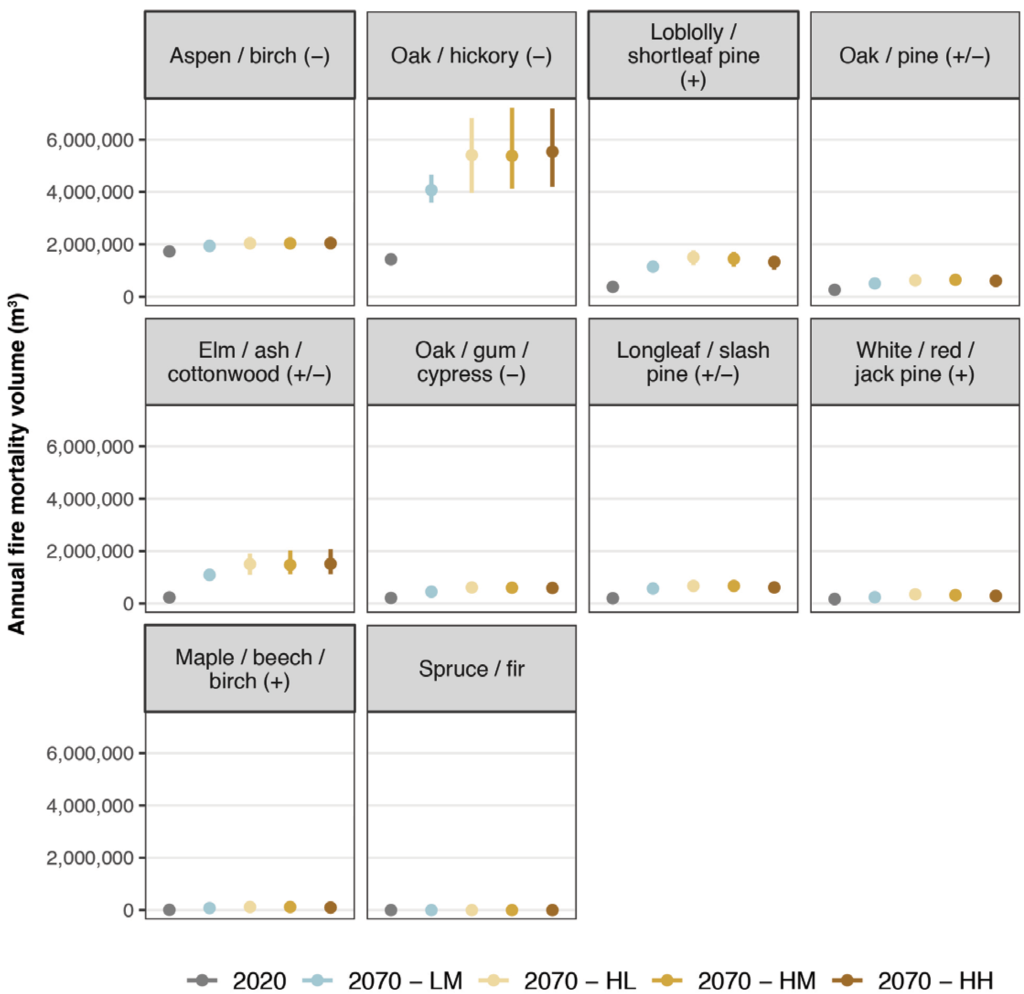


LM = lower warming-moderate U.S. growth; HL = high warming-low U.S. growth; HM = high warming-moderate U.S. growth; HH = high warming-high U.S. growth.

area of high-severity fires is projected to increase in all futures. Oak/hickory forests, like many forest types in the Eastern United States, have been experiencing reduced frequency and increased severity of fire relative to historical conditions, when fires burned frequently and resulted in low tree mortality (Nowacki and Abrams 2008). As a result, oak/hickory forests have recently declined. While the specific local ecological effects of fire depend on many factors, an increase in fire mortality volume could be beneficial to oak/hickory forests in the East if it signals more fire overall in that forest type. However, an increase in the area of high-severity fires could further alter the oak/hickory forest ecosystems.

The projected changes in fire mortality volumes of trees provide some insights into the changing dynamics of fire in U.S. forests. In addition to direct effects on forests themselves, increases in fire mortality volume and high-severity fires also have implications for human health and property in the wildland-urban interface (WUI) and

Figure 5-10. Annual fire mortality volume for eastern forest type groups in 2020, and projected in 2070 for all RPA scenarios. Results summarize output from RPA Forest Dynamics Model simulations (see the Forest Resources Chapter for more details on the model). For the values in 2070, dots represent the mean of the five RPA climate projections under each RPA scenario, while vertical bars indicate the range of values across those climate projections. Forest type groups are arranged according to their 2020 observed annual fire mortality volume (highest at the top left to lowest at the bottom right). Pluses and minuses in parentheses after each forest type group name indicate an increase (+) or decrease (-) in annual area of high-severity fire projected by 2070, defined as fires that result in at least 70 percent of live volume killed, or whether an increase was projected for some futures and a decrease was projected for others (-/+). The spruce/fir and longleaf/slash pine forest type groups had no high-severity fire projected in 2020 or 2070.



LM = lower warming-moderate U.S. growth; HL = high warming-low U.S. growth; HM = high warming-moderate U.S. growth; HH = high warming-high U.S. growth.

beyond. Expansion of the WUI and increasing fire activity are already contributing to loss of human life and property from fire, presenting challenges for fire suppression and increasing costs associated with suppression (Abt et al. 2009, Radeloff et al. 2018). The increases in high-severity fires projected in most regions and forest types could add to those already-substantial challenges and costs of fire management. Any substantial increase in fuel treatments, such as thinning or prescribed burning, across large landscapes or regions could result in reduced fire severity and reduced risk of large, difficult-to-manage fires in some forests. Forest types such as ponderosa pine forests, which are adapted to frequent, low-severity fires and have experienced a build-up of fuels resulting from fire suppression, could especially benefit from such treatments (Halofsky et al. 2020, Moritz et al. 2014, Schoennagel et al. 2004). Furthermore, these projections do not include any changes to fire ignitions, such as increased numbers of human-caused ignitions during periods with high fire hazard (Balch et al. 2017, Fusco et al. 2016) that could occur in the future. Additional ignitions could increase fire occurrence and severity in some forest ecosystems (Pausas and Keeley 2021). Further work could incorporate increased treatment levels or changes in ignitions and fuel availability into the RPA Forest Dynamics Model and examine the effects of those on projected fire mortality volume and fire severity.

Rangelands

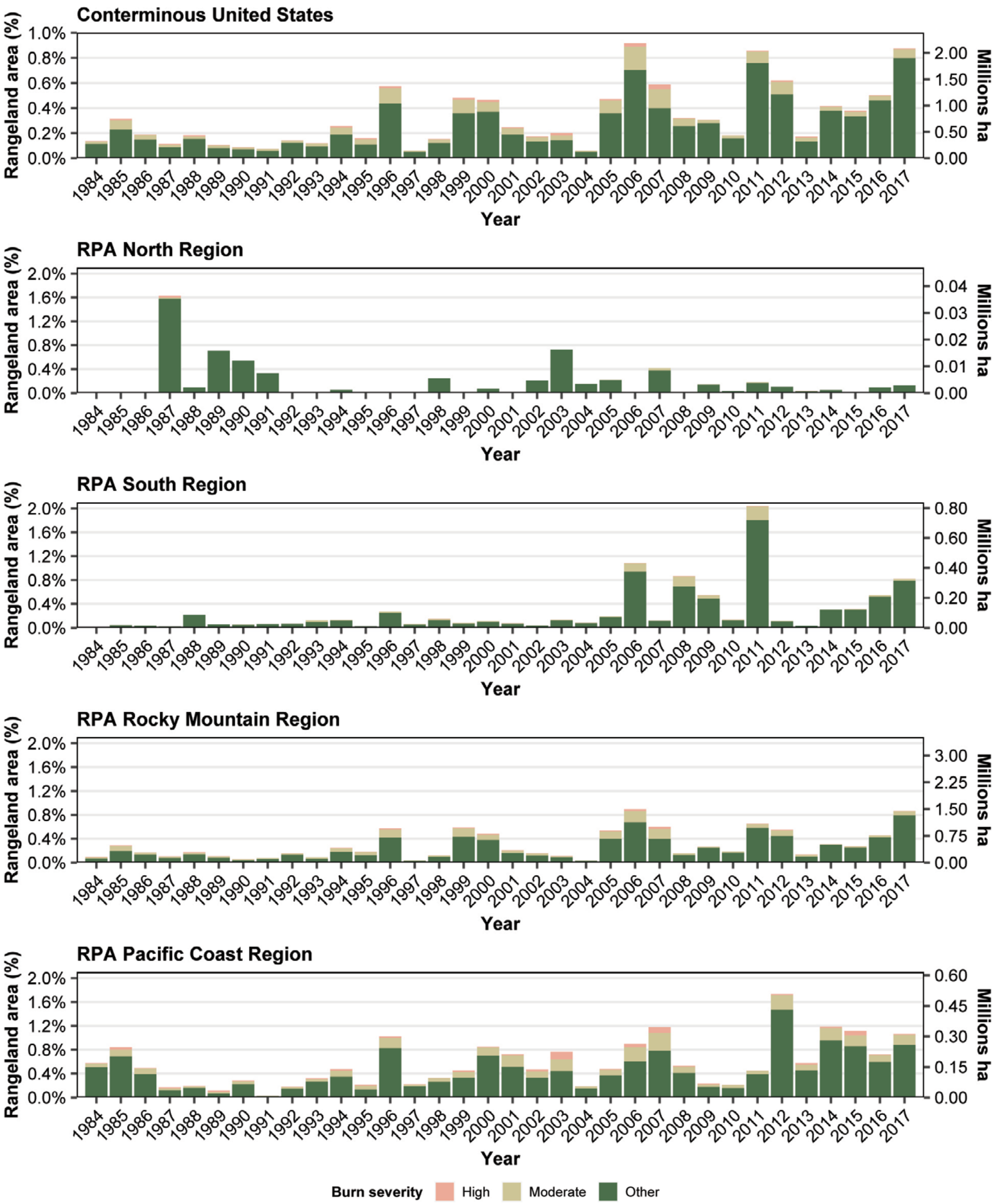
Fire plays an important role in maintaining vegetation and ensuring forage for livestock in rangelands (Fuhlendorf et al. 2012, Limb et al. 2016). While fires are part of the natural dynamics of rangelands, invasive grasses and drought have led to more frequent and larger fires in some rangeland systems (Abatzoglou and Kolden 2011, Coates et al. 2016). An analysis of the rangeland areas burned by large wildfires (again defined as fires at least 405 ha in size in the Western United States and 202 ha in the Eastern United States) indicates an increase in burned rangeland area from 1984 to 2017, distributed asymmetrically across the RPA regions. Before 2000, burned area averaged about 470,000 ha per year (figure 5-11; about 0.19 percent of rangeland area). Since 2000, the total rangeland area burned per year increased substantially to an average of about 1 million ha per year (about 0.45 percent of rangeland area), an increase of 119 percent over the pre-2000 average. The 2006 fire season produced the highest annual area burned at 2.3 million ha (about 0.9 percent of the rangeland area). The RPA Rocky Mountain Region had the highest average annual rangeland area burned since 2000 (approximately 638,000 ha per year), followed by the Pacific Coast Region (218,000 ha burned per year). In both regions the average areas burned increased 100 percent over the pre-2000 averages. In the South Region, average area burned increased over 300 percent from the pre-2000 amounts to 168,000 ha per year, and the 2011 fire season produced the largest burned area in the record for the region, with over 800,000 ha burned that year (over 2.0 percent of the South's rangeland area). Only the North Region, which has a relatively small amount of rangeland area (approximately 6.1 million ha), exhibited a decreasing trend in the area burned per year.

The national and regional nature of this analysis obscures the fine-scale patterns of wildfires occurring in rangelands. The relationships between climate, fuels, and fire in rangeland ecosystems are complex. The annual area burned is linked with drought patterns, but the relationship is not linear, is sometimes counterintuitive, varies by ecosystem, and fires can occur months after drought has occurred (Krawchuk and Moritz 2011). Droughts can lead to larger fires and a greater number of fires, but only if sufficient fuels are present (Abatzoglou and Kolden 2013, Littell et al. 2018). Some rangeland areas consistently have high levels of vegetation productivity (figure 5-12) and thus fuels are consistently available. In those areas during drought years, relatively continuous fuels combined with low fuel moisture lead to extreme fire behavior and large areas burned. For example, in Texas and Oklahoma where annual vegetation production is consistently high, widespread extreme droughts occurred in 2011, contributing to the large rangeland area burned in the RPA South Region that year (figure 5-11; also see the section Drought in Forests and Rangelands).

In the northern Great Plains in 2011, fire activity was relatively low because of comparatively cool and mesic conditions. This low fire activity contributed to a moderate area burned in the Rocky Mountain Region in 2011 (figure 5-11). The high precipitation and high resultant annual production of 2011, however, led to large amounts of standing dead material by the end of the year. When drought occurred in the region the next year (2012), this high amount of standing dead material increased ignition potential and fire behavior (Reeves et al. 2020). While the total area burned in the Rocky Mountain Region during 2012 in our analysis is lower than for other years (figure 5-11), some of the largest individual wildfires on record occurred in 2012 during record-setting heat and drought (e.g., the Ash Creek Complex in Montana) (Karl et al. 2012, Reeves et al. 2020).

In contrast to the Great Plains, much of the rangeland area of the Western United States typically has relatively low production, which leads to small amounts of fuel available in an average year. However, some areas with relatively low production on average tend to exhibit the greatest interannual variability in production, and thus high variability in fuels, especially fine fuels less than 6.35 mm in diameter (e.g.,

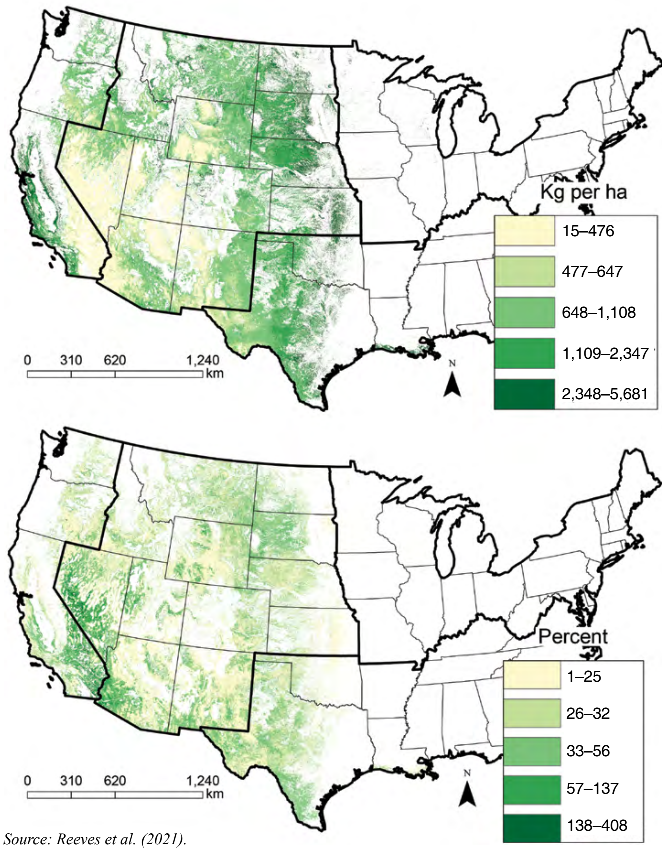
Figure 5-11. Percent and area of rangelands burned by large fires (at least 405 ha in the Western United States and 202 ha in the Eastern United States) over time by burn severity category. The “other” category combines the severity categories of underburned to low severity, low severity, and increased post-fire greenness/vegetation response.



ha = hectares.

Source: Monitoring Trends in Burn Severity (MTBS, Eidenshink et al. 2007, Picotte et al. 2020).

Figure 5-12. Average annual production (top) and average interannual variability (bottom) in U.S. rangelands from 1984 to 2020.



Source: Reeves et al. (2021).

grasses and forbs). These areas are subject to heat and dryness in most years. The ecosystems that meet these criteria, including the Sonoran and Mojave Deserts (figure 5-12), can experience substantial areas burned in some years when annual production exceeds normal.

The complex relationships between climate, fuels, and fire in rangeland ecosystems ensure a complex future of fire in those systems. While we do not include fire projections for rangelands here, existing literature and knowledge of these relationships allow some general statements about possible future fire trends. Areas toward the eastern edge of the rangeland domain that produce fuels continuously but typically have surplus moisture may have larger annual burned areas, as dry conditions become more common (Littell et al. 2018). On the other hand, areas that are fuel-limited and require wet years to produce fire, are more likely to have variation in fire activity from year to year because interannual variability of herbaceous vegetation production is expected to increase in the future (Klemm et al. 2020, Reeves et al. 2017).

Drought in Forests and Rangelands

- ❖ Forests in the RPA Pacific Coast Region have had higher exposure to drought than other regions since 2005.
- ❖ Rangelands in the RPA Pacific Coast Region have similarly experienced high drought exposure since 2005, and rangeland exposure was also high in the South and Rocky Mountain Regions from 2011 to 2012.
- ❖ Forest and rangeland exposure to drought is expected to intensify over this century, particularly if the climate tends toward the hot, dry, or middle climate futures.
- ❖ Forest and rangeland vegetation types in the Southwest are projected to have the greatest drought exposure in the future, specifically the pinyon/juniper woodlands forest type group, and the grassland and creosotebush desert scrub rangeland vegetation types.

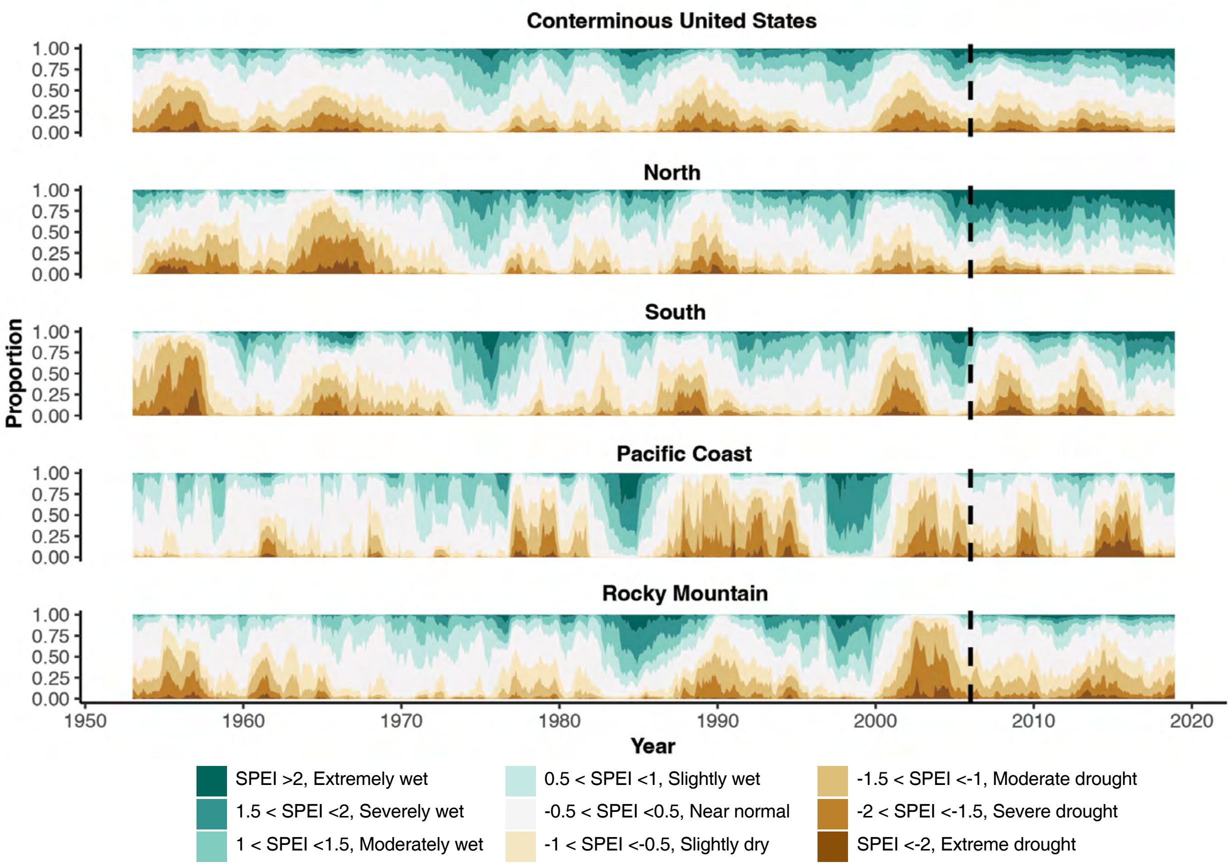
Forests

Drought, an important stressor affecting forests, is commonly defined as a period of moisture deficit resulting from below-average precipitation, high temperatures, or both (Clark et al. 2016). Alone or in combination with other disturbances, drought can reduce forest productivity, cause shifts in forest types, affect the ability of forests to regenerate, and diminish the capacity of forests to provide ecosystem services (Anderegg et al. 2013, Desprez-Loustau et al. 2006, Jactel et al. 2012, Peters et al. 2015, Trouet et al. 2010, Vose et al. 2016). As climate warms and many parts of the world become drier, droughts are expected to become more widespread, frequent, and severe (Ahmadalipour et al. 2017, Cook et al. 2015, Dai 2011, 2013, Prudhomme et al. 2014, Swain and Hayhoe 2015). While the effects of drought on trees and individual forest stands have been demonstrated for local areas, it is difficult to both measure moisture conditions in situ and determine the direct effects of drought on forests across broad geographic regions (Bennett et al. 2015, Clark et al. 2016, Gazol et al. 2018). Many scientists therefore use meteorological drought indices, which track relative departure from normal climate conditions and can be correlated with resulting effects on forests (Druckenbrod et al. 2019). Meteorological drought indices are distinct from other measures of drought, including hydrologic drought, which tracks reductions in water supply to rivers and lakes. Information on where and when forests have been exposed to meteorological drought in the past or are likely to be exposed in the future can be used to inform where management action or further research is warranted.

We use the Standardized Precipitation Evapotranspiration Index (SPEI) to summarize recent and future trends in drought exposure for forest land in the conterminous United States (Costanza et al. 2022a, 2022b; for details on SPEI, see Beguería et al. 2014, Vicente-Serrano et al. 2010). The SPEI allows for comparisons among locations for historical as well as future conditions, and can be computed over multiple time scales, making it useful for monitoring drought in different ecological contexts (Ault 2020, Slette et al. 2019, Vicente-Serrano et al. 2010). We used the 36-month SPEI, which assigns values for a given month by comparing the cumulative climatic water balance (precipitation minus potential evapotranspiration, or PET) for the previous 36 months to the same cumulative 36-month water balance for all months in a reference period (defined here as 1950 to 2005). Prolonged droughts that persist for multiple years are more likely to cause lasting impacts to forests than shorter-term droughts of equal magnitude (Berdanier and Clark 2016, Bigler et al. 2006, Guarín and Taylor 2005, Jenkins and Pallardy 1995, Millar et al. 2007). For most of the results shown here, PET was calculated using the standard method recommended by world organizations (Abatzoglou 2013, Allen et al. 1998). However, for summaries of observed SPEI (figure 5-13), calculation of PET via the preferred method was not possible because of data limitations, and we used an alternative method that has been recommended in such circumstances but may overestimate dry conditions in places with seasonally humid climate (Beguería et al. 2014, Hargreaves 1994).

The major trends in observed SPEI values (figure 5-13) corroborate known incidence of past drought, including drought periods in the 1950s across much of the RPA South and Rocky Mountain Regions (Andreadis et al. 2005, Heim 2017) and in the 1960s across much of the North Region (Barlow et al. 2001, Namias 1966). Since 2005, the Nation's forests have experienced relatively even proportions of dry and wet conditions, although regionally there has been more variation from year to year. For example, the Pacific Coast Region was exceptionally dry on forest lands during the mid-2010s, a period that has been shown to be drier than any

Figure 5-13. Proportion of forest land area in categories of observed 36-month SPEI over time, based on PRISM climate data, 1953 to 2018, for the United States and RPA regions. The period to the left of the dashed line in each graph indicates the reference period that was used to calibrate SPEI values.



SPEI = Standardized Precipitation Evapotranspiration Index.

Source: Costanza et al. 2022b.

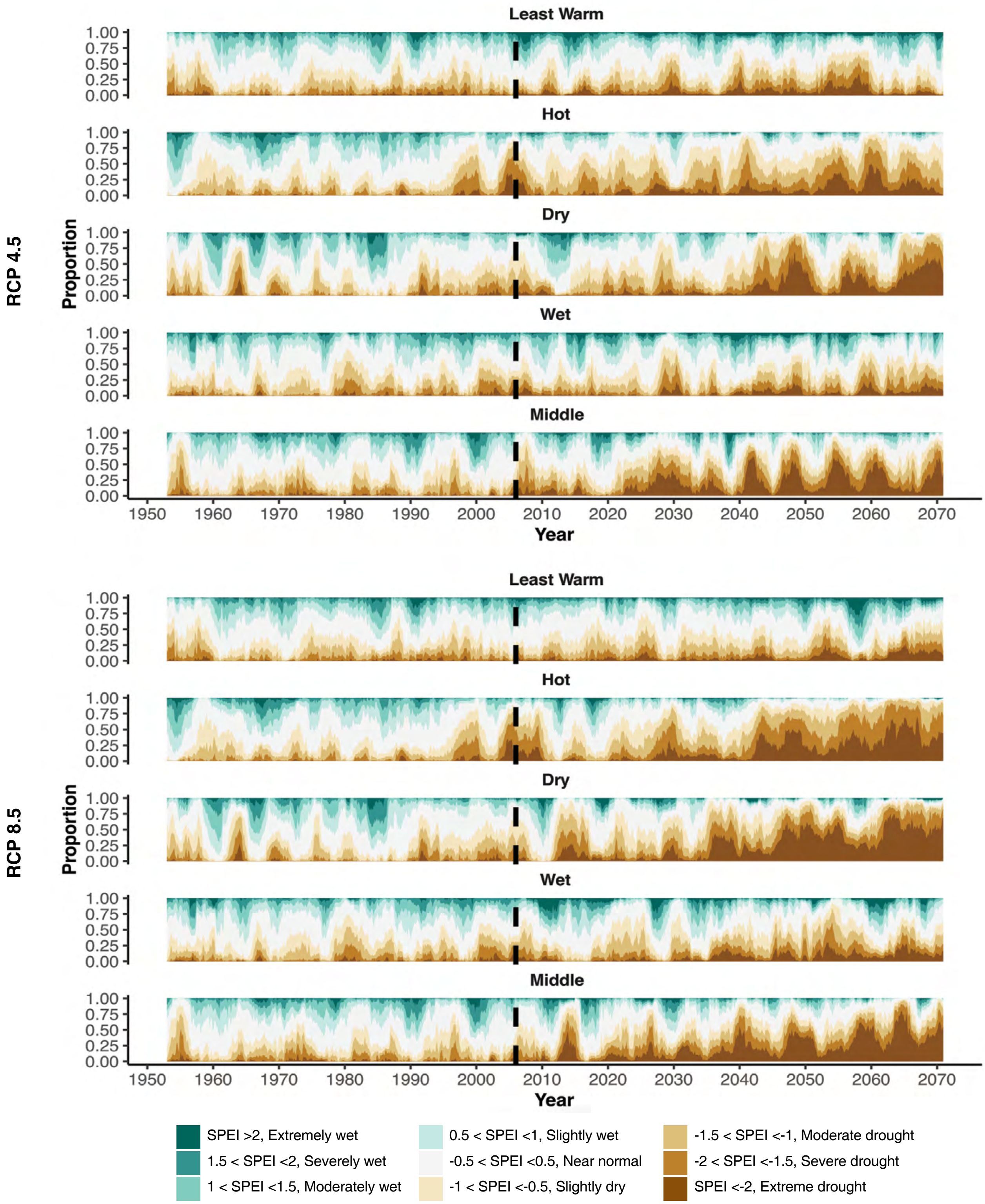
historical precedent in California (Robeson 2015), and which corresponded with high wildfire activity and insect outbreaks in the region (Fettig et al. 2019, Halofsky et al. 2020, Marlier et al. 2017, Pile et al. 2019). In contrast, the North Region was relatively wet nearly every month since 2005 (figure 5-13). Obscured in these regional trends are localized drought events that were smaller in geographic extent but had substantial forest impacts, including high rates of tree mortality and growth declines (see the sidebar Vulnerability to Drought for an example).

Forest SPEI projections provide an outlook on forest drought exposure under 10 different plausible climate futures across the United States. The integrated RPA scenarios were not used for these projections due to an inability to apply the socioeconomic factors, but we did apply the climate futures and climate projections selected by RPA (two RCPs, five climate projections; see the sidebar RPA Scenarios). The amount of forest land projected to experience drought increases under both RCPs (figure 5-14). By 2050, the hot, dry, and middle climate projections produce marked increases over the historical period in both the extent and frequency of drought across the United States under both RCPs. Under RCP 8.5 and the hot and dry climate projections, more than 50 percent of the Nation's forests are exposed to moderate, severe, or extreme drought in most years after 2040. Wetter conditions and less warming result in lower percentages of forest area exposed to drought relative to the hot and dry projections. While the middle climate projection represents moderate changes in temperature and precipitation compared with the other projections, it still projects more frequent and widespread drought conditions, similar to results from the hot and dry projections. This is likely the result of high interannual variation in precipitation under RCP 4.5 and warm temperatures under RCP 8.5 projected by the middle model.

Analysis of forest exposure to drought by FIA forest type group (figure 5-15) provides insights into geographic patterns of forest exposure. We focus on exposure to severe or extreme drought conditions (SPEI <-1.5) for a 30-year period in the future (2041 to 2070, "mid-century") and compare that exposure to a period in the modeled data during the recent past (1991 to 2020, "recent past"). The future drought exposure for several forest type groups, including three smaller type groups that occur in California—western oak, California mixed conifer, and tanoak/laurel—may be similar to the past (figure 5-15). However, projections under both RCPs using some climate projections indicate levels of drought exposure that far exceed recent exposure for many forest type groups. By mid-century, the median projected exposure to severe or extreme drought for the climate projections under RCP 8.5 in the pinyon/juniper, woodland hardwoods, aspen/birch, and ponderosa pine type groups was at least 60 percent, far exceeding the historical exposures for those type groups. For the former three of those type groups, exposure was projected at more than 75 percent, using at least one climate projection under RCP 8.5. Several of the type groups having the highest projected future exposures, including pinyon/juniper and ponderosa pine, occur in the already-arid Southwestern United States; our results agree with other assessments showing the potential for unprecedented drought and resulting ecological impacts to forests in the Southwest toward the latter half of this century (Cayan et al. 2010, Cook et al. 2015, Jiang et al. 2013, Seager et al. 2007, Thorne et al. 2018, Williams et al. 2013, 2020). By mid-century, the projected range of drought exposure for each forest type group reflects not only the wide selection of RPA climate projections—least warm, hot, dry, wet, middle—but also the geographic range of the forest type group. Planning for a dry or a hot future at the local scale may be important to address the potential risk to the resources in these forest types. However, it is important to note that the SPEI index of exposure does not capture the actual water use efficiency of different forest vegetation types in local conditions, nor any changes in that water use efficiency that could result from shifts in vegetation over time. Therefore, actual exposure could vary in ways that are not captured in this analysis.

A high level of drought exposure does not necessarily translate to significant ecological impacts for a forest type group or forested area. Information on exposure can be used in conjunction with research on the drought sensitivities of forest type groups and associated tree species to determine the degree of likely ecological effects from drought and guide management efforts to ameliorate these impacts (see the sidebar Vulnerability to Drought for an example using these SPEI data). For example, recent severe droughts in combination with other stressors including herbivores, parasites, and wildfires, have played a role in widespread tree mortality and growth declines in pinyon-juniper forests (Flake and Weisberg 2019a, 2019b, Shaw et al. 2005), with higher mortality occurring on the driest sites as well as sites with deeper soils and higher stand density (Flake and Weisberg 2019a). This suggests that management actions, such as stand thinning to reduce tree density, might be necessary to increase the adaptive capacity of pinyon-juniper forests in response to these impacts (Bradford and Bell 2017). On the other hand, the longleaf/slash pine type group that occurs in the Southeastern United States is projected to face low to moderate drought exposure, and at least one of its dominant species (longleaf pine, *Pinus palustris*) is likely more drought-tolerant than other tree species (Samuelson et al. 2012, 2019). This type group may therefore be relatively resilient to future drought exposure, despite a projected increase in exposure by mid-century (figure 5-15). The likely drought resilience of longleaf pines is one reason why restoration of forests in the Southeast has recently begun to emphasize creating or maintaining a prominent longleaf pine component as a strategy for climate adaptation (Clark et al. 2018b).

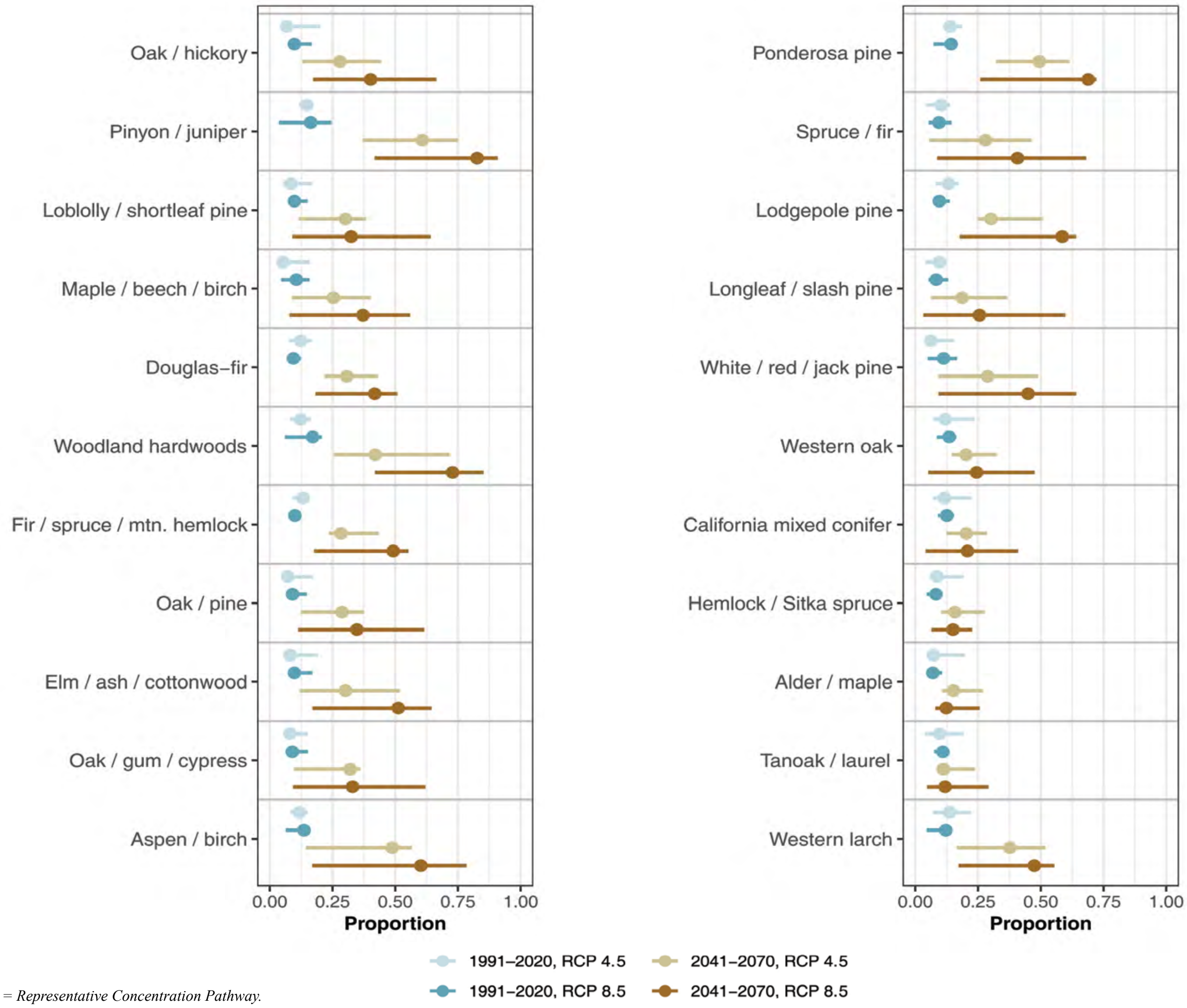
Figure 5-14. Proportion of forest land area in categories of 36-month SPEI for historical (1953 to 2005) and future (2006 to 2070) periods using the RPA climate projections under RCP 4.5 (top) and RCP 8.5 (bottom). The period to the left of the dashed line in each graph indicates the reference period that was used to calibrate SPEI values.



RCP = Representative Concentration Pathway; SPEI = Standardized Precipitation Evapotranspiration Index.

Source: Costanza et al. 2022a.

Figure 5-15. Comparison of monthly proportion of forest type groups in severe or extreme drought for each of the RCPs at mid-century (2041 to 2070) with the same metric during the recent past (1991 to 2020). Dots represent the median of the five RPA climate projections for the given time period, and horizontal bars indicate the range of values across those climate projections. Forest type groups are arranged according to their area (largest at the top left to smallest at the bottom right; see figure 5-8 for areas of forest type groups).



RCP = Representative Concentration Pathway.

Exposure and sensitivity of forests to drought are only one set of factors in determining ecological effects and resulting impacts on goods and services. Drought impacts to forests depend on a number of factors, including landscape characteristics such as the extent and configuration of forest and other land uses, and patterns of human activities related to water supply and demand, as well as management (Crausbay et al. 2017; also see the Water Resources Chapter). For example, evidence from the 2011 drought in east Texas shows that pines, and especially those in managed pine stands that had been thinned, had lower drought mortality rates than other genera (Klockow et al. 2020), suggesting that tree species and management both affected forest drought impacts. Recent emerging frameworks of ecological drought aim to integrate across these ecological and socioeconomic factors to characterize water deficits that result in substantial impacts to ecosystems and ecosystem services. Integrated metrics of ecological drought that incorporate both exposure to drought and measures of impact to forests, rangelands, and the ecosystem services they provide (as in the sidebar Vulnerability to Drought) can be expanded nationwide. Approaches that account for expected human population and land use shifts within and among U.S. regions can help mitigate future drought impacts (Warziniack and Brown 2019). Human adaptations to drought such as groundwater mining can help ameliorate impacts in the short term, but are ineffective in the long term (Brown et al. 2019, USDA Forest Service 2016). Additional research is needed regarding ways to meet the water demands of cities and agriculture while ensuring that forests are sufficiently drought-resilient in the face of climate change.

Vulnerability to Drought: The Case Study of Tree Mortality and Rangeland Productivity in Texas

The vulnerability of forests and rangelands to drought depends on their degree of exposure, sensitivity to drought conditions, and capacity to adapt to those conditions (Crausbay et al. 2017). While individual species and the ecosystems to which they belong can have different levels of drought tolerance (Archaux and Wolters 2006, Berdanier and Clark 2016, Brodrick et al. 2019, Peters et al. 2015), the impact of an event that approaches or exceeds historical extremes in duration or magnitude can be substantial, particularly if it occurs over a large geographic area (Clifford et al. 2013, Schwantes et al. 2017). We illustrate this with a case study of a period of exceptional drought in Texas.

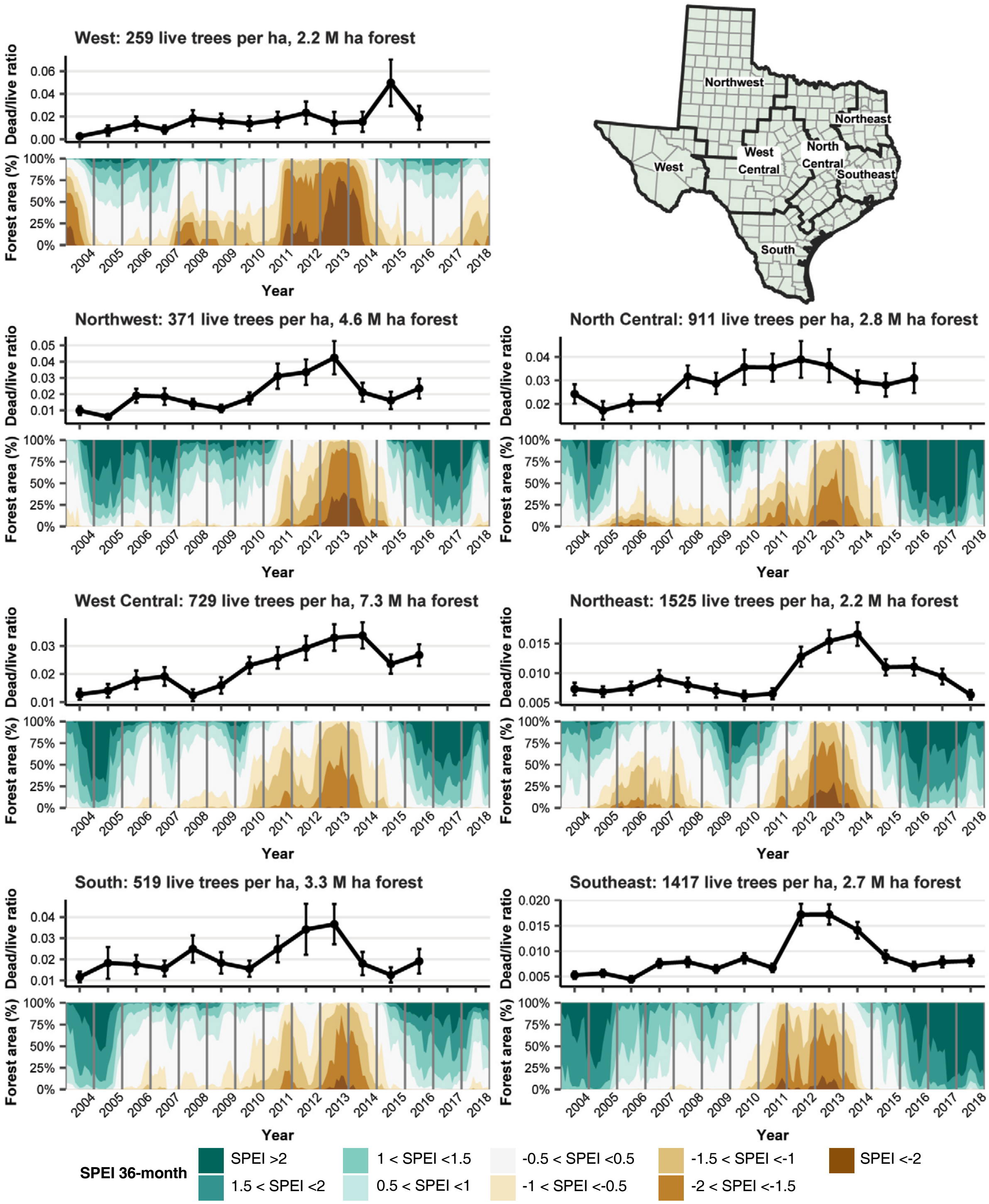
Texas and other parts of the Central United States experienced one of the worst droughts on record in 2011 (Fernando et al. 2016, Grigg 2014, Moore et al. 2016, Nielsen-Gammon 2012). After a relatively dry winter, extreme drought conditions extended throughout Texas during the spring and summer of 2011, persisting in some parts of the State through the end of the year (Fernando et al. 2016). A heat wave during the summer of 2011 exacerbated the drought (Hoerling et al. 2013) and was a secondary contributor to widespread forest mortality. Similar compound extreme events could become more common in the future, highlighting the importance of understanding the impact of this compound event on forests and rangelands. According to FIA data, an estimated 301 million trees, more than 6 percent of trees statewide, were killed by a combination of drought and historically high temperatures (Hoerling et al. 2013, Moore et al. 2016). Rainfall during early 2012 improved moisture conditions across much of Texas, but extreme drought lasted throughout 2012 and into 2013 in some locations elsewhere in the Central United States (Fernando et al. 2016, Tadesse et al. 2015). In Texas alone, agricultural losses from the drought were estimated at $7.6 billion (Fannin 2012), exceeding the previous record of $4.1 billion in 2006. Of this $7.6 billion, livestock losses were estimated at $3.2 billion, reflecting increased feeding costs and market losses. Rangeland impacts were felt beyond these economic effects. The drought resulted in forage yields far below any levels recorded since 1984, the first year of annual production measures from the Rangeland Production Monitoring Service (Reeves et al. 2020, 2021). We show how two metrics of drought sensitivity—forest tree mortality and rangeland production—and their relationships with meteorological drought measured via SPEI changed over space and time for forests and rangelands in Texas.

Distinct signatures of the drought can be seen in each of the seven regions of Texas (figure 5-16). Darker brown areas reveal drier conditions, both in magnitude (taller on the Y axis) and duration (wider range on the X axis). Because of the 36-month window used when computing SPEI, the signatures of the 2011 drought are evident until 2014, even though moisture conditions in Texas generally followed long-term trends from early 2012 until early 2014 (Fernando et al. 2016). At certain points during the signature period, severe or extreme drought conditions (SPEI <-1.5) extended across at least 70 percent of the forested areas in every region. Most importantly, the plots suggest a consistent relationship between the SPEI, a metric of drought exposure, and forest mortality (as depicted by the standing dead tree/live tree ratio), a metric of drought sensitivity. The relationship appears strongest in the northeast and southeast regions of Texas, which have the highest forest density, and weakest in the west region, where forest is sparsely distributed. Differences between the regions in terms of forest mortality, such as when the ratios of standing dead/live trees reached their peak values, may be partly explained by differences in the regions' predominant tree species, which can exhibit varied mortality rates based on their capacity to survive drought stress or associated disturbances, such as drought-triggered pest outbreaks (Klockow et al. 2018).

Figure 5-17 shows the temporal and spatial relationships between meteorological drought measured via 6-month SPEI and rangeland production, another metric of drought sensitivity, on about 69 million ha of rangeland in regions of Texas for the 1984 to 2018 period. There is a notable relationship between the SPEI and production data over time and by region. During drier periods, a corresponding decrease in annual production can be seen in the rangeland production trend. In most regions, 2011 and 2012 show the longest and most far-reaching sustained period of extreme drought (SPEI <-2) in the record. During that time, forage conditions were the second worst since 1984, except for the northwest region of the State, where forage conditions were by far the worst on record.

These figures suggest that the SPEI can be a useful metric for examining forest and rangeland health. The SPEI can also inform management actions to increase adaptive capacity of forests and rangelands to drought, including thinning and prescribed burning in forests and removal of

Figure 5-16. SPEI and the ratio of dead/live trees by region in Texas, 2004 to 2018. For each region, the line chart shows the annual ratio of standing dead trees to live trees, estimated from FIA data and representing forest mortality. The plot below the line chart shows meteorological drought as the monthly proportion of the region's forest area in each of the SPEI categories. The number of live trees per hectare and area of forest (FIA data circa 2016) are listed for each region because the regions differ in forest area and density.

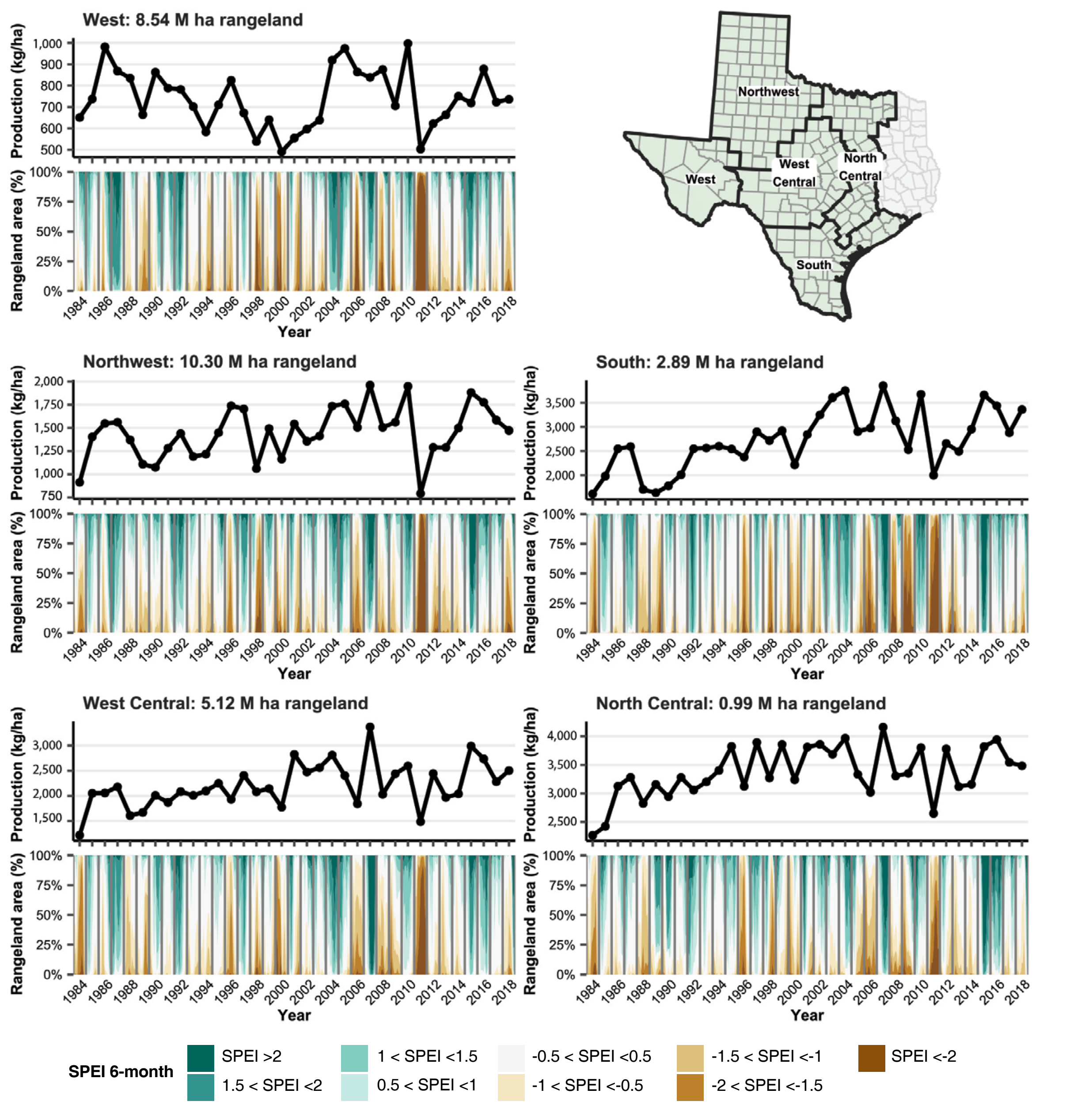


FIA = Forest Inventory and Analysis; SPEI = Standardized Precipitation Evapotranspiration Index.

Source: Costanza et al. 2022b.

trees or large shrubs where encroachment has occurred on rangelands. The incidence of droughts of this magnitude and duration are projected to increase in the future (figures 5-14, 5-21), suggesting that substantial tree mortality and decreases in rangeland productivity, along with associated economic losses, will become more frequent in these regions of Texas and elsewhere. Similar analyses are needed for other U.S. forest and rangeland ecosystems to further explore relationships between exposure and sensitivity to drought.

Figure 5-17. SPEI and rangeland production by region in Texas, 1984 to 2018. For each region, the line graph shows annual production obtained from the Rangeland Production Monitoring Service. The plot below the line chart shows meteorological drought as the monthly proportion of the region's rangeland area (circa 2011) in each of the SPEI categories.



Sources: Rangeland Production Monitoring Service (Reeves et al. 2020, 2021); Costanza et al. 2022b; Reeves and Mitchell (2011).

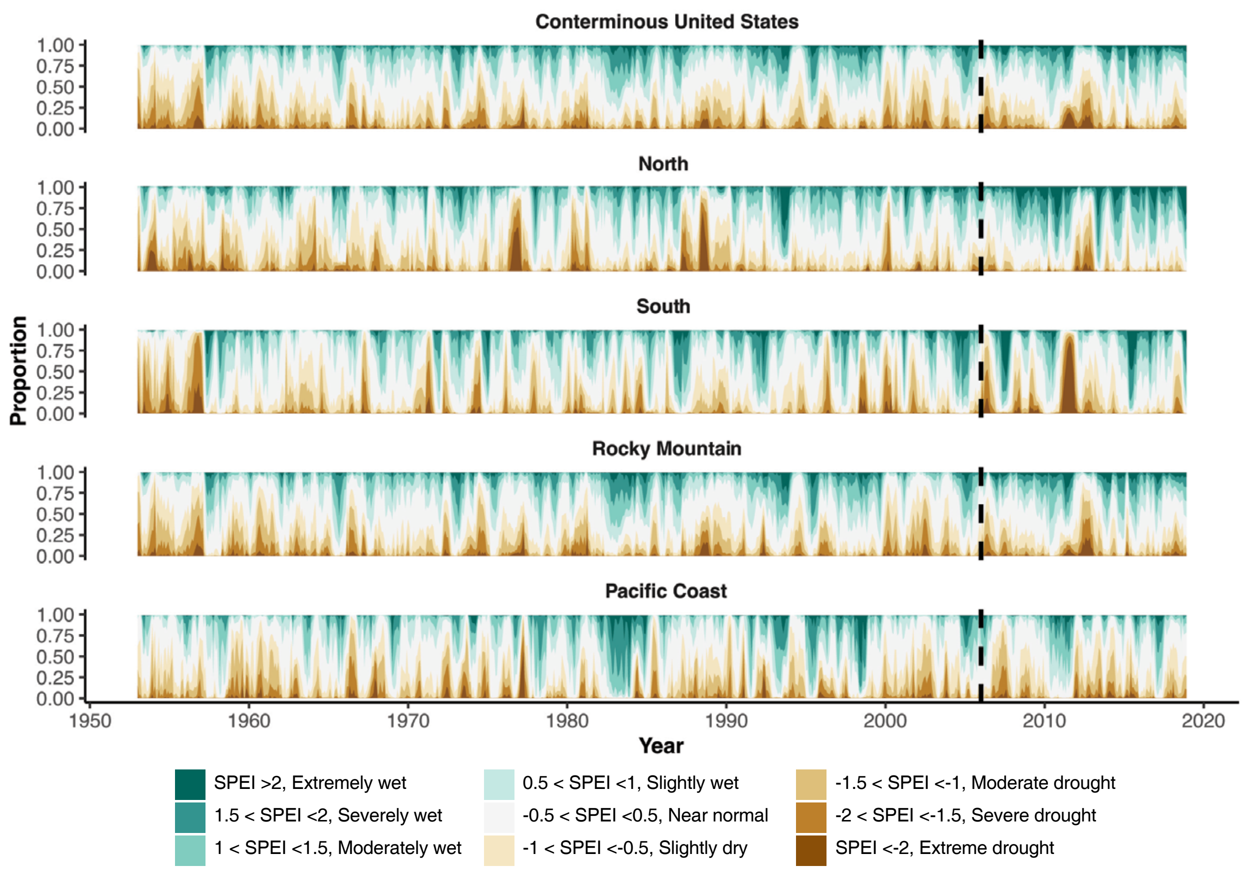
Rangelands

Rangeland drought effects are similar to forest drought effects. Ecologically, drought results in reduced growth rates, defoliation, and increased stress on rangeland vegetation. From a range management perspective, drought generally reduces the supply of water and associated forage vegetation, which can lead to reduced livestock production, and in some cases substantial economic losses (Kelley et al. 2016). Additionally, because many rangeland droughts are driven by warm temperatures that lengthen the growing season, the vegetation that remains during droughts can exhibit increasing demand for water through increased evapotranspiration (Udall and Overpeck 2017). Rangeland droughts have been increasing in frequency and severity over the last 50 years, particularly in the central Great Plains and Southwest, and the trend is expected to continue (Cook et al. 2015).

To assess current and future exposure of rangelands to drought, we used the 6-month SPEI, rather than the 36-month SPEI employed for forests. This shorter period reflects the fact that rangelands are dominated by herbaceous or shrub vegetation, which respond more quickly to drought than forests in terms of both effects and recovery (Finch et al. 2016).

Results from SPEI analysis for the observed historical period generally confirm known intervals of drought and relatively wet conditions, both across the U.S. and within RPA regions (figure 5-18). Major recent rangeland drought events occurred in 2002 in the Rocky Mountain Region, 2011 and 2012 in the South Region, and 2012 through 2016 in the Pacific Coast Region. Of these, the droughts of 2011 and 2012 produced the greatest economic impacts in the rangeland sector (see the sidebar Vulnerability to Drought). Evaluating drought trends at national and regional levels may obscure highly significant events occurring at sub-regional levels. For example, although the summary of SPEI across the Rocky Mountain Region does not show a marked drought signal in 2018, Coconino, Navajo, and Apache counties in Arizona had such severe drought conditions at the time that they were designated as natural disaster areas by the U.S. Secretary of Agriculture (https://www.fsa.usda.gov/state-offices/Arizona/news-releases/2019/stnr_az_20190328_rel_01). Coupling national and regional

Figure 5-18. Proportion of rangeland area in categories of observed 6-month SPEI over time, based on PRISM climate data, 1953 to 2018. The period to the left of the dashed line in each graph indicates the reference period that was used to calibrate SPEI values.



SPEI = Standardized Precipitation Evapotranspiration Index.

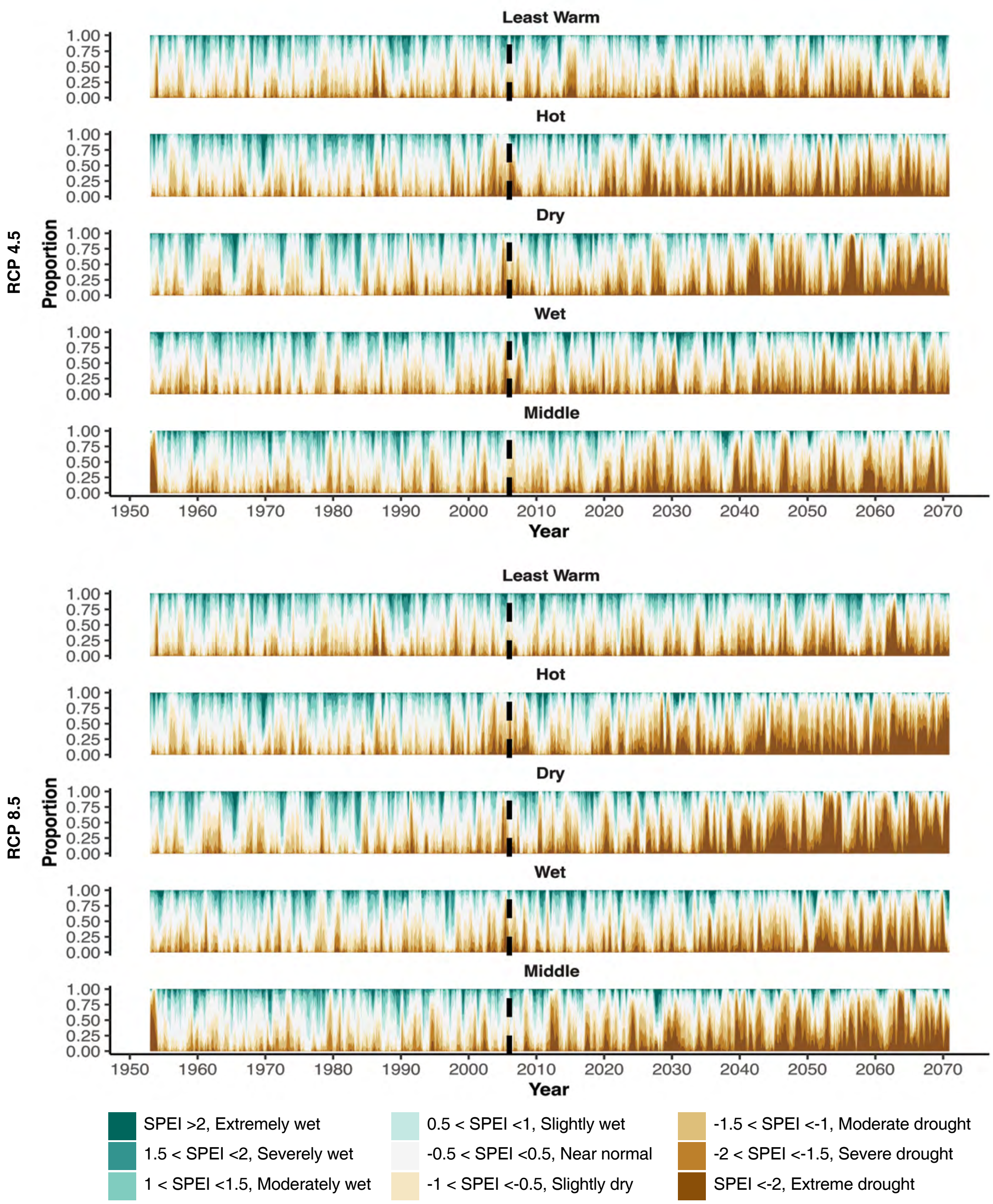
Source: Costanza et al. 2022b.

analyses with analysis and monitoring of local drought conditions is critical for determining drought extent and for more accurate accounting of impacts.

Future projections of drought show that the frequency of drought exposure is expected to increase for rangelands across the United States, under both RCPs and all RPA climate projections (figure 5-19), especially by mid-century (2041 to 2070). The hot and dry futures projected the most frequent, widespread, and severe drought across U.S. rangelands, particularly during the period approaching 2070 under both RCPs. A substantial increase in drought was also projected under RCP 8.5 using the middle climate projection.

We assessed the projected future drought exposure of dominant rangeland vegetation types (figure 5-20). We summarized the monthly proportion of each vegetation type in severe or extreme drought (SPEI <-1.5) for the same time periods assessed in the forest type group analysis (recent past, mid-century). Overall, the analysis shows the potential

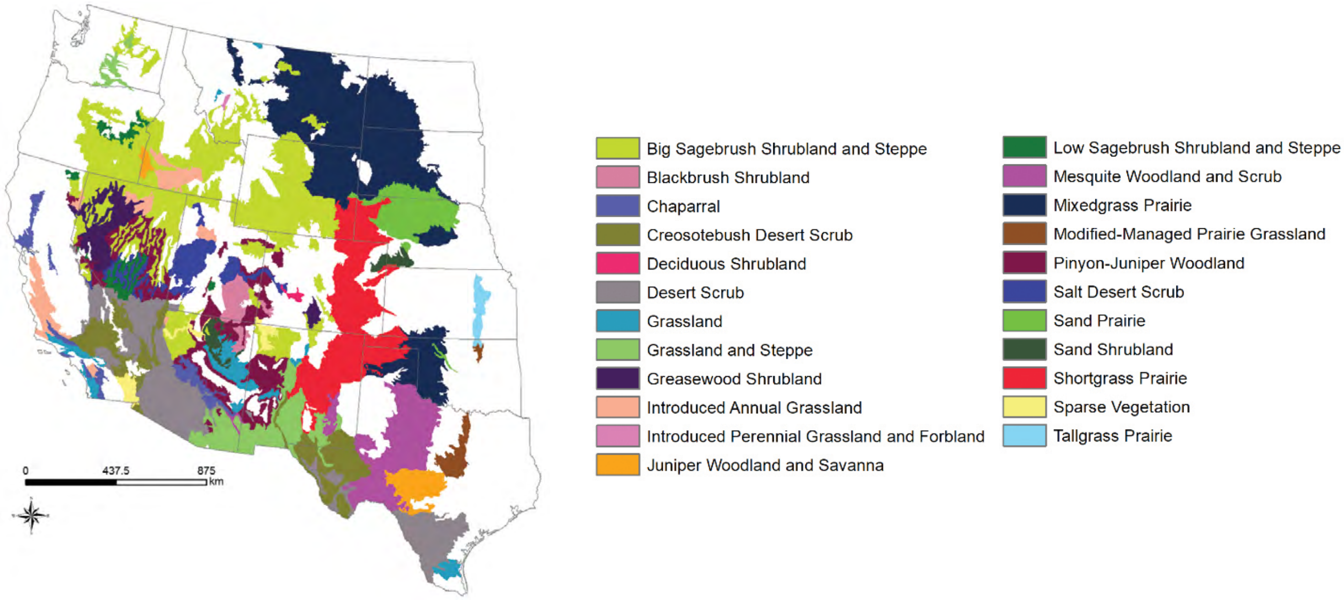
Figure 5-19. Proportion of rangeland area in categories of 6-month SPEI for historical (1953 to 2005) and future (2006 to 2070) periods using the RPA climate projections under RCP 4.5 (top) and RCP 8.5 (bottom). The period to the left of the dashed line in each graph indicates the reference period that was used to calibrate SPEI values.



RCP = Representative Concentration Pathway; SPEI = Standardized Precipitation Evapotranspiration Index.

Source: Costanza et al. 2022a.

Figure 5-20. Ecological subsections and their associated dominant vegetation types for summarizing SPEI projections.



SPEI = Standardized Precipitation Evapotranspiration Index.

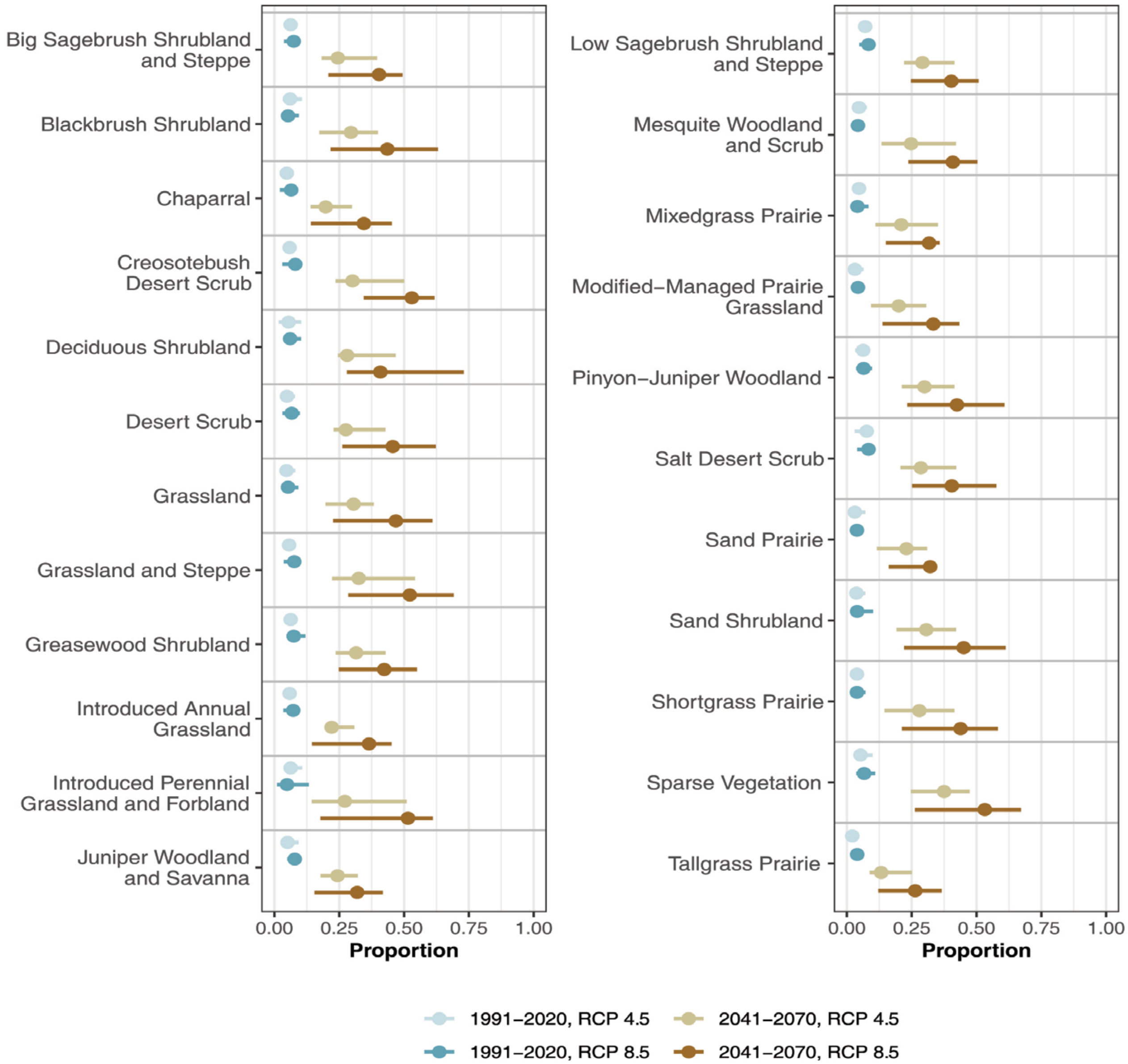
Sources: Ecological subsections are from Cleland et al. (2007). Vegetation types are Ecological Systems (Comer et al. 2003) that were mapped in 2012 LANDFIRE Existing Vegetation Type data (LANDFIRE 2012).

for much higher exposure to drought nearly everywhere by mid-century, with differing amounts of exposure by vegetation type, and higher exposure generally under RCP 8.5 (figure 5-21). By mid-century, the vegetation types with the highest level of exposure projected under RCP 8.5 using at least one climate projection include those located in the Southwestern United States, such as creosotebush desert scrub, grassland, and grassland and steppe. Each of those types is common in Arizona and New Mexico, and the former two are also present in southern California (figure 5-21). A comparison of the median exposures for the two time periods indicates that these and other vegetation types occupying the arid regions of the Southwest are expected to experience a four- to five-fold (RCP 4.5) or six- to eight-fold (RCP 8.5) increase in exposure to severe or extreme drought conditions by mid-century (figure 5-21). The increase seen here is similar to results from other recent research showing the potential for unprecedented drought in the Southwestern United States toward the latter half of this century (Cook et al. 2015), and a general agreement among climate models that drought exposure will increase in already-dry regions of the West (Bradford et al. 2020). In addition to those three southwestern types, median projections for other vegetation types that have had moderate drought exposure in the recent past, shortgrass prairie and sand shrubland indicate even greater changes in exposure rates by mid-century. Six- to seven-fold (RCP 4.5) or 10-fold (RCP 8.5) increases in exposure to severe or extreme drought are projected for those types by mid-century (figure 5-21).

By mid-century, the projected range of drought exposure for each rangeland type reflects not only the wide selection of RPA climate projections (least warm, hot, dry, wet, middle) but also the geographic distribution and extent of the rangeland system. Planning for a dry or a hot future may be important to address the potential risk to the resources in these rangeland types at the local scale.

Higher future exposure to severe or extreme drought nearly everywhere, especially in the arid Southwestern United States suggests that the water resources already scarce in that region could be further strained by the end of the projection period, having impacts on ecosystem goods and services (see the Water Resources Chapter). Altered timing of peak flows and shifts from perennial to more intermittent flow, especially in streams in the Southwest (Gutzler and Robbins 2011, Zipper et al. 2021) may further complicate the timing and amount of water availability. Forage resources would likely become sparse under these conditions, suggesting that significant reductions in the density of native and domestic ungulates may be necessary (Ford et al. 2019, Reeves et al. 2017). In addition, the expansion of invasive species such as red brome (*Bromus rubens*) and Lehmans lovegrass (*Eragrostis lehmanniana*) may be enhanced if native perennials and annuals undergo more stress related to soil moisture deficits (Curtis and Bradley 2015). Projection results for all rangeland vegetation types show the possibility of worsening exposure to severe or extreme drought under both RCPs by mid-century compared with the early century time period, suggesting the importance of timely implementation of management or mitigation actions to enable adaptation that is robust to worsening drought (see the Water Resources Chapter for examples).

Figure 5-21. Comparison of monthly proportion of rangeland ecosystems in severe or extreme drought for each of the RCPs at mid-century (2041 to 2070) with the same metric during the recent past (1991 to 2020). Dots represent the median of the five RPA climate projections for the given time period, and horizontal bars indicate the range of values across those climate projections. See figure 5-20 for a map of these rangeland systems.



RCP = Representative Concentration Pathway.

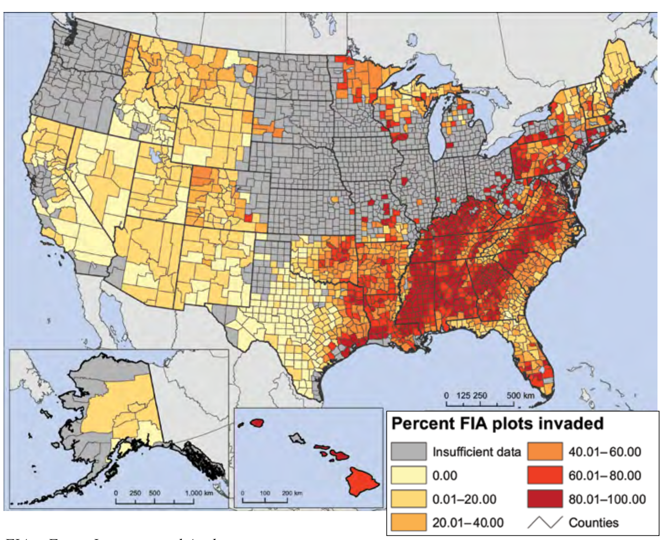
Nonnative Invasive Plants in Forests and Rangelands

- ❖ The highest rates of forest invasion have occurred throughout the RPA South Region as well as in metropolitan areas and agriculture-dominated counties in the RPA North Region.
- ❖ Forest type groups in those regions had the highest rates of invasion, especially where forest was privately owned.
- ❖ Future increases in developed or agricultural land use in the Eastern United States could lead to higher forest invasion rates.
- ❖ Counties in the RPA Pacific Coast Region had the highest rates of rangeland invasion, specifically in coastal and southern California.

Forests

Nonnative invasive plant species cause long-term detrimental effects on forest ecosystems, including declines in biological diversity, alterations to forest succession, and changes in nutrient, carbon, and water cycles (Liebhold et al. 2017, Mack et al. 2000, Martin et al. 2009). The damage caused by these invasive species, and the efforts to control them, are costly (Pimentel et al. 2005), even before accounting for the impacts to nonmarket economic services such as recreation and landscape aesthetics (Holmes et al. 2009). The Forest Inventory and Analysis (FIA) program collects invasive plant data based on expert-derived lists of problematic invasive plant species (Oswalt et al. 2015), defined as those of any growth form likely to cause economic or environmental harm (Ries et al. 2004). A national analysis of FIA plot data across the United States (including Alaska and Hawaii) from 2005 to 2018 revealed a strong differentiation in the percent of invaded plots between counties in the East and West (figure 5-22). Counties throughout much of the RPA South Region and the mid-Atlantic and Midwestern States of the RPA North Region had the highest percent of invaded plots, with lower levels of invasion in parts of the southern Appalachians, the southeastern Coastal Plain, northern Florida, and the Great Lakes States. These results likely underestimate the overall presence of invasive plant species because field crews only record species that have been identified previously as problematic. The geographic patterns are consistent with recent work that also detected the highest prevalence of forest plant invasion in the Southeast, in the agriculturally-dominated Midwest, and near metropolitan areas (Iannone et al. 2015). These results further underscore the finding that eastern FIA plots are most likely to be invaded in relatively more productive, fragmented forest in interface landscapes containing more than 10 percent agriculture or developed land cover (Riitters et al. 2017; also see the Land Resources Chapter).

Figure 5-22. Percent of FIA forest plots invaded by county. Counties with fewer than five plots that were surveyed for invasive plants were omitted and are shown in gray.



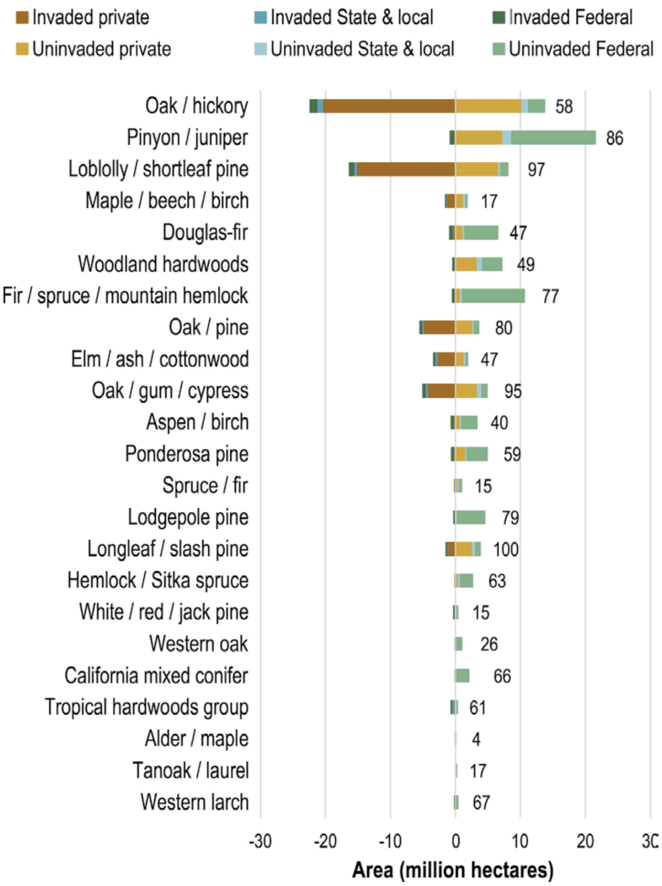
FIA = Forest Inventory and Analysis.
Source: Potter and Riitters 2023.

We used FIA data to estimate the forest area that has been invaded by nonnative plant species nationally, within RPA regions, and by ownership within major forest type groups (Riitters and Potter 2019). Nationally, approximately 62.7 million ha of forest were invaded (36.2 percent of the forest inventoried for invasive plants, figure 5-23). Forest land in the South Region had the highest proportion of invaded forest area (57.7 percent of inventoried area, 52.7 million ha), followed by the North Region (54.5 percent). The forest area in the two western regions was considerably less invaded (7.5 percent in the Rocky Mountain Region and 5.0 percent in the Pacific Coast Region). These proportions and areas of invaded forest are likely substantial underestimates because only 61 percent of all forest was inventoried for invasive plants, with much smaller percentages inventoried in the North and Pacific Coast Regions.

For the most invaded, commonly occurring forest type groups, such as oak/hickory, loblolly/shortleaf pine, oak/pine, and oak/gum/cypress, the large majority of invaded forest was in private ownership (figure 5-23). The large proportion of invaded forest in private ownership agrees with previous research showing that privately owned forest lands in the Eastern United States had the highest rates of invasion (Riitters et al. 2018), likely because they are closer to human land uses, which contribute seed sources that are responsible for plant invasions.

As land use changes, future projected increases in forest area contained within the WUI (see the sidebar Wildland-Urban Interface in the Land Resources Chapter) or exposed

Figure 5-23. Area of forest invaded and not invaded, by ownership within FIA forest type groups. The numbers at the end of each bar indicate the percent of forest within each type group that was surveyed for invasive plants. Bars to the left of the 0 line indicate invaded; bars to the right indicate not invaded.



FIA = Forest Inventory and Analysis.

to nearby agriculture and development (see the section Projected Forest Fragmentation and Landscape Context in the Land Resources Chapter) will likely increase seed sources and thus increase invasion rates in forest land. Road construction is similarly expected to increase rates of forest plant invasions in nearby forests (Forman and Alexander 1998). While privately owned forest land had higher rates of invasion than public land, the proximity of private land to human land uses, rather than ownership per se, is likely the underlying factor responsible for the difference. Therefore, changes in ownership or protection status alone are unlikely to prevent future invasions (Riitters et al. 2018). In addition to land use change, widespread intercontinental movement of plants for ornamental purposes is almost certain to ensure future introductions of new nonnative invasive plants into forests (Theoharides and Dukes 2007). Once forest land is invaded, it is unlikely to become un-invaded in most future circumstances, given that management of invasive plant species in forests often results in their replacement by other nonnatives (Reid et al. 2009). These results add up to a future in which invasion rates are likely to increase on forest land.

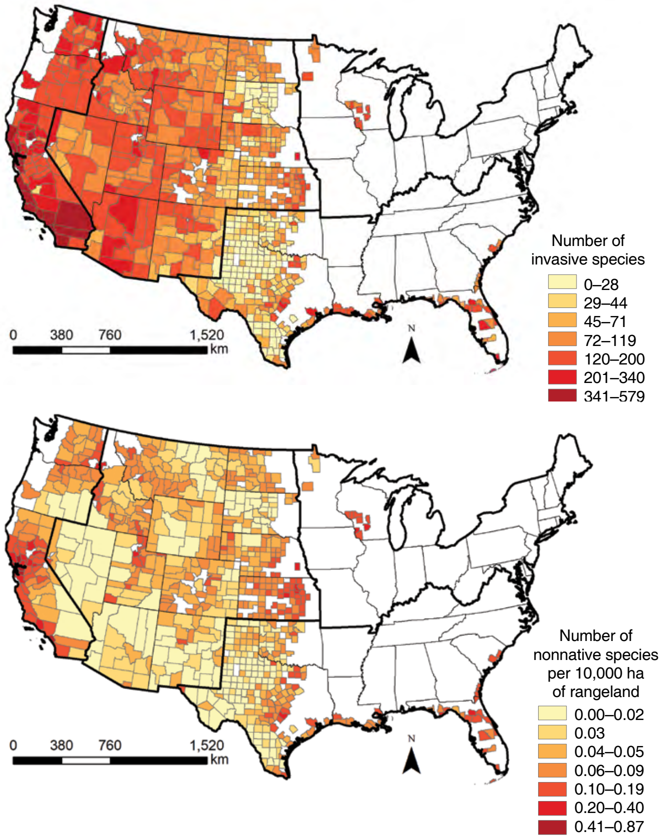
While these summaries of invaded forest areas do not directly address the ecological or economic impacts to forests, some impacts to forests are likely because the invasive species surveyed by FIA are considered problematic (Oswalt et al. 2015). Information about forest invasion rates and impacts is likely to improve as a temporal record of data from invasive plant surveys at broad scales is accumulated and if FIA expands invasive plant inventories to include forest land that has not yet been surveyed for invasive plants (Oswalt et al. 2021).

Rangelands

Nonnative invasive plant species can cause wholesale changes to the ecological and economic health of rangeland ecosystems. Many rangelands that were dominated by perennial bunchgrasses have been invaded by nonnative annual grasses, which increase water demand; cause more frequent, higher severity, larger fires; lower livestock yields and forage quantity; and lead to substantial economic losses (DiTomaso 2000, Rottler et al. 2015). No consistent national invasive species rangeland inventory is available that covers all public and private lands. Hence, we used data from the Center for Invasive Species and Ecosystem Health at the University of Georgia (the Bugwood Program, www.Bugwood.org) to investigate nonnative plants in counties containing substantial rangeland area (exceeding 60,703 ha, based on Reeves and Mitchell 2011; see figure 5-1 for the distribution of rangeland). Data for the Bugwood Program is usually collected by volunteers recording locations of nonnative species and thus may be biased toward higher counts in populous areas or counties with more public land (Wallace 2020).

The number of nonnative plant species in rangeland counties generally increased from east to west, peaking in coastal California (figure 5-24). San Diego, Los Angeles, and Marin counties are reported to host 579, 566, and 494 nonnative species, respectively. Counties in the RPA Pacific Coast Region contained the highest numbers of nonnative species, followed by counties in the western portion of the Rocky Mountain Region. The lowest numbers of nonnative species were exhibited by grassland areas of the Great Plains, including the eastern portion of the Rocky Mountain Region as well as parts of Oklahoma and Texas in the South Region. A few counties in the North Region had enough rangeland area to be included in this analysis but were insufficient for discerning a geographic pattern. When the number of nonnative species in each county was standardized by the area of rangeland in the county ("density" of nonnative species; figure 5-24), the geographic pattern was slightly different. Similar to the result for the overall number of nonnative species, the RPA Pacific Coast Region had the

Figure 5-24. Total number (top) and density (bottom) of nonnative plant species in rangeland counties. Rangeland counties are defined as those that contain more than 60,703 ha of rangeland (Reeves and Mitchell 2011). See figure 5-1 for distribution of rangeland.



ha = hectares.

Source: Center for Invasive Species and Ecosystem Health at the University of Georgia (the Bugwood Program, www.Bugwood.org).

greatest density of nonnative plant species, with the highest densities in counties in and around the California bay area and along the California coast. Unlike the overall geographic pattern for number of nonnative species per county, the geographic pattern of nonnative species density did not increase generally from east to west. Scattered counties in central Utah, the upper Snake River Plain, and in eastern Kansas also had high densities of nonnative species.

The large numbers of nonnative plant species in many western counties may suggest that rangelands have a relative lack of resistance to invasion. Research in many rangeland ecosystems has demonstrated an invasive grass-fire cycle, wherein longer, more favorable growing conditions, inappropriate grazing regimes, and altered fire regimes can allow nonnative annual grasses to survive (D'Antonio and Vitousek 1992, Fusco et al. 2019). Those grasses subsequently alter the moisture and fire regimes, creating new environments that favor even greater richness and abundance of nonnative annual grass species (Roundy et al. 2018). On the other hand, the low numbers of nonnative plant species in parts of the Great Plains could reflect greater resistance to invasion in some rangeland ecosystems. An emerging framework that summarizes the rangeland ecosystem attributes and landscape characteristics that affect resilience to plant invasion and resulting wildfire (Chambers et al. 2014, 2019) could be incorporated in future RPA Assessments to provide further insights into invasion patterns.

Given the potential biases in the data toward higher counts on public lands, caution is recommended for interpretation of these results. For example, many counties in Texas show relatively low numbers of nonnative species, but rangeland counties in the State exhibit approximately 98 percent private land ownership, and some private landowners might be reluctant to make data about their land widely accessible. In addition, because these data document even individual occurrences of a nonnative plant species in a given county, they do not necessarily represent geographic patterns of ecological or economic impact. While data collection efforts in several agencies do cover such occurrences, including the National Resources Inventory of the USDA Natural Resources Conservation Service and the Assessment, Inventory, and Monitoring Strategy of the U.S. Bureau of Land Management, obtaining those data in rangeland counties is challenging due to privacy concerns. Nonetheless, using those datasets in tandem could improve the assessment of invasive plant distributions in rangelands, improve understanding of their impacts, and enable future projections of their spread.

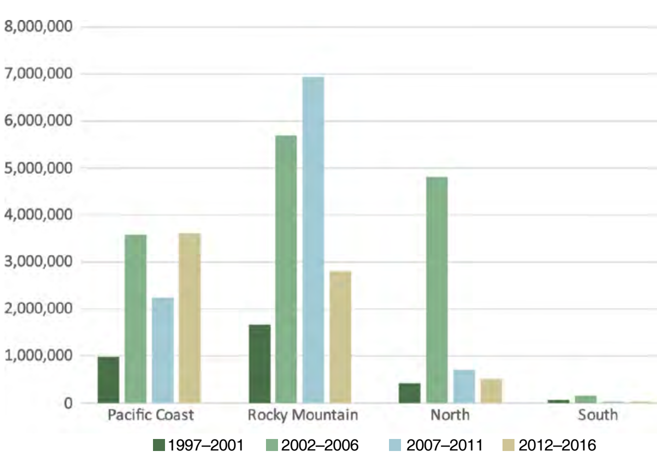
Insect and Disease Disturbances in Forests

- ❖ The overall area of forest tree canopy mortality caused by insects and diseases was usually higher in the RPA Rocky Mountain and Pacific Coast Regions than in the South and North Regions.
- ❖ Nonnative insects and diseases had a larger effect on forest mortality in the North Region than in other regions.
- ❖ Defoliation was more widespread in the North and South Regions than in the two western regions.
- ❖ The future effects of insects and diseases in forests are uncertain, but most factors associated with a warmer climate contribute to a greater potential for outbreaks.

Insects and diseases, especially nonnative invasive agents, have the capacity to cause ecological and economic damage to forests (Lovett et al. 2016, Tobin 2015). Individual insects and diseases have extirpated entire tree species or genera and fundamentally altered forests across broad regions. For example, chestnut blight, a canker disease caused by the introduced fungus *Cryphonectria parasitica*, functionally eliminated the American chestnut from its range across the Eastern United States (Loo 2009). This elimination process is now being repeated for several ash species in the United States and Canada by the emerald ash borer (*Agrilus planipennis*), an insect introduced from northeastern Asia (Klooster et al. 2018). Tracking insect and disease infestations over time is necessary to understand the extent and duration of their impacts on forest ecosystem structure, function, and dynamics. Twenty years of Insect and Disease Survey (IDS) data, collected annually by the Forest Health Protection program of the U.S. Department of Agriculture, Forest Service (FHP 2019), enable trend detection over time for insect and disease damage (Potter et al. 2020). We summarized the forest area in which tree canopy was affected by insects or diseases nationally (including Alaska and Hawaii) and within RPA regions in four 5-year time windows (1997 to 2001, 2002 to 2006, 2007 to 2011, and 2012 to 2016) to highlight places where forests were impacted by insect or disease agents.

The tree canopy area affected by native and nonnative mortality-causing agents has been consistently large across the three most recent 5-year assessment periods. The RPA North Region experienced its greatest affected area in 2002 to 2006, the Pacific Coast Region (which here includes Alaska and Hawaii) in 2002 to 2006 and 2012 to 2016, and the Rocky Mountain Region in 2007 to 2011 and 2002 to 2006, while the South had comparatively limited area with mortality (figure 5-25). Forest mortality from insects and diseases may be underrepresented in the South Region because of the more intense management cycles including rapid removal of affected trees, and higher growth and decay rates leading to more rapid forest recovery after disturbance. Forest mortality is likely overrepresented in

Figure 5-25. Area of mortality attributed to both insect and disease agents in 5-year intervals, by RPA region (Alaska and Hawaii are included in the Pacific Coast Region).



Source: Insect and Disease Survey (IDS) data (FHP 2019).

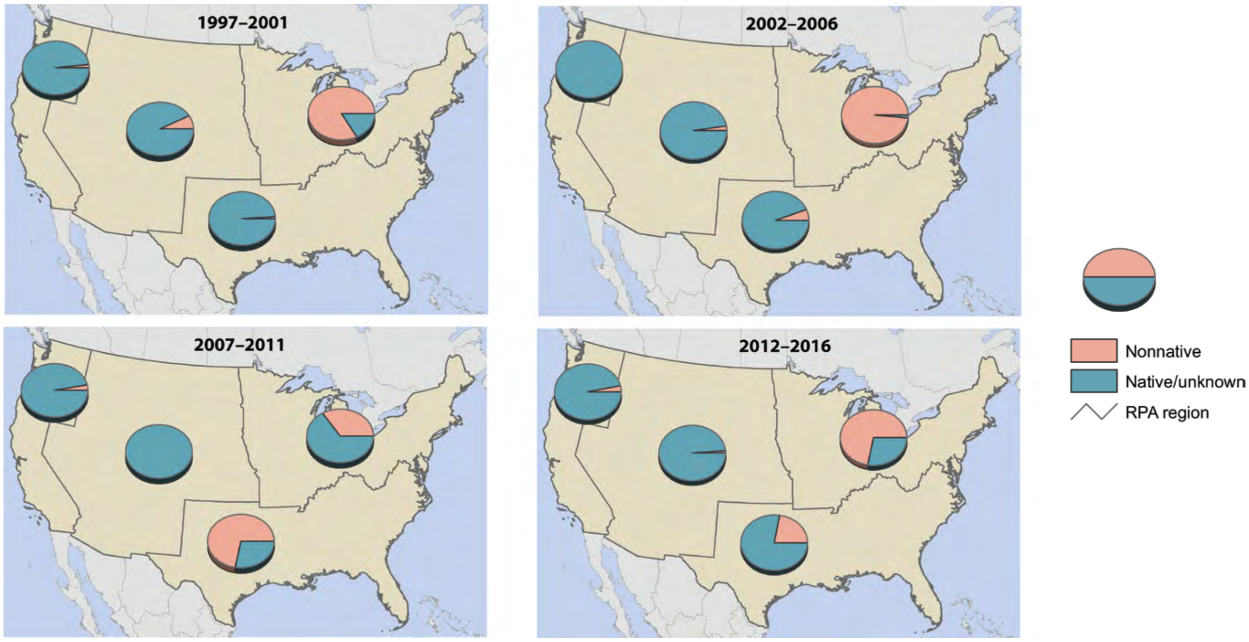
the North Region during the 2002 to 2006 period because surveyors drew polygons to encompass large areas affected by dispersed emerald ash borer and balsam woolly adelgid (*Adelges piceae*) infestations, rather than defining only the affected areas as was done in other regions. Documented mortality has generally been much more widespread from insects than diseases, with bark beetles consistently reported as the most important mortality agents across all regions and over time, particularly in the West (Potter et al. 2020). Mountain pine beetle (*Dendroctonus ponderosae*) was responsible for a mortality peak in the Rocky Mountain Region from 2007 to 2011, while fir engraver (*Scolytus ventralis*) and western pine beetle (*Dendroctonus brevicomis*) caused increased mortality in the Pacific Coast Region from 2012 to 2016.

Nonnative invasive insects and diseases had a larger relative contribution to forest mortality in the North Region than elsewhere in the United States (figure 5-26). The list of such species in the North Region is lengthy, including emerald ash borer, hemlock woolly adelgid (*Adelges tsugae*), balsam woolly adelgid, beech bark disease (caused by the insect *Cryptococcus fagisuga* and associated *Neonectria* fungus), and oak wilt (caused by the fungus *Bretziella fagacearum*). Nonnative invasive agents had substantial impacts elsewhere as well, including Hawaii, where rapid ʻōhiʻa death, a fungal disease caused by *Ceratocystis huliohia* and *C. lukuohia*, is causing considerable mortality to one of the State's most ecologically and culturally important tree species (Fortini et al. 2019). Elsewhere, and especially in the West, native agents including the western pine beetle mentioned above have been consistently important causes of mortality.

While tree canopy mortality is one critical effect of insects and diseases, some agents also cause substantial damage via defoliation. The tree canopy area affected by defoliation agents has remained relatively consistent over time and has usually equaled or exceeded the area affected by mortality agents, with nonnative defoliators more significant in the RPA North Region (including European gypsy moth, *Lymantria dispar*; larch casebearer, *Coleophora laricella*; and winter moth, *Operophtera brumata*) and South Region (European gypsy moth) compared to the western regions (Potter et al. 2020). This evaluation of recent mortality and defoliation from insects and diseases provides context for managers about the implications and scope of current forest health threats at a national scale.

Knowing how these trends will change in the future can provide critical information for land management planning and decision making. The future impacts of forest insects and diseases are highly uncertain, compounding uncertainty about climate change with uncertainty about the effects of climatic conditions on insects and diseases, as well as on the distribution of tree host species, and about what new

Figure 5-26. The proportion of mortality attributed to nonnative invasive agents versus native agents and those with unknown origin in 5-year intervals, by RPA region (Alaska and Hawaii are included in the Pacific Coast Region).



Source: Insect and Disease Survey (IDS) data (FHP 2019).

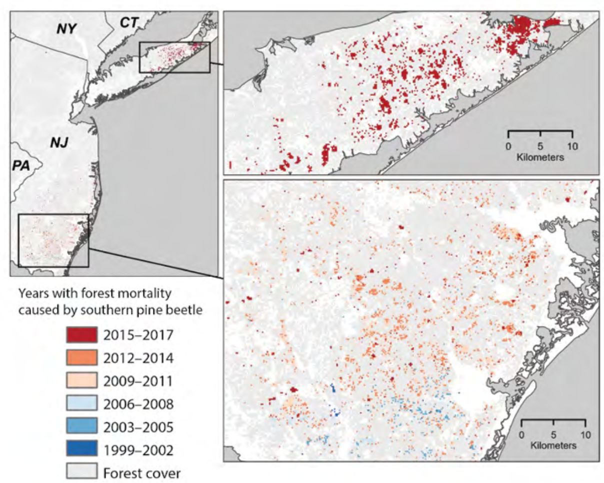
invasive agents will be introduced into the United States. Specifically, predicting the consequences of climate change on the forest health impacts of pests is difficult given the complex relationships among abiotic stressors, host trees, insect herbivores, and the natural predators and parasitoids of those insects (Jactel et al. 2019). Several factors suggest an increased potential for insect and disease outbreaks in the future. For example, it is possible that warmer temperatures may result in higher numbers of broods within a year for some insects, resulting in population outbreaks (Bentz et al. 2019), and allow insect herbivores to expand their ranges into areas that were previously too cold (Dukes et al. 2009). The local expansion of the ranges of some insects and diseases due to climate change has already caused forest mortality and presents challenges for management (see the sidebar Southern Pine Beetle Recent Range Expansion for a summary and example). In addition, climate model projections point to more drought under some plausible futures (see the section Drought in Forests and Rangelands). Droughts may benefit forest insect pests by reducing tree resistance, with bark beetles, sap feeders, and leaf chewers more likely than other insect guilds to benefit from drier conditions (Jactel et al. 2012), although the degree of drought stress affects how well trees resist bark beetles (Raffa et al. 2008). Finally, changing climate conditions may increase the frequency and severity of storms that result in fallen or broken trees that trigger bark beetle outbreaks (Marini et al. 2017, Raffa et al. 2015). At the same time, other factors related to changing climatic conditions may counteract the potential for increased future pest outbreaks. For example, forest insect developmental rates decrease rapidly between an optimal temperature and a hot lethal threshold (Davídková and Doležal 2019), so warming conditions could result in increased insect mortality (Mech et al. 2018). Higher temperatures may also result in smaller size and lower dispersal capacity of newly emerged adult insects (Pineau et al. 2017), while variability in temperatures could reduce forest insect survival (David et al. 2017). Increased CO_2 may also negatively impact forest insect performance, although this could be offset by elevated temperatures (Zvereva and Kozlov 2006). Climate change may also affect relationships between forest insects and their predator and parasitoid enemies, although how these relationships change is likely to be complicated by several factors (Jeffs and Lewis 2013). Changing climate conditions are generally expected to benefit forest pests, but negative effects of warming may mitigate their impacts on forest health in some circumstances (Jactel et al. 2019) while interactions among disturbances could produce feedbacks that prevent worst-case outcomes (Lucash et al. 2018).

Southern Pine Beetle Recent Range Expansion into New Jersey and New York

Climate change has already enabled the spread of some native forest insects and diseases into areas outside their historical ranges (Dodds et al. 2018, Heuss et al. 2019, Weed et al. 2013). In many of these instances, warmer winter temperatures have reduced or removed cold-temperature restrictions that previously kept populations in check (Kolb et al. 2016, Lesk et al. 2017). Such range shifts give pests access to novel, nonadapted host species or areas that previously were only marginally suitable for a pest, and can therefore have notable ecological and economic consequences for forests. Ecological consequences can include direct impacts to trees in terms of mortality or stress, as well as disruption of existing disturbance regimes and increased susceptibility to related forest health threats such as wildfires and drought (Anderegg et al. 2015, Pureswaran et al. 2018). Economic consequences include mitigation costs as well as direct economic losses from tree mortality (Heuss et al. 2019, Kolb et al. 2016, Weed et al. 2013).

The southern pine beetle (*Dendroctonus frontalis*) is the most economically significant forest pest in the Southeastern United States. Prior to the 2000s, most outbreaks of the beetle occurred in a region extending from Texas to Virginia, although infestations were infrequently reported as far north as Pennsylvania and southern New Jersey (Dodds et al. 2018). Outbreaks were historically most common in forests dominated by loblolly (*Pinus taeda*) and shortleaf (*P. echinata*) pines. Since 2001, southern pine beetle outbreaks have followed a steady northward progression into forests dominated instead by pitch pine (*P. rigida*); this expansion coincides with a documented warming trend (Dodds et al. 2018, Lesk et al. 2017). Insect and Disease Survey (IDS) data show areas of forest mortality caused by the southern pine beetle in New Jersey and New York from 1999 to 2017 (figure 5-27). Gradual northward advancement of mortality is evident in southern New Jersey, and by the 2015 to 2017 period, the beetle was widespread in the pitch pine barrens of Long Island, an area where it had not been previously recorded (Heuss et al. 2019). Pitch pine has been nearly eliminated from affected sites, which have shifted toward hardwood dominance as a result. Efforts to suppress the infestations have also led to accumulation of downed woody debris, increasing fire risk (Heuss et al. 2019). The beetle has since been captured in traps in Connecticut, Rhode Island, and Massachusetts (Dodds et al. 2018), raising concerns that climate-driven range expansion could allow it to exploit other potential hosts such as red pine (*P. resinosa*) and jack pine (*P. banksiana*). This expansion of southern pine beetle, and similar range expansions by other forest insects and diseases, presents a challenge to managers, who may have to adapt their methods to a possibly unfamiliar pest based on knowledge acquired in other geographic settings, which may not translate well to their circumstances (Weed et al. 2013).

Figure 5-27. Forest mortality caused by southern pine beetle in New York and New Jersey from 1999 to 2017.



Source: Insect and Disease Survey data (FHP 2019).

Forest Removal Areas

- ❖ While removals have wide-ranging effects on forests, removals are an important forest management tool for preventing or mitigating impacts from natural disturbances.
- ❖ The annual area of forest canopy loss from removals in the United States averaged 2.44 million ha between 1986 and 2010, with 65 percent of the total occurring in the RPA South Region.

Removals are trees taken out of forests during timber harvesting or other cultural treatments, or due to land-use change. Like other types of disturbances, removals can have wide-ranging effects on forests and their associated goods and services. Removals can negatively affect forest community assembly, structure and function, and productivity (Duncker et al. 2012, Fall et al. 2004, Jactel et al. 2009); carbon storage (Birdsey et al. 2006); water and soil quantity and quality (Birdsey and Lewis 2002, Nave et al. 2010, Yanai et al. 2003); and wildlife habitat and biodiversity (Verschuyl et al. 2011). Removals to decrease forest stand densities, however, can serve to prevent or mitigate impacts from other disturbances such as fire or insect and disease outbreaks (Fettig et al. 2014, Leverkus et al. 2018, Lindenmayer and Noss 2006, Mason et al. 2006), help some forests adapt to increasing water stress (Bottero et al. 2017, Bradford and Bell 2017), increase productivity for timber management (D'Amato et al. 2011, Fox 2000), and provide critical early-succession habitat for wildlife species in the absence of other disturbances (King and Schlossberg 2014). Removals can be directly and immediately influenced by policy, economic incentives, and management goals (Cubbage and Newman 2006, Ellefson et al. 2006, Legaard et al. 2015), unlike many other disturbance processes (but see the sidebar Effects of Air Pollution on Forest Ecosystems for an exception in which the Clean Air Act has had substantial effects on acid deposition). Characterizing the spatial and temporal patterns of removal regimes is an important component of understanding sustainability in light of disturbance interactions and climate change (Kurz et al. 1998, Leverkus et al. 2018, Seidl et al. 2008).

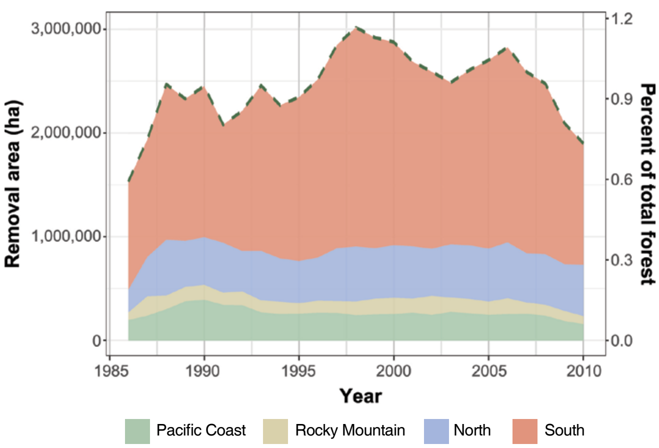
Annual areas of forest removal, measured here in terms of the area of forest canopy loss from removals each year, were derived from a time series of Landsat satellite imagery for the period 1986 to 2010 (Schleeweis et al. 2020) (figure 5-28). Nationally, removals occurred at a mean annual rate of 2.44 million ha (roughly 1 percent of total forest per year) and ranged between 1.53 million ha and 3.01 million ha (dashed line in figure 5-28). The RPA South Region had the highest removal rate in all years, accounting for more than 65 percent of all removals each year, and the most variability from year to year. Although substantially lower than the South Region, the North Region had the next highest annual removal rate on average, followed by the Pacific Coast and Rocky Mountain Regions.

It is important to benchmark these results against the area of annual removals estimated from ground-based forest inventories for similar periods. Reports based on FIA data show consistent national average removal rates of 4.5 million ha yr^{-1}, across multiple decades (although this estimate includes 0.35 million ha reported in Alaska) (Birdsey and Lewis 2002, Oswalt et al. 2014, Smith et al. 2009). While forest inventory data can have a more inclusive definition of removals, optical satellite imagers like Landsat can only detect removals that result in overstory tree canopy loss, and are less accurate when less than 20 percent of canopy cover has been removed (Cohen et al. 2016, Zhao et al. 2018).

The observed trends in removal areas correspond with known trends in policy and markets. First, the peak removal rate and subsequent decrease observed from 1988 to 1990 in the RPA Pacific Coast Region corresponds to documented shifts of regional timber sales due to endangered spotted owl habitat restrictions (Huang et al. 2012, Wear and Murray 2004). Second, record lumber consumption from 2003 to 2005, high levels of housing starts in 2005, and the subsequent crash in housing prices and lumber markets during the global financial crisis of 2007 to 2009 correspond to the timing and directions of removal trends across all regions (Ince and Nepal 2012, Woodall et al. 2012). Third, the timing of the peak removal rate in the South Region occurring around 1997 to 1998 corresponds to regional trends in volume removal for roundwood production (Smith et al. 2009, Wear and Greis 2013). Fourth, all regions show steep increases in removal rates at the beginning of the record. Data from FIA also show a steep increase in the South's annual volume removal rate over the period 1986 to 1997 (Smith et al. 2009), and all regions had an increase in lumber volume supply during that time (Wear and Murray 2004).

We report summaries of removals in terms of area because the remote sensing products we used focus on area estimates. Other sources, including reporting based on FIA, have summarized removals in terms of volume estimates (Smith et al. 2009; see the Forest Resources Chapter for volume-based reporting). It is therefore useful to understand the relationship between volume and area of removals, which depends on three factors: (1) the harvest intensity (i.e., volume per unit area harvested); (2) the natural or managed timber productivity of the land (volume available per unit area); and (3) how variable the harvest intensity is across time and space. While total regional productivity is relatively stable over time, FIA data have shown that harvest intensity varies considerably across and within regions (Masek et al. 2011, Schleeweis et al. 2013). In lower productivity areas, where it takes more forest area to reach a certain volume of removal, a decrease in low-intensity harvesting can have a substantial effect on area-based metrics, even if total volume removed only changes slightly. For example, the Pacific Northwest's highly productive forests report an average extraction intensity roughly twice as high as in the Southeast's forests (200 m³/ha versus 100 m³/ha) (Masek et al. 2011). For every 1 m³ decrease in total annual volume harvested in the South, there is a 0.5 ha decrease in harvested area, whereas the same decrease in volume harvested (1 m³) leads to a 1 ha decrease in harvest area in the Pacific Northwest. While volume metrics remain steady or show only slight trends, area-based summaries of removals may be more variable through time. The disconnect between volume and area-based metrics may be greater especially in locations with lower productivity and/or more variable harvest intensities, such as the South (figure 5-28).

Figure 5-28. Annual areas of forest canopy loss events attributed to removals and percent of total forest that was lost to these removal events, 1986 to 2010, by RPA region. Regional areas are stacked on top of one another, so that the dotted line represents the total area for the conterminous United States. See text for a discussion of removal areas compared with removal volumes.



Source: Schleeweis et al. (2020).

Discussing removals in terms of both area and volume from traditional inventories and remote sensing gives a more robust understanding of the disturbance. Information from remote sensing, like that reported here, can include higher temporal detail than tree volume information from forest inventories, while forest inventory data can include more detail on the size, age, or species of the trees removed and the management objectives of the removal. Recent studies have shown that in some areas, such as the Southern States, intensity and ratio of partial to clear-cut harvest can vary dramatically on an annual time step (Huang et al. 2015, Tao et al. 2019). In the future, combining information from satellite image time series with plot-based data can provide additional information and allow a wider range of removal intensities to be detected and mapped (Tao et al. 2019). Additionally, outcome-based metrics, such as those related to the effectiveness of removals at reducing fuels on forest land with high fire risk but low volume and acreage, could be a good addition to area- and volume-based metrics in national reporting and assessment.

Multiple Forest Disturbances: A Neighborhood Perspective

- Ninety-four percent of places where forest was lost between 2001 and 2010 had at least one identifiable disturbance process occurring nearby, and 15 percent of forest loss locations experienced cumulative pressures from more than one change process.
- During the same time, nearly half of all forest area was exposed to forest removals occurring nearby, with smaller proportions exposed to stress or fire, and even smaller areas exposed to land conversion.
- Most forest type groups in the Eastern United States had higher exposure to removals and lower exposure to stress and fire. In contrast, most forest type groups in the Western United States had higher rates of exposure to stress and fire and relatively lower exposure to removals.

Multiple Disturbances Near Recent Forest Loss

Earlier sections in this chapter focused on individual disturbances occurring in isolation. Many disturbance processes occur in close proximity to one another, and can together put cumulative pressure on forests and their resources (Drummond et al. 2017, Drummond and Loveland 2010). By assessing the extent to which multiple disturbances have occurred in or near forests, we can gain insight into those cumulative pressures.

Regional trends and rates of forest cover change have varied since 2001 across the conterminous United States (see the Land Resources Chapter). From 2001 to 2010, the total gross forest loss was approximately 140,000 km² (14 million ha, 6 percent of the 2001 forest area). To gain insights about which disturbance processes have occurred near forest loss, we summarized the co-occurrence of multiple disturbances nearby. We evaluated disturbances occurring within a 4.41-ha neighborhood of forest cover loss from 2001 to 2010, with forest cover loss defined as pixels that changed from forest to nonforest over this time period in the National Land Cover Database (USGS 2019a, 2019b). Although co-occurrences of common forest disturbance processes are rarely mapped over large spatial extents, there have been recent strides in creating the datasets needed for such analyses in the United States (Huo et al. 2019; Schleeweis et al. 2013, 2020; Vogelmann et al. 2011). These new disturbance attribution data allow novel insights about the likely causes of change (Riitters et al. 2020). The data described in the section Forest Removal Areas use a consistent methodology to map forest

Effects of Air Pollution on Forest Ecosystems

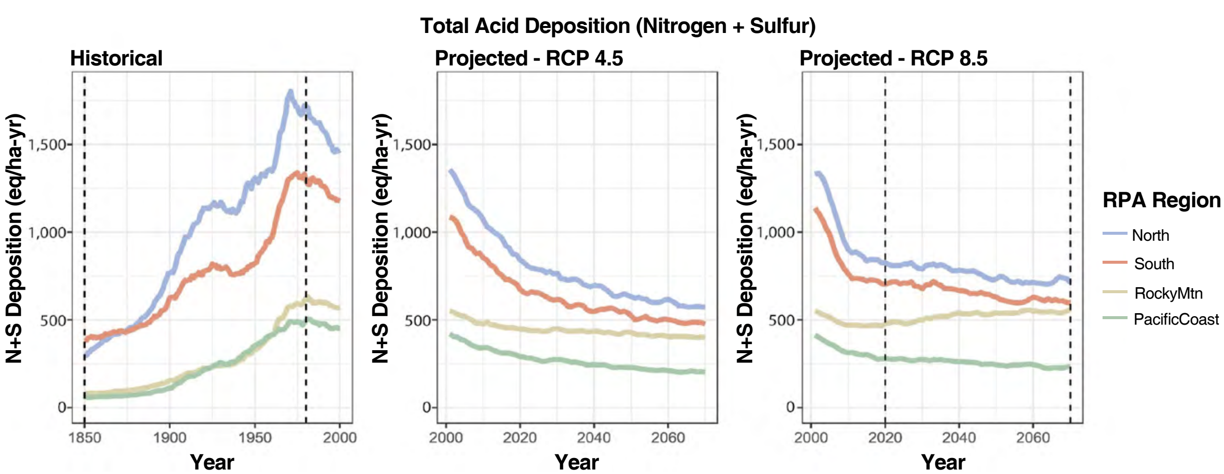
Impaired air quality stresses forest and rangeland ecosystems, leading to altered species composition, modified ecological function, and impacts to ecosystem goods and services (for example, Agathokleous et al. 2020, Pardo et al. 2011, Sams 2007). Air quality trends in the United States are therefore relevant and important to the management of forests and rangelands. Some air quality effects are already incorporated into the RPA water quality assessment (see the Water Resources Chapter) and forest productivity modeling (see the Forest Resources Chapter). Here we provide an overview of specific types of air pollutants, recent and future trends in the deposition of air pollution, and potential effects on forest and rangeland ecosystems and resources.

Emissions from a variety of sources, including agriculture, oil and gas development, fossil fuel combustion, and natural sources such as wildfire, contribute to impaired air quality (US EPA 2020). Deposition of emitted pollutants from the air to the ground leads to effects on forest and rangeland ecosystems that vary by pollutant (Davidson et al. 2012, Fenn et al. 2011). For example, sulfur and nitrogen deposition have been shown to significantly impact forest resources through the acidification of soils and surface waters, leading to decreased growth of certain tree species, reduced species richness, and diminished nutrient availability (Fenn et al. 2011, Pardo et al. 2011).

Critical loads are deposition levels above which components of forests or rangeland ecosystems experience harmful ecological effects; deposition levels greater than the critical load result in a critical load exceedance for a given ecosystem component (Porter et al. 2005). We can identify where ecosystems are likely impacted by air pollution by comparing maps of past or future deposition with maps of critical load thresholds.

Historical and recent trends in exceedances of surface water critical loads can serve as a case study to highlight the effect of air pollution on renewable resources. Surface waters in the United States, especially in the Northeast and along the Appalachian Mountains, have been impacted by deposition of sulfur and nitrogen in the form of "acid rain," predominantly from industrial and fossil fuel sources (Aber et al. 1989, Driscoll et al. 2001, Greaver et al. 2012). As emissions and acid rain increased throughout the 20th century (Galloway et al. 2004) (figures 5-29, 5-30a, 5-30b), surface water critical loads were exceeded at many locations in the RPA North and South Regions (figure 5-30b). Resulting acidification degraded soils, which affected water chemistry and reduced the presence of aquatic organisms, from macroinvertebrates to game species of fish. These effects on habitats and wildlife ultimately impacted ecosystem services such as drinking water and recreation (Beier et al. 2017)

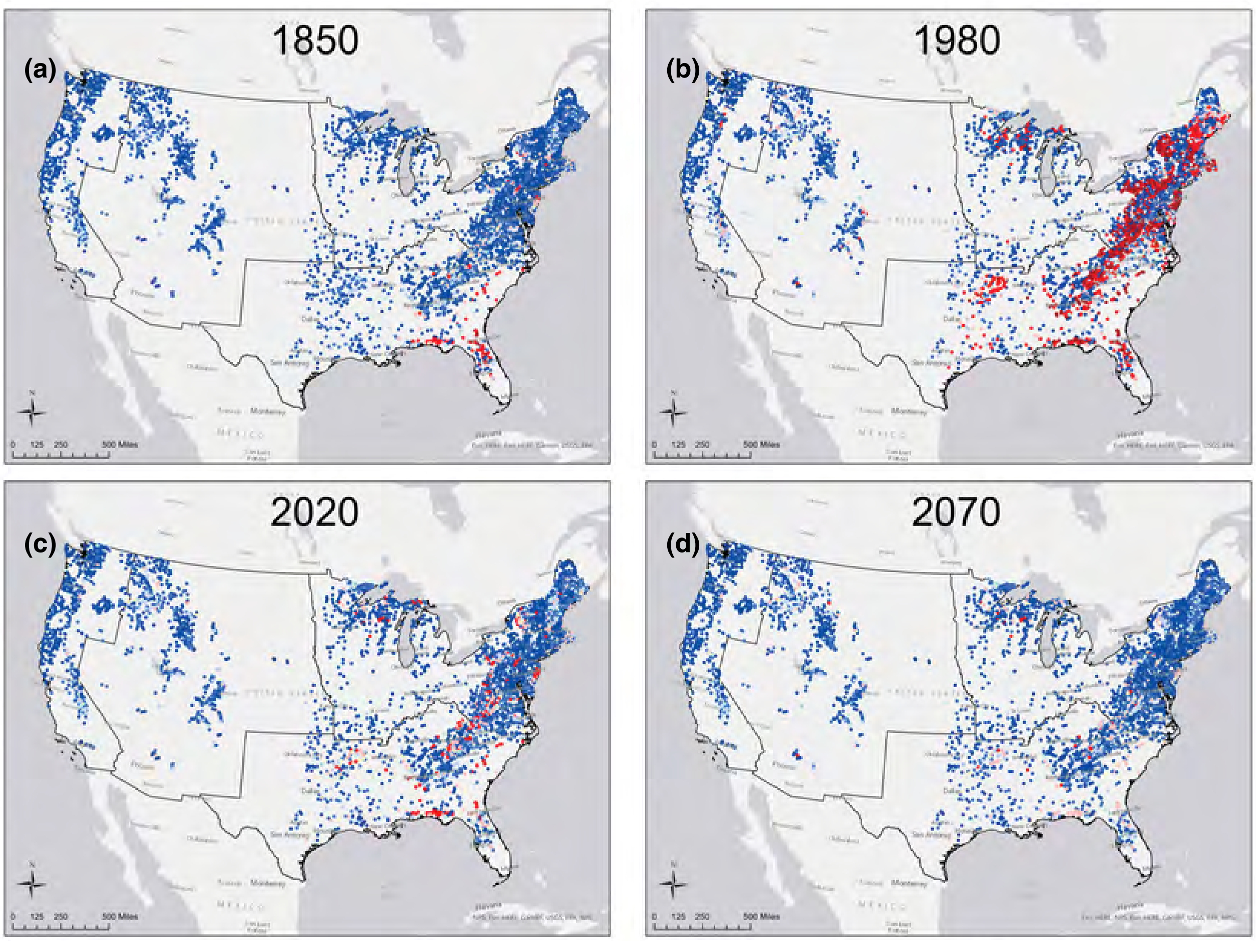
Figure 5-29. Historical (1850 to 2000) and projected (2000 to 2070) average annual acid deposition for each RPA region. Projections are shown for RCPs 4.5 and 8.5. Acid deposition is the total deposition of sulfur and nitrogen compounds. Dashed lines represent time points where deposition values are used to map critical load exceedances in figure 5-30.



ha = hectares; N= nitrogen; RCP = Representative Concentration Pathway; S = sulfur.

Sources: Lamarque et al. 2010 (historical) and Lamarque et al. 2011 (projection), accessed through the Environmental Protection Agency's Critical Loads Mapper webtool (https://clmapper.epa.gov/).

Figure 5-30. Maps of critical load exceedances for surface water acidification for four periods from 1850 to 2070: (a) 1850, before intense industrialization and accompanying increases in emissions and acid deposition; (b) 1980 at peak of emissions and acid deposition in most areas of the U.S.; (c) 2020; and (d) 2070. Negative critical load exceedance values (shades of blue) indicate that acid deposition levels are below the critical load, while positive critical load exceedance values (shades of red) mean that acid deposition is above the critical load and indicate that that area is likely experiencing ecological impacts. For 2020 and 2070, maps are depicting deposition levels from projections based on RCP 8.5.



Total N+S (eq)

- <-1,000
- -1,000 to -350
- -350 to -70
- -70 to 0
- 0 to 70
- 70 to 350
- 350 to 1,000
- >1,000

N = nitrogen; RCP = Representative Concentration Pathway; S = sulfur.

Sources: Lamarque et al. 2010 (historical) and Lamarque et al. 2011 (projection), accessed through the Environmental Protection Agency's Critical Loads Mapper webtool (https://clmapper.epa.gov/).

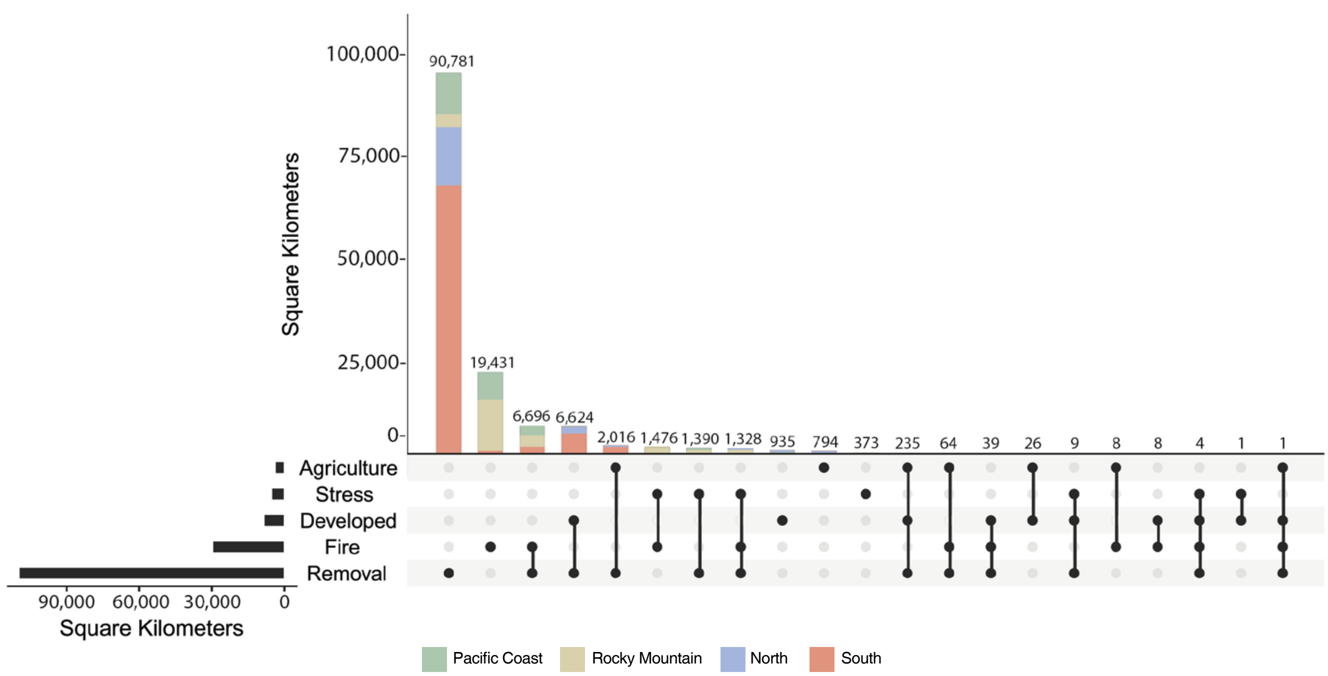
Congress passed the Clean Air Act Amendments of 1990 to reduce the impacts of acid rain by targeting sulfur and, to a lesser degree, nitrogen emissions (Greaver et al. 2012). Subsequent emissions reductions have decreased acid deposition substantially in all regions, from a nearly 25-percent reduction in the Rocky Mountain Region to an over 50-percent reduction in the North Region (figure 5-29). In numerous places, these reductions have eliminated critical load exceedances and allowed ecosystems to recover, some to the point of allowing the reintroduction of previously extirpated fish species (Sullivan et al. 2018, Sutherland et al. 2015) (figure 5-30c). In some locations, however, the severity of acid deposition and/or the sensitivity of the ecosystem created long-lasting effects that could continue to impact ecosystems into the future (Burns et al. 2020, Sullivan et al. 2018).

Future projections of acid deposition and its impacts have been made for both selected RPA climate futures: RCPs 4.5 and 8.5 (Clark et al. 2018a, Lamarque et al. 2010, 2011). Acid deposition is projected to continue to decrease under RCP 4.5 and, to a lesser extent, RCP 8.5, except for the Rocky Mountain Region under RCP 8.5 (figure 5-29). Projected increases in the Rocky Mountain Region are primarily driven by nitrogen deposition, which is more complicated than sulfur deposition with a broader suite of chemical compounds, sources, and effects (Galloway et al. 2004, Gruber and Galloway 2008). Although the Clean Air Act Amendments of 1990 decreased emissions of nitrogen compounds that contribute to acidification, emissions of other nitrogen compounds have continued to increase, complicating ecosystem recovery (Butler et al. 2001, Davidson et al. 2012, Sullivan et al. 2018). Projected decreases in acid deposition are expected to continue to decrease critical load exceedances and further reduce impacts to surface waters (figure 5-30d); however, the changing chemical composition of deposition means some ecosystems may experience additional impacts and a disrupted recovery. Research on air pollution impacts and the development of critical loads have enabled mapping impacts to ecosystem goods and services and developing projections of future impacts.

canopy cover loss attributed not only to removal, but also to fire and "stress" (drought, insects, diseases) (Schleeweis et al. 2020). Our analysis also included two types of disturbance from land-use change: increased agriculture and development from the National Land Cover Database (Homer et al. 2020; USGS 2019a, 2019b). Our estimates of the area with combined pressures in a 4.41-ha neighborhood are different from the disturbance areas reported elsewhere in this document. Here, we consider a disturbance process to have affected a particular forested location if that process was observed at that location or on forest nearby. We summarize disturbance occurrence only for areas where forest loss was observed, not for all forest land.

Ninety-four percent of pixels where forest cover was lost had at least one disturbance identified nearby, while two or more disturbance processes were identified near 15 percent of all forest loss locations. Removal was the most common disturbance process, occurring near a total of 109,187 km^2 (10.9 million ha) of forest cover loss (black horizontal bar in figure 5-31). Fire was next most common, occurring near 29,060 km^2 (2.9 million ha) of forest cover loss.

Figure 5-31. Summary of forest disturbance processes for locations with forest cover loss, 2001 to 2010. The figure depicts the occurrence of each process alone or in combination with one or more others. The horizontal black bars indicate the total area of forest cover loss that had each process in its local neighborhood, whether alone or in combination with another process. The vertical bars indicate the area of forest cover loss that had a unique combination of processes. The combinations captured in each vertical bar are depicted by black dots beneath the vertical bar, with a connecting line if two or more are included in the set.



Stress, conversion to developed land use, and conversion to agricultural land use were less common (<10,000 km^2 or <1 million ha each).

Removal occurred alone in 83 percent (90,781 km^2 or 9.1 million ha) of the places where it occurred (figure 5-31). Sixty-six percent (72,417 km^2 or 7.2 million ha) of the removal that occurred near forest cover loss occurred in the RPA South Region. Where removal co-occurred with other processes, it was found most often with either fire or increases in developed land use.

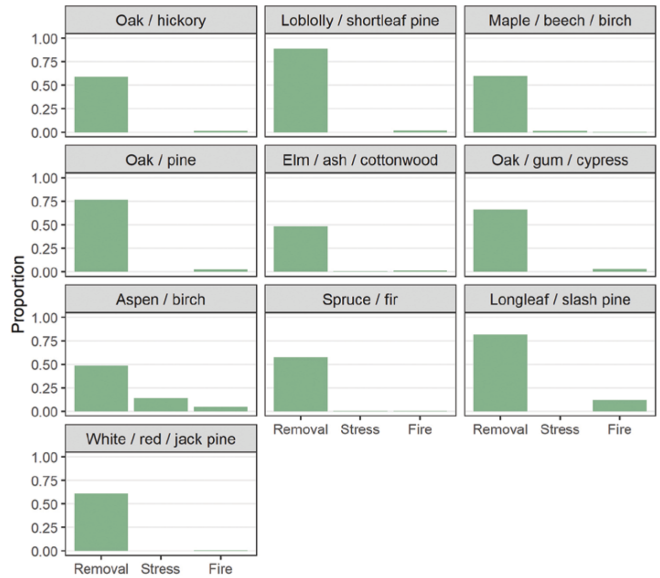
After removal alone, the next most common process near forest cover loss was fire alone, which occurred twice as often alone as with other processes (19,431 km^2 or 1.9 million ha versus 9,629 km^2 or 1.0 million ha). Sixty-two percent (11,988 km^2 or 1.2 million ha) of the places where fire events occurred alone near forest cover loss were in the RPA Rocky Mountain Region, with an additional one-third (6,510 km^2 or 651,000 ha) occurring in the Pacific Coast Region. When fire was observed with another process, it was found most often with removal.

Stress was observed near forest cover loss much less frequently than removal or fire, and co-occurred with removal, fire, or both processes 11 times more often than it occurred alone. The co-occurrence of stress with fire and removals reinforces other research that has found coincidence between insect outbreaks, drought, fire, and removal (Hood et al. 2017, Rhoades et al. 2018).

Like stress, increases in developed and agricultural land uses also occurred near other processes more frequently than by themselves. Conversion toward both of these land uses co-occurred most frequently with removal. While this analysis summarizes events occurring nearby one another during a 10-year period and not in sequence with one another at the same forested location, the co-occurrence of the two suggests that those removal events may be related to land use conversion. An increase in developed land use (alone or combined) was 2.5 times more common than increased agriculture (alone or combined) near places where forest was lost, suggesting that forest cover was more often lost for development than for agriculture.

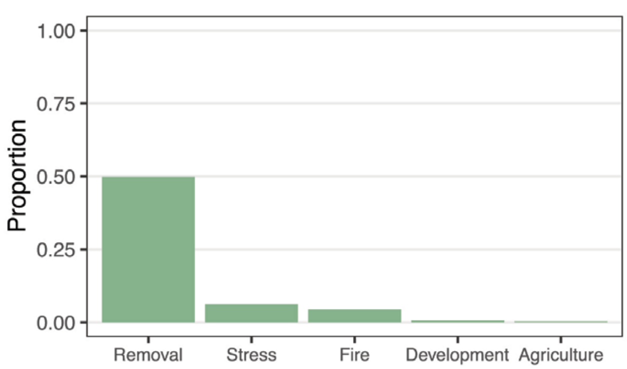
The differences in the frequencies of these processes by region have important implications for forest loss and change. In the RPA South Region, removal alone was by far the most common process observed near forest cover loss, demonstrating forest management. While co-occurrence of removal and increased development was rare nationally, it occurred most often in the South Region, reflecting the fact that housing development is a comparatively frequent phenomenon in the region's forests (Radeloff et al. 2018). Similarly, removal alone and the co-occurrence of removal with increased development were the top two types of processes occurring near forest loss in the North Region. These results suggest that forests in the North and South Regions face similar pressures. However, the areas of forest

Figure 5-33. Proportion of FIA forest land in each FIA forest type group in the Eastern United States that was exposed to removal, stress, and fire events, 2001 to 2010. Exposure is defined as an observed loss of forest canopy within a 4.41-ha neighborhood surrounding FIA plot locations. Forest type groups are arranged by decreasing area from top left to bottom right (see figure 5-8 for areas). Some of the aspen/birch group occurs in the Western United States.



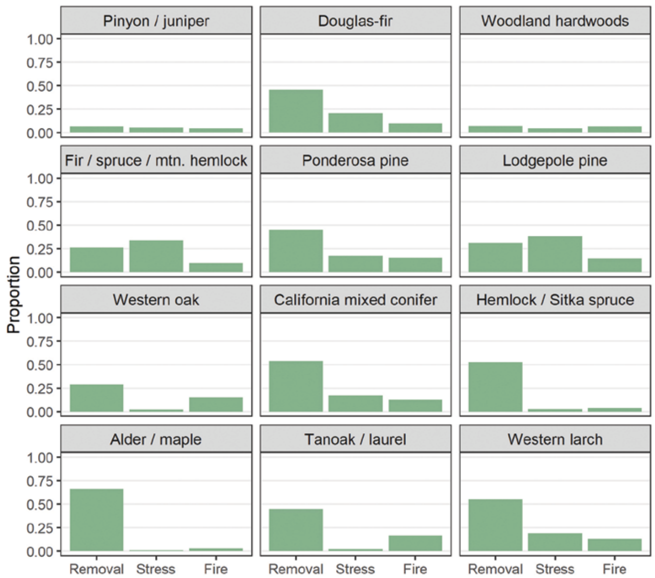
FIA = Forest Inventory and Analysis; ha = hectares.
Source: Schleeweis et al. 2020.

Figure 5-32. Proportion of FIA forest land exposed to removal, stress, fire, increase in developed land, or increase in agriculture observed within a 4.41-ha neighborhood from 2001 to 2010.



FIA = Forest Inventory and Analysis.
Sources: Removals, fire, and stress came from canopy disturbance attribution data for 2001 to 2010 and represent the proportion exposed to at least one event over that period (Schleeweis et al. 2020), while increase in agriculture and/or developed land uses came from NLCD data for 2001 to 2011 and represent the proportion exposed to at least one event over that period (Homer et al. 2020; U.S. Geological Survey 2019a, 2019b).

Figure 5-34. Proportion of FIA forest land in each FIA forest type group in the Western United States that was exposed to removal, stress, and fire events, 2001 to 2010. Exposure is defined as an observed loss of forest canopy within a 4.41-ha neighborhood surrounding FIA plot locations. Forest type groups are arranged by decreasing area from top left to bottom right (see figure 5-8 for areas).



FIA = Forest Inventory and Analysis; ha = hectares.

cover loss associated with these events were smaller in the North than in the South Region (figure 5-31), suggesting that forests in the South face these pressures more often. In the Pacific Coast Region, removal alone was the top process occurring near forest loss, but fire alone was a close second, followed by fire and removal together. The Rocky Mountain Region was the only region where the most common process was fire alone, rather than removal alone. This region has less merchantable timberland than other regions (Oswalt et al. 2019), a higher proportion of forest that is public or protected (Nelson et al. 2020), and more area burned during the period of observation (see the section Fire in Forests and Rangelands). The Rocky Mountain Region also contained the most observations of stress, alone and in combination with other processes, which reflects the high rates of insect and disease activity as well as drought in that region.

Exposure of All Forest Lands to Disturbance Processes

To gain insights about the degree to which all current forest land in the conterminous United States was exposed to disturbances occurring nearby, we applied a similar approach to existing FIA forest land (as opposed to forest loss areas). We summarized the proportion of FIA forest land area with each of the five forest canopy cover disturbance processes occurring within a 4.41-ha neighborhood from 2001 to 2010. This summary, reported by forest type group, is supplemented by a parallel analysis of "core" forest cover loss in the Land Resources Chapter. Exposure of forest land to removal during the period 2001 to 2010 was substantially higher than any other process: nearly half (49 percent) of forest land was exposed to at least one removal event from 2001 to 2010 (figure 5-32). By contrast, only 6.2 percent and 5.2 percent of forest land, respectively, was exposed to stress and fire. Even smaller portions of forest land were exposed to increases in developed and agricultural land uses (0.7 percent and 0.4 percent of forest land, respectively) (figure 5-32). This result highlights the common occurrence of removal events in forest land across the country (Cohen et al. 2016), whether for silvicultural or other purposes, and confirms the highly dynamic nature of forest cover documented in earlier RPA reports (Nelson et al. 2020). While locally important, increases in agriculture and developed land are relatively rare near FIA forest land overall (figure 5-32), and therefore excluded from further analyses.

The forest canopy disturbances described above occur in some forest types more often than others. Like the results for all forest land, many individual FIA forest type groups (figure 5-8) had a higher exposure to removal events than to any other process (figures 5-33, 5-34). Specifically, the forest type groups that are relatively widespread in the Eastern United States were among those with a high proportion exposed to removal and little or no exposure to fire and stress events (figure 5-33). Examples include the oak/hickory, loblolly/shortleaf pine, and maple/beech/birch groups, as well as the white/red/jack pine group, which has a smaller range (figures 5-8, 5-33). This result further underscores the relatively large areal footprint of removal in the Eastern United States. Eighty-nine percent of the commercially important loblolly/shortleaf group was exposed to removal nearby over the 10-year period. Relatively high exposure to removal is not unexpected in this group, and removal for timber harvest is usually quickly followed by replanting and intensive management (Drummond et al. 2017). While fire may occur relatively frequently in some of those eastern forest types, it generally is of low enough severity not to disturb the forest canopy and therefore largely does not appear in the eastern type groups. The longleaf/slash pine group is a notable exception, having 12 percent of total area exposed to fire over the 10-year period, likely because frequent fire is important for maintaining ecosystem function and biodiversity (Peet et al. 2018). The aspen/birch type group was the only eastern group with notable exposure to stress (14 percent), but some of that type group also occurs in the Western United States.

Forest type groups occurring primarily in the Western United States tended to have greater exposure to fire and stress events than those occurring primarily in the Eastern United States (figure 5-34). This result is consistent with the high rates of large, high-severity wildfires, drought, and insect disturbances shown for the western regions in the earlier sections of this chapter. The Douglas-fir, ponderosa pine, and California mixed conifer type groups had higher exposure to stress and fire than any of the eastern type groups, while still having relatively high exposure to removal, underscoring the multiple pressures those forests face. The fir/spruce/mountain hemlock and lodgepole pine type groups were also exposed to all three forest canopy threats, with exposure to stress being highest for both groups during the 10-year period. The hemlock/Sitka spruce and alder/maple groups had relatively low exposure to both stress and fire, as expected given the distributions of those forest type groups in relatively moist sites. The pinyon/juniper and woodland hardwoods type groups had low exposure to all three canopy disturbance types; however, we know that these forests are subject to disturbance events including drought, as shown in the section Drought in Forests and Rangelands. Given that the forest canopy is often relatively sparse in these forest types, disturbance events may not always lead to measurable loss of the forest canopy, meaning that those disturbance events are likely not well captured in this exposure analysis for these forest type groups.

While this analysis focused on exposure of forests and forest type groups to disturbance, the results can be used in conjunction with information on the sensitivities of these forests to the disturbance processes to determine the ecological or economic impacts of these disturbances. One example of demonstrated high sensitivity to multiple disturbance processes occurs in dry portions of Douglas-fir and ponderosa pine forests of the Western United States, where high-severity wildfires combined with warm and dry climate can cause tree regeneration failure and subsequent conversion to nonforest (Coop et al. 2020, Davis et al. 2019, 2020). Forest type groups represent assemblages of tree species, each with its own disturbance sensitivities to consider. As a result, shifts in forest species composition may be likely because of differential responses of tree species to these disturbance processes. Summaries of these disturbance processes at a finer level of forest classification, such as by species, or within more restricted areas, would likely allow for more insight about how these disturbances affect forests. In addition, summaries of exposure of FIA forest land to additional disturbances not included here, such as hurricanes and other storms and sea level rise (see the sidebar Sea Level Rise Effects on Forests for a synthesis of forest impacts) would provide a more holistic picture of the disturbances and stressors facing our forests.

Management Implications

Disturbance is relevant to both management and policy, especially as climate changes, human populations increase, and developed land use expands. Management actions, policies, and initiatives can help restore natural disturbance regimes, where appropriate, and increase the capacity of forests and rangelands to adapt to changing regimes or recover following disturbance. In those ways, management can reduce the vulnerability of forests and rangelands to disturbances themselves and help increase the resilience of those ecosystems to climate change and other global change drivers. As in the case of removals, however, management actions can themselves be considered disturbances. While some management implications of single disturbance types in forests or rangelands have been mentioned throughout this chapter, a few cross-cutting ideas apply.

In some places, management of forests and rangelands to mitigate multiple disturbances may be desirable. Our analysis shows that forests in the RPA Pacific Coast Region may be particularly exposed to multiple co-occurring disturbances. Dry forests of California have experienced recent tree mortality due to interactions of drought, wildfires, and bark beetles (Fettig et al. 2019). Forest thinning and prescribed fire together have reduced the effects of those interacting disturbances (Knapp et al. 2021). Similarly, fuel treatments like thinning in forests of the Pacific Northwest may help increase resilience to fire, insects, and drought, and facilitate post-disturbance recovery (Halofsky et al. 2020).

As the characteristics of disturbances and disturbance regimes change—becoming more severe, more frequent, longer in duration, or spreading to previously unaffected ecosystems—they could challenge the effectiveness of existing management techniques and paradigms, and may force changes or adjustments. For example, management actions that include accepting a range of fire severities when and where they are safe, reducing wildfire occurrence in the wildland urban interface (WUI), and improved planning of residential communities to avoid or withstand wildfires may be appropriate in the Western United States, where climate and land-use change are increasing both the total area burned by wildfires and the area burned in the WUI (Calkin et al. 2014, Kelly et al. 2020, Radeloff et al. 2018, Schoennagel et al. 2017). In rangelands, managers are searching for novel approaches to curb the spread of nonnative annual plants, especially cheatgrass (*Bromus tectorum*) and red brome (*Bromus rubens*), to break the annual grass-fire cycle. Incorporating more flexible grazing strategies, specifically targeted grazing that aims to reduce the cover of these species, shows promise, and the USDA Forest Service and U.S. Bureau of Land Management are increasingly looking for ways promote and expand targeted grazing. Doing so faces several challenges, including increased flexibility in grazing allotment administration. New technologies such as the Rangeland Production Monitoring System (Reeves et al. 2020, 2021) are part of a strategic support system that may help managers detect nonnative grasses and identify targeted grazing opportunities.

In addition to changing disturbance regimes, the ability for professionals to conduct management to mitigate larger or more severe disturbances and increase ecosystem resilience may also be affected by global change drivers. As the area and severity of wildfires increases and the WUI expands in the Western United States, wildfire management is becoming more challenging. Prescribed burning is already becoming more difficult in some places, at least in part due to climate and land use change, and increased challenges are projected in the future. Reductions in the number of days with suitable meteorological conditions for prescribed burning are projected in the future in the South Region (Kupfer et al. 2020), suggesting that decreases in the area burned are likely, especially as the expanding WUI places additional challenges on burning (see the sidebar COVID-19 as a Constraint on Prescribed Burning in the Southeastern United States for more information on recent challenges). Such reductions in wildfire management, prescribed burning, or any other management, can result in forests and rangelands that are less resilient through time, having concomitant effects on the resulting resources and services.

Partnerships and collaborations among scientists, managers, and public and private landowners can help address the increasing need for management, growing challenges associated with management, and uncertainties in future conditions (Glick et al. 2021). Adaptive silviculture for climate change is an effort among scientists and managers to identify the management actions that are likely to increase the adaptive capacity of forests to the effects of changing climate, including disturbance (Nagel et al. 2017). Several recent initiatives involving the USDA Forest Service have aimed to create partnerships among agencies to identify treatments and other management actions to meet multiple objectives, including reducing risk of wildfire and other disturbances (USDA Forest Service 2018). These initiatives include the Collaborative Forest Landscape Restoration Program, the Wildfire Crisis Strategy, and the Shared Stewardship Strategy. In rangelands, the ecological and economic threat that invasive grasses pose to local communities has inspired an unprecedented level of cooperation among land managers, nonprofits, government agencies, and the business community. One example of a cooperative model is the Southern Arizona Buffelgrass Coordination Center, which uses cross-jurisdiction coordination and community engagement to help control buffelgrass (*Pennisetum ciliare*), an invasive perennial threatening several rangeland ecosystems. Fostering more cooperation and coordination throughout U.S. rangelands may be beneficial in the future, as increased frequency and duration of drought combine with invasive species to exacerbate changes in fire regimes in many places. Partnerships, especially when conducted at large scales or when replicated in different regions, could benefit future management of a wide variety of disturbances in forests and rangelands.

Conclusions

Disturbance is a constant presence in many forest and rangeland ecosystems. For the first time in an RPA Assessment, the analysis in this chapter provides a comprehensive look at the recent, and in a few cases, future disturbances in both forests and rangelands across the United States. Our results highlight that many of these disturbances are becoming more frequent, widespread, or severe over time, and that regional variability exists in the type, amount, and intensity of disturbances that occur in forests and rangelands.

In terms of recent historical trends, the average annual area burned by fire in both forests and rangelands has increased nationwide and in all RPA regions except the North Region. Drought exposure has been high in forests and rangelands in the West, particularly the Pacific Coast Region. Nonnative invasive plants have been most prevalent in forests near agricultural and developed areas in the East, and in rangelands within counties in California. In addition to the direct exposure of forests to disturbances, many forests exist in dynamic landscapes that experience multiple disturbance pressures, including combinations of removals, stress, and fire, as well as conversion of land use to agriculture or development.

Looking ahead to 2070, the disturbance types discussed in this chapter have the potential to become more frequent, widespread, or severe in many locations (with the notable exception of acid deposition in forests, see the sidebar Effects of Air Quality on Forest Ecosystems). Forest mortality from fire is expected nationwide and within each RPA region. Increases in the area of moderate- and high-severity fire are also projected in many locations, especially in the RPA Pacific Coast and South Regions. Forest and rangeland exposure to drought is projected to increase as well, particularly for ecosystems in the Southwest. While not explicitly projected, literature summarized in this chapter suggests potential for increasing threats from insects and disease and nonnative invasive plants.

The Nation's forests and rangelands face pressures from these disturbances against a backdrop of changing climate, socioeconomic conditions, and land use. These disturbances, alone and in concert, are affecting forests and rangelands and the goods and services they provide. For example, fire and drought together are already transforming some dry forests to grasslands in the Western United States, and the co-occurrence of drought with extreme heat preceded forest mortality and reduced rangeland production in

Texas. The magnitude of disturbance impact on ecosystems, however, can vary with a number of factors, including species composition and landscape characteristics. Not all fires are threats to forests or rangelands, and not all forests or rangelands have the same vulnerability to drought. These additional factors are relevant to comprehensive assessment of effects on forests and rangelands. The impacts from disturbance can also be affected by management, as increasing evidence is pointing to the importance of actions like prescribed fire and thinning for improving the resilience of forests to disturbance and other global change drivers.

Disturbances are integral parts of forest and rangeland ecosystems that affect the goods and services those ecosystems provide. Disturbances are likely to continue to increase in many locations, especially as climate changes, human population increases, and developed land use expands. Information about status and trends in these disturbances over time informs forest and rangeland management that can better facilitate adaptation of the Nation's forests and rangelands to global change.

Sea Level Rise Effects on Forests

Past and Future Sea Level Rise

Thermal expansion of ocean waters and glacial and ice sheet melting, both consequences of global warming, have contributed to sea level rise (SLR) over the past 200 years. Studies indicate that the pace of global mean SLR has accelerated in the recent past, from about 0.05 inches per year during 1901 to 1990 to 0.12 to 0.14 inches per year during the period 1993 to 2010 (Dangendorf et al. 2017, Hay et al. 2015). While the rate of future SLR depends on global temperature change, current projections are for global mean sea level to rise by 0.4 to 2.5 m by 2100 (Oppenheimer et al. 2019).

Coastal forest retreats, replacement of coastal forests by saltmarsh, and the appearance of ghost forests (dead trees adjacent to marshes) due to SLR have already been observed on low-lying coastal and estuarine landscapes (Kirwan and Gedan 2019). Future SLR could lead to permanent inundation, increased frequency and intensity of flooding from storm surges, increased coastal erosion, and expanded saltwater intrusion into the soil, groundwater, and freshwater systems. This, in turn, will result in loss, alteration, and degradation of coastal ecosystems and natural resources, including forests and wetlands (Kirwan and Gedan 2019, Schuerch et al. 2018), which can have indirect effects on the forest sector, including altered supply and demand conditions in markets for ecosystem services and forest goods.

Direct Effects of SLR on Coastal Forests

Direct effects of SLR on forests include: (1) loss of coastal forests due to flooding and extreme sea level events such as storm surges and tidal waves, and (2) altered structure, composition, growth, regeneration, and productivity of coastal forests due to saltwater intrusion, impeded drainage, and flooding. The availability of current and future space for coastal forest retreat is a critical factor determining future gain or loss of such ecosystems and is affected by many factors, such as the economic factors driving coastal land use changes (Kirwan and Gedan 2019, Schuerch et al. 2018).

Two types of coastal forests can be distinguished for the purpose of describing SLR effects: estuarine coastal forests that are adapted to saltwater (e.g., mangrove, beach, and peat swamp forests), and freshwater coastal forests that cannot tolerate salt. The effects on and likelihood of losing coastal forest differs between these two types of forest.

The effects of SLR on coastal forests that are adapted to saltwater are projected to be minimal at the current and projected mid-century SLR, although several studies suggest that mangrove forests are threatened in many parts of the world and are not keeping pace with local SLR rates (Friess et al. 2019). For example, in the tropics under the high-warming scenario (RCP 8.5), relative SLR is expected to exceed the tolerance of mangroves because rates of SLR in the tropics are expected to be higher than the global average (Saintilan et al. 2020). The likelihood of losing coastal forests to SLR depends on many factors, such as the local rates of SLR and the rate of sediment accretion for these ecosystems.

Limited research is available on the effects of SLR on freshwater coastal forests, and most of our understanding is based on research conducted in the United States. Increasing saline and frequent flooding are thought to cause declines in forest health and productivity, basal area and tree density, species diversity, seed germination and regeneration, and increased tree mortality (Grieger et al. 2020). Ghost forests are also reported primarily along the Atlantic coast of North America, where SLR is currently occurring at a rate greater than the global average (Kirwan and Gedan 2019, Smart et al. 2020). The likelihood of losing these coastal forests to SLR will depend on local rates of SLR, rate of saltwater intrusion into the groundwater, species composition, and tolerance to saltwater especially for regeneration.

Indirect Effects of SLR on the Forest Sector

The indirect effects of SLR on the forest sector include dynamics that are tied to changes in supply and demand for forest goods and ecosystem services. SLR-induced losses in forest area are likely to affect forest product markets by reducing the overall availability of timber, leading to a combination of reduced timber product output and higher timber prices. At the same time, about 350 to 480 million people globally are projected to be exposed to SLR by 2100 (Kulp and Strauss 2019), requiring replacement of their present dwelling. As a result, demand for wood products for new housing is likely to increase (Desmet et al. 2018, Hauer et al. 2020, Nepal et al. 2022).

Increased demands for wood to rebuild could affect not only coastal regions but also noncoastal timber-growing regions through altered harvesting activity, changing local market conditions, and altered international flows of traded forest products (Nepal et al. 2022). Higher product demands by the construction sector can lead to increased forest product prices, which can affect the competitive advantage of a country or a region to harvest timber and to produce, consume, and trade in forest products. Price increases also provide an economic incentive to keep forests as forests or to invest in intensified forest management activities such as thinning or fertilization (e.g., Daigneault and Favero 2021, Nepal et al. 2019). Changes in timber harvests, forest management, and wood products manufacturing activities, indirectly induced by SLR through increased prices, may have additional consequences for net carbon emissions mitigation by the forest sector. Mitigation potential would be affected through changes in the total quantities of carbon stored in forests and in harvested wood products. Likewise, mitigation potential would also be affected by avoided fossil carbon emissions resulting from substitution of wood for more carbon-emissions-intensive nonwood materials in construction, such as steel or concrete (Leskinen et al. 2018, Nepal et al. 2016, Nepal et al. 2022, Sathre and O'Connor 2010). As shown by Nepal et al. (2022), increased global harvests to accommodate higher wood product demand for rebuilding SLR-destroyed residential structures would shrink global forest carbon by up to 2.0 percent. However, policies favoring rebuilding destroyed residential structures with wood construction materials worldwide could reduce global CO_2 equivalent emissions by 0.47 to 2.13 tons per ton of CO_2 equivalent carbon contained in those additional wood construction materials. This emissions reduction was connected most directly to the replacement of fossil fuel-intensive building products with wood.

Assessing the Future Effects of Sea Level Rise on Coastal Forests: Critical Needs

Coastal forests provide a wide variety of ecosystem services globally, including provisioning (fisheries, fuel, water supply, tourism, and cultural resources), regulating (coastal protection, carbon sequestration, sustaining biodiversity) and supporting (soil, sediment and sand formation, nutrient cycling, habitat). In addition to altering existing coastal forests, future SLR could disrupt local economies and even result in humanitarian crises around the world. Advancing science on the effects of SLR on coastal forests is critical for assessing the effects and designing adaptation strategies.

Improved understanding and representation of coastal processes and feedbacks in global forest sector models would provide better information on sea level rise from local to global extents, and on its interactions with projected loss or gain of coastal ecosystems (Ward et al. 2020). On the local level, better understanding of how SLR affects groundwater salinity and the gradual losses of coastal forests is needed. Scientific evidence on the linkages between SLR-related coastal forest health and other forest disturbances (e.g., cyclones, insects and diseases, invasive species, and wildfires) is limited yet critical for assessing the full set of potential impacts of SLR. Establishing the effects of sea level rise on habitat for aquatic and terrestrial wildlife is also a critical need.

Coastal forest conservation efforts could benefit from additional research on the potential feasibility and outcomes of alternative coastal forest conservation strategies, including protection and expansion of open spaces to enable coastal ecosystem migration, engineering approaches that might include the creation of physical structures, and assisted migration of coastal ecosystem species. Research could additionally explore how such strategies could be implemented through possible incentives. Furthermore, because the effects of SLR are not restricted to coastal areas, scientific analysis could focus on how the losses of residential and other structures could affect forest land in locations away from coasts.

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Chapter 6

Forest Resources

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Since the 2010 Resources Planning Act (RPA) Assessment, the forests of the United States have been affected by changes in disturbance rates, forest management (including forest harvesting and planting), forest ownership, and land use. At the same time, forests have continued to mature and provide a suite of ecosystem services. This chapter summarizes recent and projected trends in the forest resources of the conterminous United States. In the first section, we present historical forest trends with respect to area, volume, and removals based on U.S. Department of Agriculture, Forest Service Forest Inventory and Analysis (FIA) data. The second section covers historical trends in forest ownership based on FIA's National Woodland Owner Survey. The third section focuses on projections of forest area, volume, and removals, and examining how socioeconomic and climate drivers influence projected trends. The fourth section examines historical and future trends in forest carbon.

Key Findings

- Important forest types are expected to lose area due to forest loss, conversion to planted pine following harvest, climate, and succession. These forest types include aspen/birch in the North, oak/gum/cypress in the South, ponderosa pine in the Rocky Mountains, and hemlock/Sitka spruce in the Pacific Coast Region.
- Timberland growing stock volume is projected to increase through 2050. Post-2050, growing stock volume trajectories depend on roundwood demand and land use choices.
- Aboveground biomass carbon density (carbon per unit area) is projected to increase by 17 to 25 percent over 2020 densities by 2070, while annual carbon stock change is projected to decrease, indicating increasing carbon saturation of U.S. forests. The forest ecosystem is projected to become a net source of CO_2 by 2070 under futures that include high roundwood demand and net forest loss.
- Projections suggest that harvested wood carbon annual stock change rates in 2070 will be greater than net forest ecosystem annual stock change rates under moderate and high growth future scenarios.
- Although forest area increased 3.6 percent between 1977 and 2017, forest area is projected to decrease between 2020 and 2070, with net losses primarily driven by conversion to developed uses.
- There are an estimated 9.6 million family forest ownerships across the United States, and they control more forest land than any other ownership category (39 percent excluding interior Alaska).

Historical Trends in U.S. Forests

- ❖ Forest and timberland area increased 3.6 percent from 1977 to 2017 but showed signs of decreasing from 2012 to 2017.
- ❖ Despite increases in forest area from 1977 to 2017, several forest types have decreased in extent, including lodgepole pine and ponderosa pine types in the Western States and aspen/birch, longleaf/slash pine, and oak/pine types in the Eastern States.
- ❖ Growing stock volume on timberland increased 39 percent between 1977 and 2017. The largest increases occurred in the RPA North and South Regions.
- ❖ Based on 2016 estimates, average harvest removals from timberland for products have not recovered to pre-recession levels.

Forest Land and Timberland Area

In 2017, the total forest area in the United States was 765 million acres, where 514 million acres was classified as timberland (Oswalt et al. 2019). Across the conterminous United States, forest area was 635.3 million acres, an increase from 612.4 million acres in 1977 (3.6 percent). Forest area has remained relatively stable over time, peaking at 635.9 million acres in 2012. Most forest land is timberland (see the sidebar Definitions; 500.7 million acres in 2017, or 78.8 percent of all forest land), and the share of forest land that is timberland has increased over time. The area of

Definitions

Aboveground biomass: Intergovernmental Panel on Climate Change (IPCC) carbon pool that tracks all living biomass above the soil including stem, stump, branches, bark, seeds, and foliage. This pool includes live understory.

Belowground biomass: IPCC carbon pool that tracks all living biomass of coarse living roots with diameters greater than 0.08 inches (2 mm).

Dead wood: IPCC carbon pool that tracks all nonliving woody biomass either standing, lying on the ground (not including litter), or in the soil.

Forest converted to other land: IPCC land use category that accounts for land that was converted from a forest land use at time 1 to a nonforest use by time 2.

Forest land: Land at least 120 feet (37 meters) wide and at least 1 acre (0.4 hectare) in size with at least 10 percent cover (or equivalent stocking) by live trees, including land that formerly had such tree cover and that will be naturally or artificially regenerated. Trees are woody plants having a more or less erect perennial stem(s) capable of achieving at least 3 inches (7.6 cm) diameter at breast height, or 5 inches (12.7 cm) diameter at root collar, and a height of 16.4 feet (5 meters) at maturity in situ. The definition here includes all areas recently having such conditions and currently regenerating or capable of attaining such condition in the near future. Forest land also includes transition zones, such as areas between forest and nonforest lands that have at least 10 percent cover (or equivalent stocking) with live trees, and forest areas adjacent to urban and built-up lands. Unimproved roads and trails, streams, and clearings in forest areas are classified as forest if they are less than 120 feet (37 meters) wide or an acre (0.4 hectare) in size.

Forest remaining forest: IPCC land use category that accounts for land that has persisted in a forest land use over an approximate 6-year time period in the Eastern United States and a 10-year time period in the Western United States. The time period is defined as the difference between a time 2 measurement and a time 1.

Growing stock: All live trees 5.0 inches (12.7 centimeters) diameter at breast height or larger that meet (now or prospectively) regional merchantability requirements in terms of saw-log length, grade, and cull deductions. Excludes rough and rotten cull trees.

Harvested wood products (HWP): IPCC carbon pool that tracks carbon in long-lived wood products such as paper, wood panels, and sawn wood that are in use and store carbon over the products life cycle. Short-lived products, such as wood pellets, are considered immediate emissions of the biomass.

Litter: IPCC carbon pool that tracks all duff, humus, and fine woody debris above the mineral soil, including woody fragments with diameters of up to 7.5 centimeters.

Major eastern forest type groups

Aspen/birch: Forests in which aspen, balsam poplar, paper birch, or gray birch, singly or in combination, comprise a plurality of the stocking. Common associates include maple and balsam fir.

Elm/ash/cottonwood: Forests in which elm, ash, or cottonwood, singly or in combination, comprise a plurality of the stocking. Common associates include willow, sycamore, beech, and maple.

Loblolly/shortleaf pine: Forests in which loblolly pine, shortleaf pine, or southern yellow pines, except longleaf or slash pine, singly or in combination, comprise a plurality of the stocking. Common associates include oak, hickory, and gum.

Longleaf/slash pine: Forests in which longleaf or slash pine, singly or in combination, comprise a plurality of the stocking. Common associates include other southern pines, oak, and gum.

Maple/beech/birch: Forests in which maple, beech, or yellow birch, singly or in combination, comprise a plurality of the stocking. Common associates include hemlock, elm, basswood, and white pine.

Oak/gum/cypress: Bottomland forests in which tupelo, blackgum, sweetgum, oaks, or southern cypress, singly or in combination, comprise a plurality of the stocking, except where pines comprise 25 to 50 percent, in which case the stand is classified as oak/pine. Common associates include cottonwood, willow, ash, elm, hackberry, and maple.

Oak/hickory: Forests in which upland oaks or hickory, singly or in combination, comprise a plurality of the stocking, except where pines comprise 25 to 50 percent, in which case the stand is classified as oak/pine. Common associates include yellow poplar, elm, maple, and black walnut.

Oak/pine: Forests in which hardwoods (usually upland oaks) comprise a plurality of the stocking, but in which pine or eastern redcedar comprises 25 to 50 percent of the stocking. Common associates include gum, hickory, and yellow poplar.

Spruce/fir: Forests in which spruce or true firs, singly or in combination, comprise a plurality of the stocking. Common associates include white cedar, tamarack, maple, birch, and hemlock.

White/red/Jack pine: Forests in which eastern white pine, red pine, or jack pine, singly or in combination, comprise a plurality of the stocking. Common associates include hemlock, aspen, birch, and maple.

Major western forest type groups

California mixed conifer group: a complex association of ponderosa pine, sugar pine, Douglas-fir, white fir, red fir, and incense cedar. Generally, five or six conifer species are intermixed, either as single trees or in small groups. Mixed conifer sites are often on east-facing slopes of the California Coast Range and on the west-facing and higher elevation east-facing slopes of the Oregon Cascades and Sierra Nevadas.

Douglas-fir: Forests in which Douglas-fir comprises a plurality of the stocking. Common associates include western hemlock, western redcedar, true firs, redwood, ponderosa pine, and larch.

Fir/spruce: Forests in which true firs, Engelmann spruce, or Colorado blue spruce, singly or in combination, comprise a plurality of the stocking. Common associates include mountain hemlock and lodgepole pine.

Hemlock/Sitka spruce: Forests in which western hemlock and/or Sitka spruce comprise a plurality of the stocking. Common associates include Douglas-fir, silver fir, and western redcedar.

Lodgepole pine: Forests in which lodgepole pine comprises a plurality of the stocking. Common associates include alpine fir, western white pine, Engelmann spruce, aspen, and larch.

Ponderosa pine: Forests in which ponderosa pine comprises a plurality of the stocking. Common associates include Jeffrey pine, sugar pine, limber pine, Arizona pine, Apache pine, Chihuahua pine, Douglas-fir, incense cedar, and white fir.

Other forest land: Reserved forest land or nontimberland forests where the forest land is not capable of producing 20 cubic feet per acre per year of volume.

Other land converted to forest: IPCC land use category that accounts for land that was converted from a nonforest use at time 1 to a forest use at time 2.

Parcelization: The division of larger parcels of land, typically owned by a single entity, person, or family, into smaller parcels with multiple owners.

Reserved forest land: Forest land withdrawn from timber utilization through statute, administrative regulation, or designation without regard to productive status.

Soil organic C (SOC): IPCC carbon pool that tracks all organic material in soil to a depth of 1 meter but excludes the coarse roots of the belowground pools.

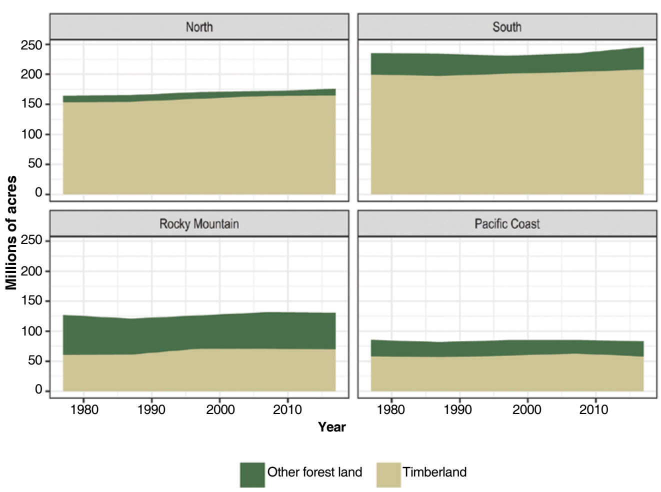
Solid waste disposal site (SWDS): IPCC carbon pool that tracks HWP carbon by product and end use once it has been disposed of.

Timberland: Forest land that is producing or capable of producing 20 cubic feet per acre per year or more of wood at culmination of mean annual increment. Timberland excludes reserved forest lands.

timberland increased by 29 million acres from 1977 to 2017 (6.1 percent), while the area of other forest land decreased by 6.1 million acres (4.3 percent).

Changes in forest land and timberland area varied across the conterminous United States (figure 6-1). The area of forest land in the RPA North, South, and Rocky Mountain Regions increased from 1977 to 2017, while forest land area decreased in the Pacific Coast Region. The North Region saw the largest gain, increasing from 164.2 million acres to 175.8 million acres (a gain of 11.6 million acres, or 7.1 percent of the 1977 area), followed by the South and Rocky Mountain Regions, which gained 10.1 and 3.4 million acres, respectively (4.3 and 2.7 percent, respectively). In contrast, the Pacific Coast Region lost 2.3 million acres (2.6 percent). The three RPA regions that gained overall forest area from 1977 to 2017 also gained timberland, while the Pacific Coast Region lost timberland. The overall loss of other forest land across the United States came from moderate to large losses in the two western regions, while other forest land increased in the two eastern regions.

Figure 6-1. Area of forest land by RPA region for the conterminous United States, 1977 to 2017. Timberland is distinguished from other forest land uses.



Planted Forest

Planted forests represent some of the most actively managed timberland in the United States. Forests are planted to meet management objectives, including restoration and supplying roundwood for forest products (Oswalt et al. 2019). Roughly 13 percent (68 million acres) of timberland showed evidence of planting in 2017. Most planted timberland is in the RPA South Region (71 percent), followed by the Pacific Coast Region (19 percent), North Region (9 percent), and Rocky Mountain Region (1 percent). Of the planted timberland, there are several commercially important forest type groups (FTGs) that make up a relatively large share of total planted area: loblolly/shortleaf (51 percent), Douglas/fir (12 percent), longleaf/slash pine (11 percent), white/red/jack pine (5 percent), and ponderosa pine (2 percent).

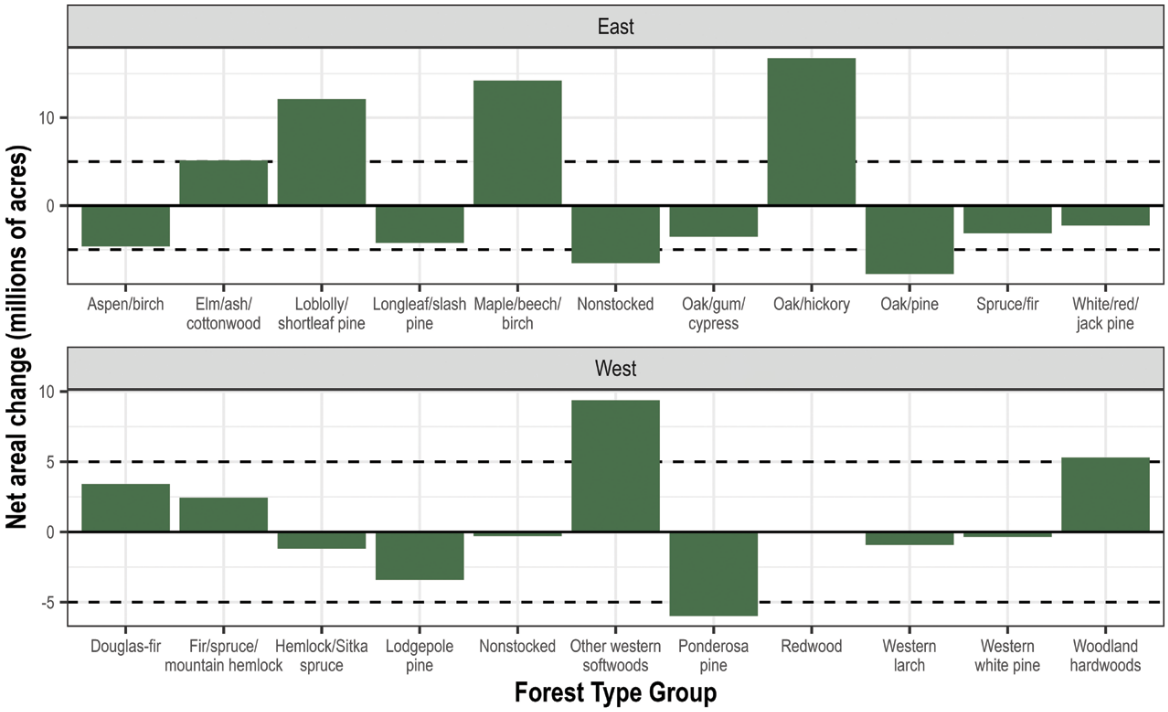
Timberland Area by Forest Type Group

Timberlands across the conterminous United States experience changes in areal extent, forest type composition, and stand origin. Shifts in these attributes are driven by land use change, investment in plantation forestry, forest succession, and disturbance. The current distribution of timberland forest type groups (FTGs) is a result of these drivers (see the sidebar Definitions for a description of major eastern and western forest type groups). Eight FTGs saw a net increase in timberland area from 1977 to 2017, ranging from 2.4 million acres (fir/spruce/mountain hemlock) to 16.7 million acres (oak/hickory) (figure 6-2). The most widespread FTGs in the Eastern United States—oak/hickory, maple/beech/birch, and loblolly/shortleaf pine—all gained substantial areas of timberland over that time. The loblolly/shortleaf pine forest type group increased in area due to agricultural abandonment (natural seeding and growth) and tree planting for commercial or conservation purposes (South and Harper 2016, Wear and Greis 2013). The Douglas-fir and fir/spruce/mountain hemlock type groups, which are relatively widespread in the Western United States, also increased in area from 1977 to 2017.

Twelve FTGs lost timberland area from 1977 to 2017, ranging from -0.4 million acres (western white pine) to -6.8 million acres (oak/pine) (figure 6-2). Several western FTGs dominated by pine species lost area, including the ponderosa pine, lodgepole pine, and western white pine groups. Many of those FTGs have been subject to a series of interacting disturbances since at least the early 20th century, including fire suppression and mountain pine beetle, which have resulted in decreased extent of those forests (Stanke et al. 2021). In addition, increases in background mortality have been documented in many western tree species, with pines showing the greatest rates since the 1990s (Van Mantgem et al. 2009). The western white pine FTG lost the most area relative to its small 1977 range (78 percent loss, from 0.5 million acres in 1977 to 0.1 million acres in 2017), having faced threats from white pine blister rust in addition to area reductions due to fire and beetles (Dudney et al. 2020, Schwandt et al. 2010). The aspen/birch FTG, distributed in the RPA North and Rocky Mountain Regions, also showed a relatively substantial decline in area. Recent decline and mortality of aspen forests has been linked to warming and drying climate (Hanna and Kulakowski 2012, Rehfeldt et al. 2009).

Three forest type groups that are relatively widespread in the Eastern United States have declined in area over the past 40 years: longleaf/slash pine, oak/gum/cypress, and oak/pine. Forests dominated by longleaf pine declined

Figure 6-2. Net changes to timberland areal extent from 1977 to 2017 for forest type groups in the East and West. Only FTGs with available historical information were included.



FTG = forest type group.

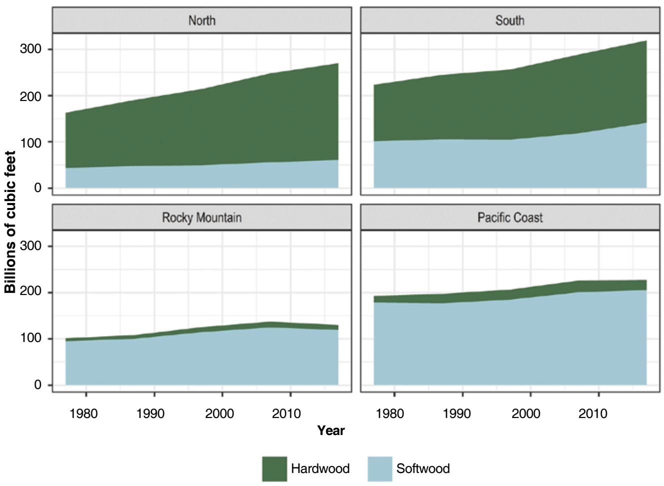
in area over much of the 20th century due to historic fire suppression, land use conversion, and conversion to other forest type groups like loblolly/shortleaf pine (Oswalt et al. 2014). While the area of longleaf pine forests started to increase in the 1990s, it has not reached previous levels (Oswalt et al. 2014, South and Harper 2016). The America's Longleaf Restoration Initiative set a goal to double the area of longleaf pine between 2009 and 2025. Based on McIntyre et al. (2018), gains in longleaf pine area have been offset by losses leading to relatively stable longleaf pine area from 2010 to 2016. However, slash pine forests have continued to decline in area (Oswalt et al. 2014). Land conversion and lack of flooding have led to decreased extent of bottomland hardwood forests (Mitchell et al. 2009) such as those found in the oak/gum/cypress FTG. The decline in area of oak/pine forests, distributed primarily in the RPA South Region, is due to land use change, succession to oak/hickory forest, and conversion to loblolly/shortleaf types.

Growing Stock Volume

The growing stock volume on timberland ("timberland volume") is a key structural component of U.S. forests. Timberland volume trends provide insight into the potential amount of wood available for forest products, as well as general forest health and productivity. Timberland volume increased across the conterminous United States from 1977 to 2017, from 680.4 billion cubic feet to 947 billion cubic feet (39.2 percent). The volume increase, on a percentage basis, was roughly 10 times greater than forest area increase (percentage basis) over the same period. Both hardwood and softwood timberland volumes increased, by 158.6 billion cubic feet (60.6 percent) and 108 billion cubic feet (25.8 percent) respectively. The annual net change in timberland volume averaged +6.7 billion cubic feet per year from 1977 to 2017; however, net change in timberland volume varied by region (figure 6-3). Robust growth in the East from 1977 to 2017 led to increased timberland volume. Specifically, timberland volumes in the North and South Regions increased 107 billion cubic feet (65.7 percent) and 95.7 billion cubic feet (42.8 percent), respectively. In the West, increases in timberland volume were less pronounced: the Pacific Coast Region increased by 35.1 billion cubic feet and Rocky Mountain Region increased by 28.8 billion cubic feet from 1977 to 2017. Over the last decade (2007 to 2017) growing stock volume on timberland was relatively static in the West, while volume in the East continued to grow.

Volume trends from 1977 to 2017 differed by species (hardwood versus softwood) and RPA region. In the North and

Figure 6-3. Growing stock volumes by RPA region from 1977 to 2017, by hardwood/softwood.



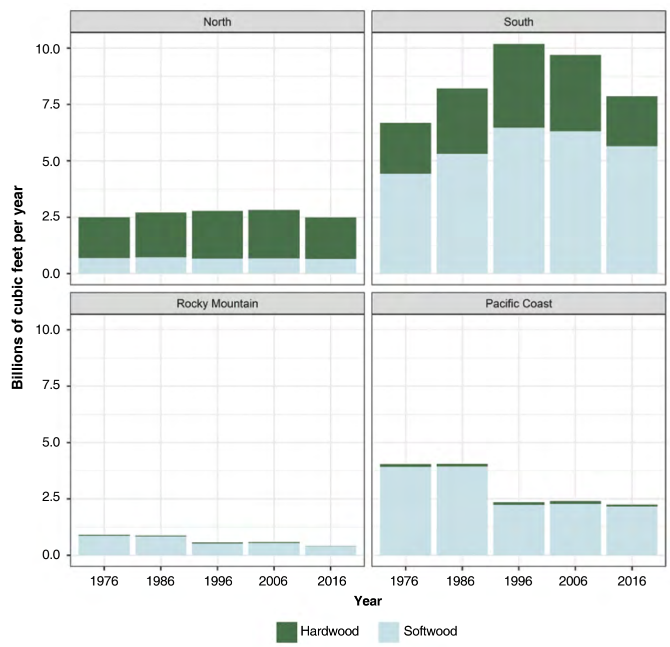
South Regions, hardwood species made up 84.3 percent (90.3 billion cubic feet) and 58.1 percent (55.6 billion cubic feet) of the increased timberland volume, respectively. In contrast, the increased timberland volume in the Rocky Mountain and Pacific Coast Regions was primarily from softwood species: 83.4 percent (24 billion cubic feet) and 77.5 percent (27.2 billion cubic feet), respectively. While all four regions experienced net increases to timberland volume from 1977 to 2017, the Rocky Mountain Region experienced a timberland volume peak in 2007 of 137.3 billion cubic feet before decreasing to 130 billion cubic feet in 2017. Timberland volume in the conterminous United States generally increased, primarily due to forest growth and a slight increase in overall timberland area.

Growing Stock Removals

Removal of timberland growing stock is driven by societal needs for forest products and land use change. Annual removals increased through the 1980s and 1990s, with peak annual removals of 15.9 billion cubic feet occurring in 1996. By 2016, annual removals had decreased to volumes lower than 1976 (13 billion cubic feet in 2016 compared to 14.1 billion cubic feet for 1976). However, based on Oswalt et al. (2019), 2016 annual removals were higher than those observed during the 2007 to 2009 recession, which drove annual removals down across the conterminous United States (Hodges et al. 2012, Woodall et al. 2012).

Most removals occurred in the South for both hardwoods and softwoods (a share that increased from 47.3 percent to 60.4 percent of removals from 1976 to 2016), with the increase in softwood removals there offsetting the decrease in softwood removals from the Pacific Coast Region (figure 6-4). By 2016, total removals from the Pacific Coast Region decreased to levels comparable with the North Region (17.3 percent of removals in 2016 came from the Pacific Coast, compared to 19.2 percent from the North). Hardwood and softwood removals differed between the two regions, with 73.8 percent hardwood removals for the North compared to 96.4 percent softwood removals for the Pacific Coast. The Rocky Mountain Region maintained the lowest removal rates of all regions, with its share of removals decreasing from 6.4 percent to 3.1 percent from 1976 to 2016.

Figure 6-4. Average annual growing stock removals by RPA region from 1976 to 2016, by hardwood/softwood.



Age Dynamics

Stand age is an important indicator of forest structure because key structural parameters such as volume, biomass, basal area, and height are correlated with stand age. Most traditional even-aged management analyses (e.g., growth and yield curves, site index) directly incorporate stand age because of this correlation. While the interpretation of stand age in uneven-aged stands is less clear, stand age remains correlated with structural stand parameters, and many inventory projection models depend on stand age information and assumptions about age transitions (see Wear and Coulston 2019 for a summary).

Stand age, as measured by the FIA program, is the average age of three dominant or codominant trees in the stand. Age transitions occur naturally over time and are influenced by forest management and treatments. The type and degree of an age transition between two points in time can be estimated using remeasured FIA field inventory plots. Age tends to progress linearly over time for undisturbed stands; however, a portion of undisturbed stands decrease in age over time when the dominant or co-dominant cohort of trees is replaced by a younger cohort. Clear-cut harvesting and stand clearing disturbance are age-resetting events. Partial cutting and other disturbances could affect stand age: there is no effect on age if the original cohort of trees remain dominant or co-dominant but stand age will be reduced by some amount if a younger cohort of trees becomes dominant or co-dominant following the disturbance. Most disturbed stands continue to age linearly with time. The age transition probabilities estimated from the FIA data suggest that the age class distribution will shift to older stands over time, even with disturbance and management annually affecting a portion of the forest land.

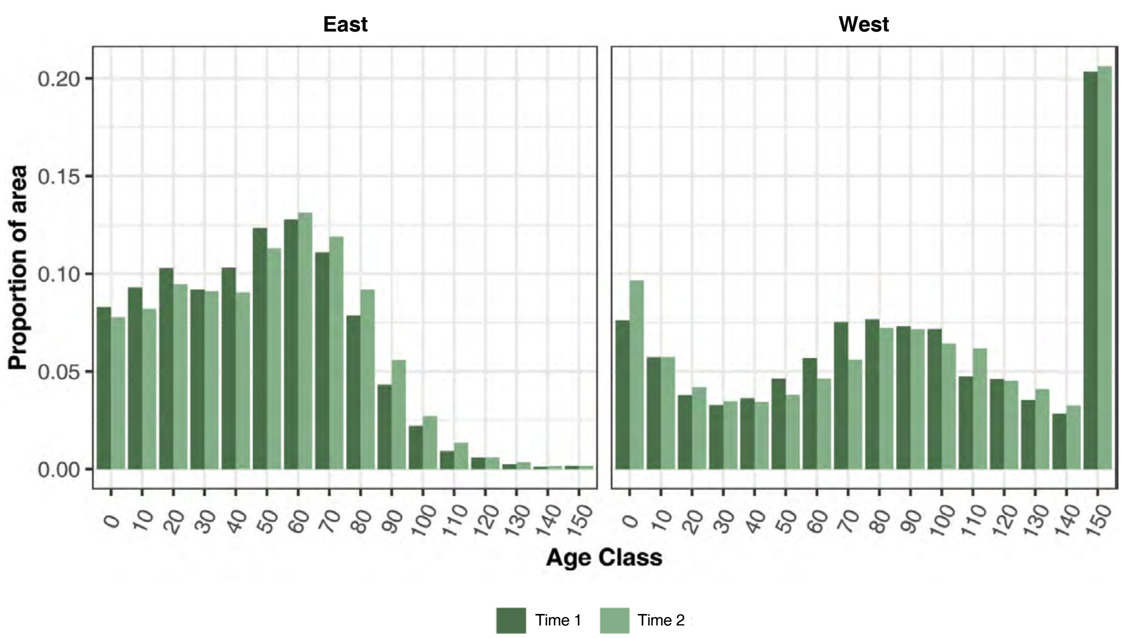
Figure 6-5 shows the forest age distributions based on the two most current measurements of the FIA inventory. In the Eastern United States, the forest area in age classes younger than 60 years decreased between time 1 and time 2 measurements, and there was a corresponding increase in forest greater than 60 years old. Even with disturbance and harvesting, the eastern forests are aging. In the West, there was generally an increase in forest area for age classes less than 30 years, followed by a decrease in forest area for age classes from 40 to 80 years, and an increase in the extent of forest greater than 100 years old. The decrease in 40- to 80-year-old forests was a result of disturbances such as fire and insects, as well as forest harvesting.

Trends in Forest Ownership

- ❖ Nationally, 60 percent of U.S. forest land (excluding interior Alaska) is privately owned, 38 percent is publicly owned, and 2 percent is within Tribal reservation boundaries (Butler et al. 2021a).
- ❖ The relative distributions of forest land by broad ownership categories have shown a general trend of increasing public ownership over the past 60+ years, but the pattern appears to have stabilized over the last decade.
- ❖ Within the private ownership category, timberland investment management organizations (TIMOs) and real estate investment trusts (REITs) have increased in importance over the past few decades.
- ❖ There are an estimated 9.6 million family forest ownerships across the country and they control more forest land than any other ownership category (39 percent, excluding interior Alaska), but most do not have a written forest management plan and have not received forest management advice.

Landowners, operating within the social, political, economic, and ecological environments, ultimately decide how land will be used and who will directly benefit from it. The set of laws, regulations, and social norms that control what

Figure 6-5. Forest age class distribution for the Eastern (left) and Western (right) conterminous United States based on the most current two measurements per forest plot of the forest inventory.



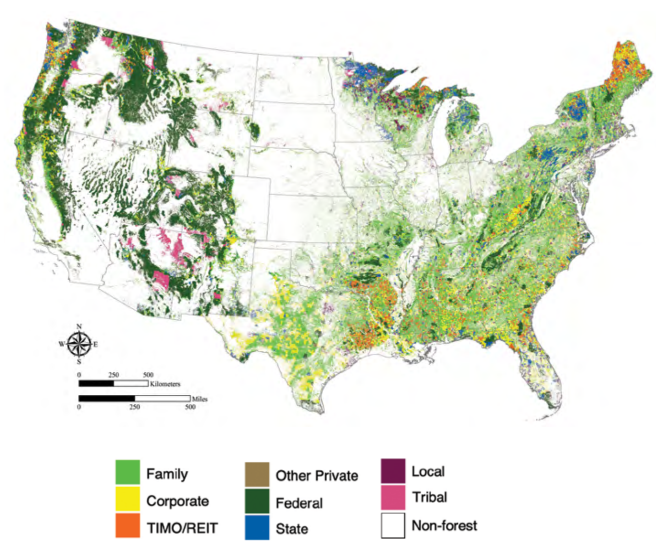
a person or organization can and cannot do with a given piece of land and its associated resources are called land tenure rights. The United States has strong and well-defined land tenure rights that help determine the exclusivity, transferability, alienability, and enforceability associated with the resources. These rights may vary depending on the resource being considered (e.g., trees versus below-ground minerals), location in the United States (e.g., riparian water rights in most Eastern States versus prior appropriation water rights in most Western States), and ownership type (e.g., public versus private versus Tribal ownership).

Ownerships are diverse in terms of legal structures, ownership objectives, size of holdings, awareness of opportunities and threats, and abilities to take advantage of opportunities. Ownership patterns consist of a patchwork of different ownerships, which vary across the country and can change as lands are bought and sold or the ownership structures and objectives shift. Patterns and trends in land acquisition/disposal, land use conversion, and harvesting impact the current state of America's forests and will continue to shape its future.

Forest Ownership Patterns

Nationally, 60 percent of the forest land, excluding interior Alaska due to data limitations, is privately owned, 38 percent is publicly owned, and 2 percent is within Tribal reservation boundaries (Butler et al. 2021a). However, these ownership patterns vary substantially across the country (figure 6-6). Family forest ownerships (i.e., individuals, families, trusts, estates, and family partnerships) control more forest land than any other ownership group. Over half of the forest land in the South and North Regions is owned by millions of family forest owners (56 percent and 52 percent, respectively). In the Rocky Mountain and Pacific Coast Regions, however, 67 percent and 57 percent of forest land, respectively, is federally owned, with much under the jurisdiction of the USDA Forest Service and the U.S. Bureau of Land Management. The highest percentage of Tribal land is in the Rocky Mountain Region (8 percent), with the Navajo Nation managing a plurality of the Tribal forest land area in the region.

Figure 6-6. Forest ownership across the conterminous United States in 2017.



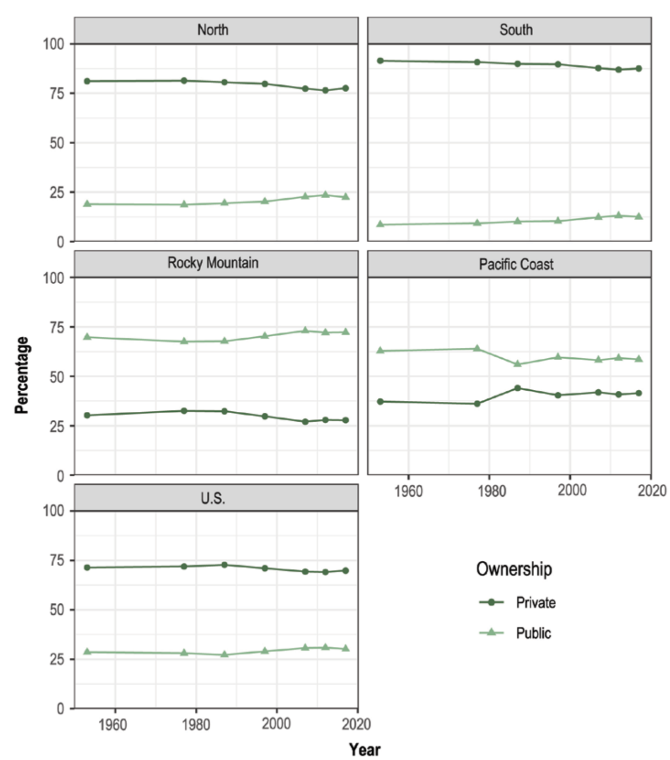
REIT = real estate investment trusts; TIMO = timberland investment management organization.
Source: Sass et al. 2020.

Ownership Dynamics

The relative distributions of forest land over the past 60+ years have shown a general trend of increasing public ownership, but the pattern appears to have stabilized over the last decade (figure 6-7; Oswalt et al. 2019). The trend was a result of some private lands being transferred to public ownership (particularly State), as well as the loss of private forest land to nonforest uses, including agriculture and development.

The emergence of timberland investment management organizations (TIMOs) and real estate investment trusts (REITs) over the past few decades has changed forest

Figure 6-7. Private and public timberland ownership by RPA region and for the conterminous United States.



Historical data are only available for timberlands. Tribal lands are included with private ownerships.
Source: Oswalt et al. 2019.

ownership in the United States. This historic restructuring was the result of changes in Federal policy, changes in expectations of investors in vertically integrated forestry companies, and opportunities for new investments (Binkley et al. 1996, Butler and Wear 2013). TIMOs and REITs now represent a large percentage of the Nation's corporate forest land, collectively controlling an estimated 41 million acres, and have a commensurately important role in the provision of timber and other resources.

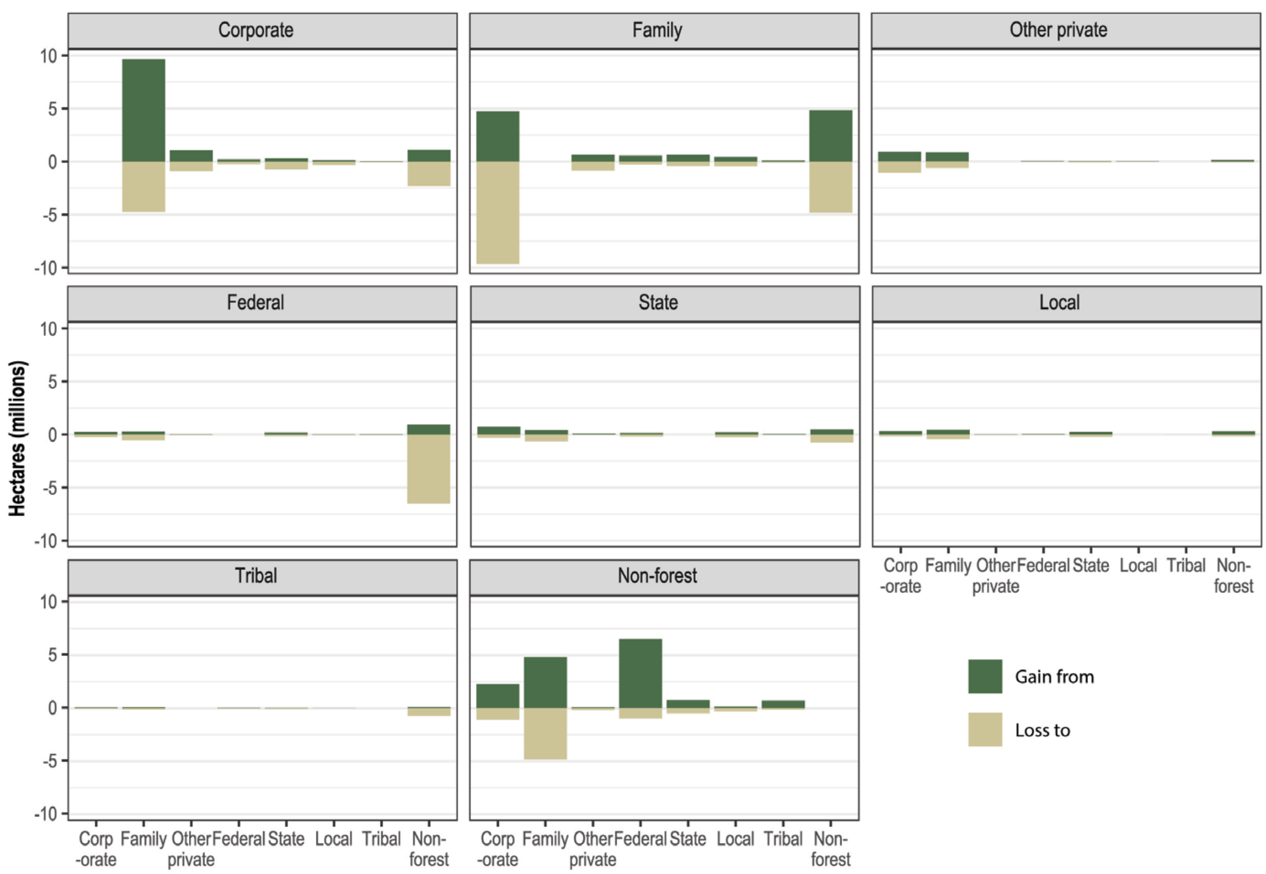
The largest net changes across ownership groups over the past decade have been an increase in corporate forest land and decreases in family and Federal forest land (figure 6-8; Sass et al. 2021). Most of the increase in corporate forest land has come from family forest lands. Although the details are unknown, it is assumed that this transfer is due to a combination of traditional corporations acquiring new lands and from family forest ownerships converting their ownerships to corporate structures for tax, inheritance, and other reasons. Some trends (e.g., Federal lands transitioning to nonforest) are likely associated with changes in the estimated productivity of forest land growing in increasingly harsh environments. Ownership transfers also occur within ownership categories, particularly on the private side, but we are unable to fully quantify those transactions given currently available data—the increasing prevalence of TIMOs and REITs within the corporate category being a prime example.

Family Forest Ownerships

There are an estimated 9.6 million family forest ownerships across the United States, and they control more forest land than any other ownership category (39 percent excluding interior Alaska). The USDA Forest Service conducts the National Woodland Owner Survey to better understand the attitudes, behaviors, and other characteristics of this important group of owners (Butler et al. 2021a).

An important attribute of family forest ownerships is size of holdings. This attribute directly impacts some activities due to economies of scale, such as the higher costs of harvesting timber on smaller parcels, and is indirectly correlated with many other attributes (Butler et al. 2021b). While most family forest owners have relatively small forest holdings (i.e., 62 percent of the family forest ownerships own less

Figure 6-8. Forest land gain and loss by ownership group between 2007 and 2017.



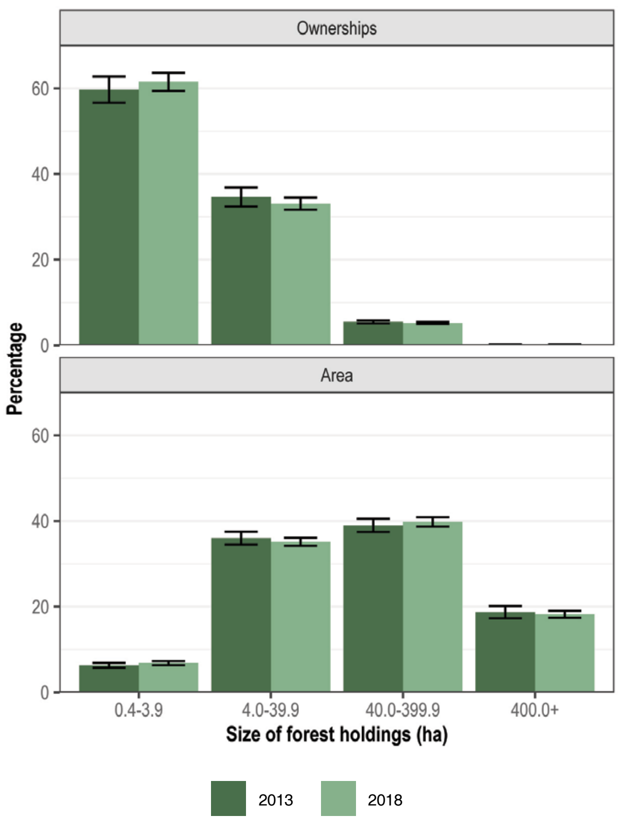
Source: Sass et al. 2021.

than 10 acres), most of the family forest acreage occurs within large holdings (i.e., 58 percent of the family forest land is in holdings of at least 100 acres; figure 6-9). The average size of family forest holdings in 2018 was 28 acres (or 69 acres, if only looking at family forest ownerships of more than 10 acres); these values are not substantially different from 2013 (Butler et al. 2016).

The objectives of family forest landowners have not changed appreciably since the first national landowner surveys were conducted in the 1990s (Birch 1996). Family forest owners cite amenity values—including aesthetics, nature protection, and wildlife—as the primary reason for owning forest land (figure 6-10). In terms of financial objectives, land investment is important for owners of 58 percent of the family forest land, and timber production is important for 34 percent. For many of the remaining family forest owners, their forests are meeting their needs and are largely "running in the background" (Kittredge 2004). While an estimated 48 percent of the family forest land is owned by people who have commercially harvested trees, the fact that 23 percent of the family forest land is owned by people who have a written forest management plan and 34 percent by people who have received forest management advice in the previous 5 years suggests that many harvests are unplanned. Efforts tailored to the owners' concerns, including property taxes, keeping land intact for future generations, trespassing/vandalism, and other self-identified issues, in addition to the concerns identified by natural resource professionals, could encourage greater interest and participation in forest management assistance programs and services (figure 6-11).

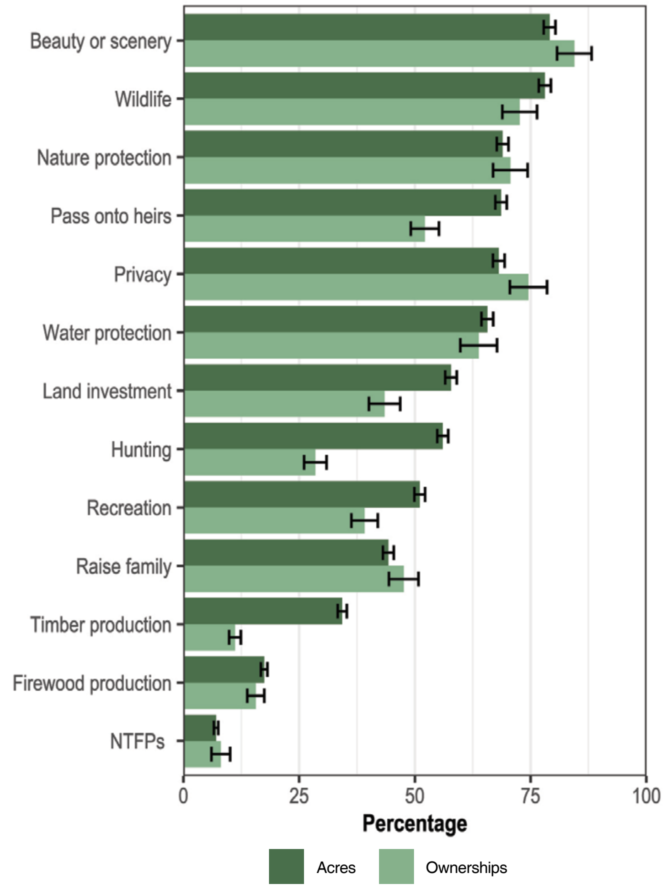
Demographics are important for understanding family forest ownership trends. Given that the age of the primary family forest decisionmaker is 65 or older for 56 percent of the family forest land, intergenerational transfer has the

Figure 6-9. Percentage of family forest ownerships and family forest acreage by size of forest holdings in 2013 and 2018. Error bars are 95 percent confidence intervals.



Source: Butler et al. 2016, 2021a.

Figure 6-10. Percentage of family forest acreage and family forest ownership by ownership objectives in 2018. Error bars are 95 percent confidence intervals.

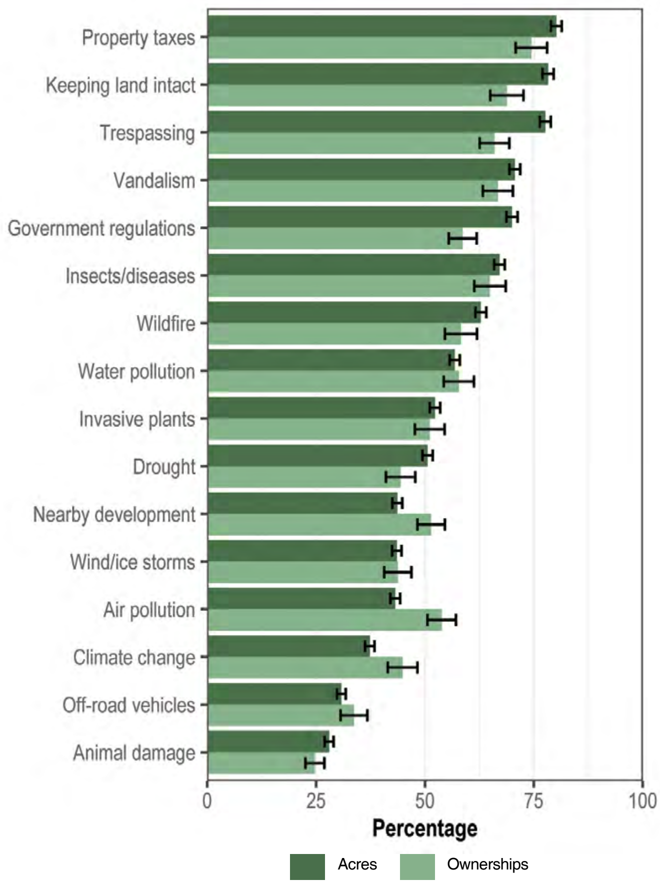


NTFPs = nontimber forest products.

Owners that identified an objective as important or very important on a 5-point Likert scale are included in percentages.

Source: Butler et al. 2021a.

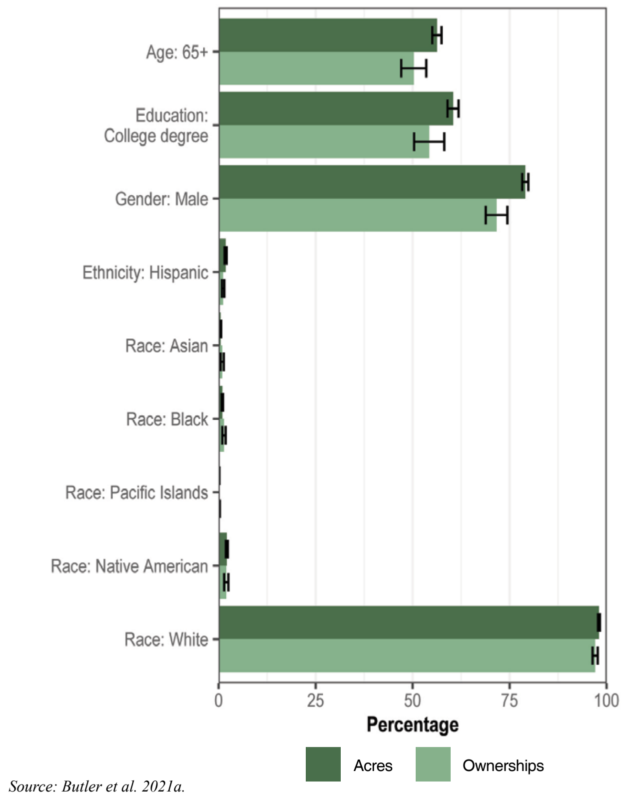
Figure 6-11. Percentage of family forest acreage and family forest ownerships identifying potential ownership concerns in 2018. Error bars are 95 percent confidence intervals.



Owners that identified an issue as a concern or great concern on a 5-point Likert scale are included in percentages.

Source: Butler et al. 2021a.

Figure 6-12. Family forest acreage and family forest ownership demographics in 2018. Error bars are 95 percent confidence intervals.



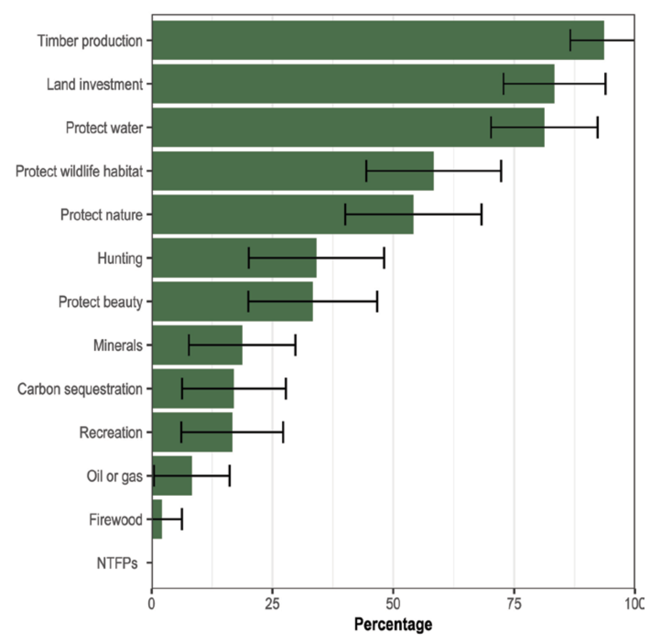
Source: Butler et al. 2021a.

potential to significantly impact future ownership dynamics (figure 6-12). Although most of the primary decisionmakers are male, we know that most family forests are owned by a married couple. Nonwhite landowners comprise a much smaller percentage of the family forest population than the general U.S. population. Nonwhite landowners have been shown to participate in programs at lower rates (Butler et al. 2020) and face some challenges not encountered by white landowners (Hitchner et al. 2017).

Corporate Forest Ownerships

For large, corporate forest landowners, the primary reasons reported for owning forest land include timber production, land investment, and the protection of water resources, aligning with their business models (figure 6-13). Large corporate ownerships—those that own more than 45,000 acres—are more likely to have formal management

Figure 6-13. Percentage of large corporate forest ownerships by ownership objectives in 2018. Error bars are 95 percent confidence intervals.



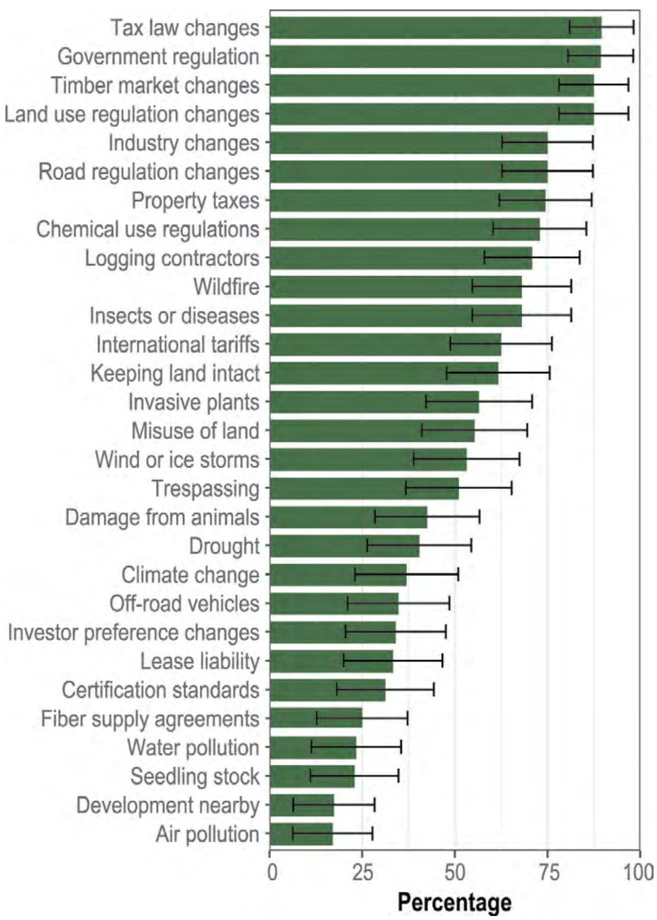
NTFPs = nontimber forest products.

Owners that identified an objective as important or very important on a 5-point Likert scale are included in percentages.

Source: Butler et al. 2021a.

structures than family forest owners: approximately three quarters of large corporations report having a written management plan that covers all of their land. Certification, such as through the Sustainable Forestry Initiative and Forest Stewardship Council, and conservation easements are also relatively common, with two-thirds of companies and half of companies reporting each item, respectively (Sass et al. 2021). Corporate owners most commonly report concerns relating to regulations and changes to taxes and markets, but biological and environmental issues, including insects, disease, invasive plants, and wildfire, are also concerning to a majority of companies (figure 6-14). Large corporate forest land ownerships, including TIMOs and REITs, report high levels of engagement with the management of their forest land to meet their financial goals.

Figure 6-14. Percentage of large corporate forest ownerships identifying potential ownership concerns in 2018. Error bars are 95 percent confidence intervals.



Owners that identified a potential concern as a concern or great concern on a 5-point Likert scale are included in the percentages.

Source: Sass et al. 2021.

Projected Futures of U.S. Forests

- Forest area in the conterminous United States is projected to decrease from 634 million acres to between 619 and 627 million acres in 2070. Net losses are primarily driven by conversion to developed uses.
- Important forest type groups are expected to lose area due to the interaction of forest loss, harvest, climate, and succession. These type groups include aspen/birch in the RPA North Region, oak/gum/cypress in the South, ponderosa pine in the Rocky Mountains, and hemlock/Sitka spruce in the Pacific Coast.
- Timberland growing stock volume is projected to increase through 2050, but trajectories after 2050 depend on roundwood demand. RPA scenarios with high roundwood demand (LM and HH) lead to decreases in growing stock volume post-2050.
- Hardwood growing stock volume is projected to increase over the 2020 to 2070 projection period, while softwood growing stock volume is projected to decrease post-2050. The magnitude of the decrease depends on demand for softwood roundwood.
- Across RPA scenarios, removals for roundwood products are expected to increase from 2020 levels. Softwood removals are expected to increase more than hardwood removals.

Forest development is driven by a suite of biological, edaphic, climate, management, and land use choices that not only determine forest function but also influence the ecosystem services arising from the forests of the United States. The projected futures of U.S. forests are based on the Forest Dynamics Model (see the sidebar Forest Dynamics Model for more information) which incorporates information from the county-level land use change model (see the Land Resources Chapter) and is harmonized with the global trade model (FOROM) described in the Forest Products Chapter. The Forest Dynamics Model projects the FIA inventory forward as influenced by biological, physical, climatic, and human factors that alter expected futures. Here we summarize results from the Forest Dynamics Model for the four RPA scenarios or the 20 RPA scenario-climate futures described in the sidebar RPA Scenarios. In cases where only RPA scenario results are presented, those results are based on averaging decadal results across the five climate projections evaluated within each RPA scenario.

Forest Dynamics Model

Model Overview

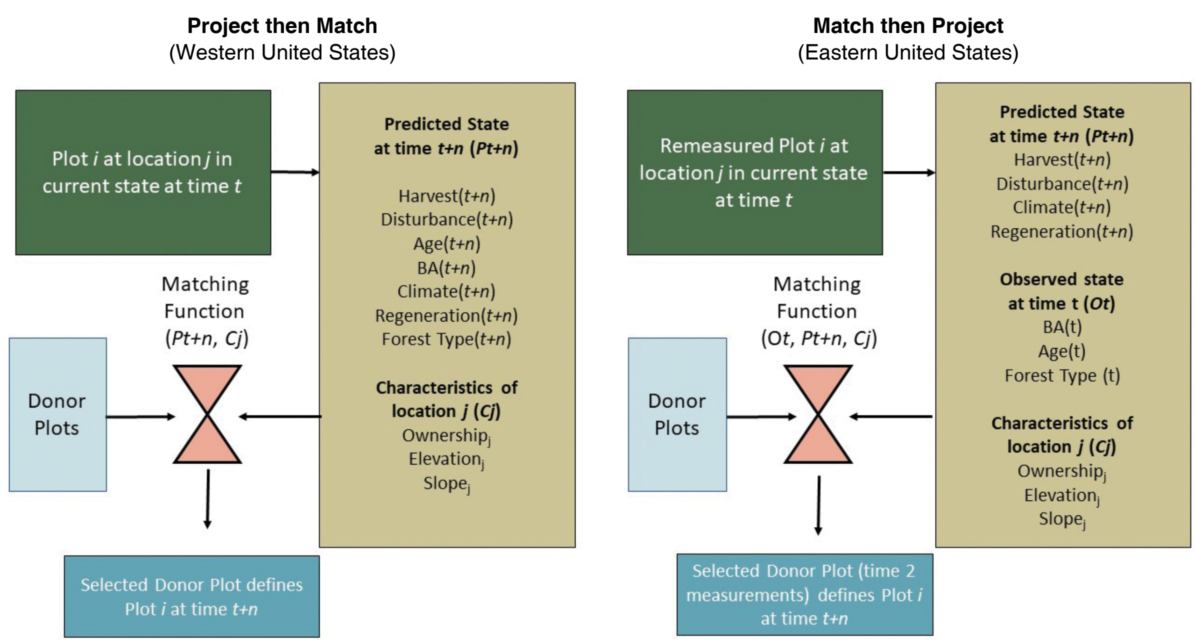
The Forest Dynamics Model is a stochastic modeling system which projects the FIA database at the plot (condition) level using an imputation approach (Coulston et al. in preparation). This approach allows for consistent projections across a range of variables of interest (e.g., volume, age, carbon, forest type) while maintaining the observed relationships among FIA variables at the plot level through the projection period. The modeling system is informed by exogenous variables such as climate, timber prices, population, and income; the system is also informed by a set of state transition submodels representing land use change, harvest choices, forest disturbance, growth, aging, regeneration, and forest type transitions over time.

Two different imputation techniques are used, depending on the availability of remeasured FIA plot data. The Project then Match technique is used in the Western United States, where remeasured plot data are limited (figure 6-15); the Match then Project technique is used in the Eastern United States where each inventory plot has two or three measurements. In both cases, the overall approach is to curate a pool of donor plots for a target plot, using the FIA database based on current (time 1) and predicted (time 2) plot states, then select randomly from that pool to update the target plot.

The forested land use change components of the Forest Dynamics Model arise from the county-level gross land use change projections discussed in the Land Resources Chapter (Mihiar and Lewis 2021). The FIA expansion factors, derived from the area sampling frame, are adjusted to reflect both forest area gains and forest area losses. Two separate submodels are used to account for differences in the forest types, planting status, and structural characteristics (e.g., age, volume) of plots experiencing gains or losses.

The Forest Dynamics Model is harmonized with the Global Trade Model (FOROM), discussed in the Forest Products Chapter. When solving for global forest sector

Figure 6-15. Imputation approaches used in the Forest Dynamics Model. Predicted states are derived from a set of state exogenous variables and transition models. Note that the primary difference between the two approaches relates to basal area (BA), stand age (Age), and forest type. In the Project then Match approach models are used to predict the state of those variables at time *t+n*. In the Match then Project approach predictions of BA, Age, and forest type are not needed since the matching occurs at time *t* for these variables. Both approaches rely on the predicted probabilities of harvest, disturbance, and forest planting (regeneration) after harvest at time *t+n*. Climate projections at time *t+n* also inform the modeling system.



solutions in FOROM, climate-induced productivity change projections made by MC2 for the United States were replaced by those made by the Forest Dynamics Model. Projections of the U.S. forest sector made jointly with FOROM and the Forest Dynamics Model were harmonized on inventory (volume) and removals (roundwood production) to find a roundwood price path where the inventory and removals for the United States aligned over the projection period. In each 5-year time step of FOROM, the Forest Dynamics Model was used to calibrate inventory growth rates across the RPA regions and were an exogenous input into FOROM. Then, FOROM projected an endogenous path of removals and roundwood prices. The roundwood prices were then used in the Forest Dynamics Model harvest choice and timber supply models to project removals. The projected removals from FOROM and the Forest Dynamics Model were then compared to ensure alignment. Because the Forest Dynamics Model used both the RPA scenarios and the individual climate model projections (least warm, hot, dry, wet, middle), the harmonization was performed for each RPA scenario where Forest Dynamics Model inventory and removals were averaged across climate projections for each time-step in the projection period.

As noted earlier, the Forest Dynamics modeling system is stochastic. Randomness enters the system in three places: (1) in the state transition models for harvest, regeneration, disturbance, and forest type; (2) in the models accounting for forest loss and forest gains; and (3) in the selection of a donor plot. The state transition models for harvest, regeneration, disturbance, and forest type are probabilistic; for example, the designation of a plot to be harvested is drawn randomly from the pool of donor plots with probability proportional to the model prediction. The forest loss and forest gain models are also probabilistic, where forest gains are distributed across plots based on the plot-level probability of afforestation and similarly for forest losses. The groups of similar donor plots (bins) have at least 20 donor plots in each bin. The donor for each plot is selected randomly with replacement.

Implementation

For each of the 20 RPA scenario-climate futures, the FIA inventory is projected forward in approximate 5-year time steps for the Eastern United States and 10-year time steps for the Western United States. These two different time step lengths are based on the differing FIA inventory cycle lengths. For each time step and RPA scenario-climate future, 100 realizations of the FIA inventory are produced. Each projected inventory is summarized based on standard FIA protocols described in Burrill et al. 2018. For the Forest Resources Chapter, projected forest parameters by time step/decade are given either: (1) as the average across the 100 realizations within each RPA scenario-climate future (four scenarios x five climate projections), or (2) as the average across the 500 realizations (five climate projections x 100 realizations) within each RPA scenario.

Forest Land and Timberland Area

The amount and quality of services provided by U.S. forests are directly related to the total amount of forest land, in addition to forest conditions, forest fragmentation, forest ownership, and forest parcelization. The U.S. forest land base is defined differently depending on the specific services being examined (Nelson et al. 2020). For example, the areal extent of timberland is typically used when quantifying timber and removal volumes, while the forest carbon land base is used to quantify C stocks and stock changes. The projected changes in forest, timberland, and forest C land bases are driven by the RPA county land use change model, which reflects both net and gross land use change to private lands across the conterminous United States (see the Land Resources Chapter). The results presented in the Land Resources Chapter identify the projected amount of non-Federal forest land use change under the RPA scenario-climate futures (see the sidebar RPA Scenarios for a description of the RPA scenarios and naming conventions used throughout the chapter). The projections presented in this chapter account for the public and private forest land base, but land use changes are only projected for private land (see the Land Resources Chapter). The total forest area across the conterminous United States was 634 million acres in 2020, but it is projected to decrease across all RPA scenario-climate futures (see the Land Resources Chapter, table 4-9) to between 619 million acres (15 million acre loss under the HH-least warm RPA scenario-climate future) and 627 million acres (7.6 million acre loss, HL-hot). Forest area projections are more sensitive to RPA scenarios than to specific climate projections, and the South and Pacific Coast Regions are projected to lose the largest amounts of forest area. The Land Resources Chapter gives a full discussion of gross and net land use change for forests, in addition to the other primary land uses.

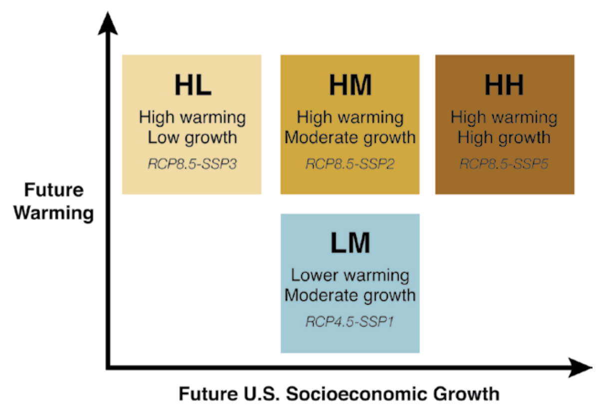
In 2020, 78.5 percent (498 million acres) of the forest land area in the conterminous United States was timberland, and timberland area futures follow the same trends as forest land use futures to a large degree. However, because timberland is partially defined by growth potential, timberland area can decrease due to productivity changes in addition to changes in land use.

RPA Scenarios

The RPA Assessment uses a set of scenarios of coordinated future climate, population, and socioeconomic change to project resource availability and condition over the next 50 years. These scenarios provide a framework for objectively evaluating a plausible range of future resource outcomes.

The 2020 RPA Assessment draws from the global scenarios developed by the Intergovernmental Panel on Climate Change to examine the 2020 to 2070 time period (IPCC 2014). The RPA scenarios pair two alternative climate futures (Representative Concentration Pathways, or RCPs) with four alternative socioeconomic futures (Shared Socioeconomic Pathways, or SSPs) in the following combinations: RCP 4.5 and SSP1 (lower warming-moderate U.S. growth, LM), RCP 8.5 and SSP3 (high warming-low U.S. growth, HL), RCP 8.5 and SSP2 (high warming-moderate U.S. growth, HM), and RCP 8.5 and SSP5 (high warming-high U.S. growth, HH) (figure 6-16). The four 2020 RPA Assessment scenarios encompass the projected range of climate change from the RCPs and projected quantitative and qualitative range of socioeconomic change from the SSPs, resulting in four distinct futures that vary across a multitude of characteristics (figure 6-17), and providing a unifying framework that organizes the

Figure 6-16. Characterization of the 2020 RPA Assessment scenarios in terms of future changes in atmospheric warming and U.S. socioeconomic growth. These characteristics are associated with the four underlying Representative Concentration Pathway (RCP) – Shared Socioeconomic Pathway (SSP) combinations.



Source: Langner et al. 2020.

Figure 6-17. Characteristics differentiating the 2020 RPA Assessment scenarios. These characteristics are associated with the four underlying Representative Concentration Pathway (RCP) – Shared Socioeconomic Pathway (SSP) combinations.

RPA Scenario (RCP-SSP)	Global Temperature Rise	U.S. Population Growth	U.S Economic Growth Rate	Bioenergy Demand	Energy Sector Focus	Global Energy Usage	International Trade Openness
LM Lower warming Moderate growth RCP4.5-SSP1	Lower	Medium	Medium-High	High	Renewables	Low	Medium
HL High warming Low growth RCP8.5-SSP3	High	Low	Low	Low	Fossil fuels	Medium	Low
HM High warming Moderate growth RCP8.5-SSP2	High	Medium	Medium	Medium	Mixed	Medium	Medium
HH High warming High growth RCP8.5-SSP5	High	High	High	High	Fossil fuels	High	High

RPA Assessment natural resource sector analyses around a consistent set of possible world views. The Scenarios Chapter describes how these climate models were selected and paired; more details are provided in Langner et al. (2020).

The 2020 RPA Assessment pairs these four RPA scenarios with five different climate models that capture the wide range of projected future temperature and precipitation across the conterminous United States. An ensemble climate projection that averages across the multiple model projections is not used because of the importance of preserving individual model variability for resource modeling efforts. The five climate models selected by RPA represent least warm, hot, dry, wet, and middle-of-the-road climate futures for the conterminous United States (table 6-1); however, characteristics can vary at finer spatial scales. Although the same models were selected to develop climate projections for both RCPs, there are distinct climate projections for each model associated with RCP 4.5 and RCP 8.5. The Scenarios Chapter describes how these climate models were selected. Joyce and Coulson (2020) give a more extensive explanation.

Throughout the RPA Assessment, individual scenario-climate futures are referred to by pairing RPA scenarios with selected climate projections. For example, an analysis run under "HL-wet" assumes a future with high atmospheric warming and low U.S. population and economic growth (HL RPA scenario), as well as a wetter climate for the conterminous United States (wet climate projection).

Table 6-1. Five climate model projections selected to reflect the range of the full set of 20 available climate models in the year 2070. Each model was run under RCP 4.5 and RCP 8.5, providing a range of different U.S. climate projections.

	Least warm	Hot	Dry	Wet	Middle
Climate model	MRI-CGCM3	HadGEM2-ES	IPSL-CM5A-MR	CNRM-CM5	NorESM1-M
Institution	Meteorological Research Institute, Japan	Met Office Hadley Centre, United Kingdom	Institut Pierre Simon Laplace, France	National Centre of Meteorological Research, France	Norwegian Climate Center, Norway

RCP = Representative Concentration Pathway.

Source: Joyce and Coulson 2020.

Timberland area is projected to decrease between 8.4 million acres (HL-hot) and 15.1 million acres (HH-least warm) between 2020 and 2070 (table 6-2). Timberland futures are strongly driven by land use choices under the different RPA scenarios. Although timberland futures are most sensitive to RPA scenario, there are climate projections for which the amount of timberland loss exceeds the overall loss of forest land. For example, the hot climate projection consistently leads to more timberland loss than forest land loss. This suggests that under the hot climate projection, some less-productive timberland will transition to other forest land over the projection period.

Table 6-2. Projected net change in timberland area and percent change from 2020 to 2070. The extent of timberland in 2020 was 498 million acres. Change and percent change are based on averaging projection results for each RPA scenario-climate future.

	Climate projection				
Scenario	Least warm	Hot	Dry	Wet	Middle
	million acres (percent)				
LM	-13.2 (-2.7)	-12.3 (-2.5)	-12.2 (-2.5)	-12.8 (-2.6)	-12.9 (-2.6)
HL	-11.8 (-2.4)	-8.4 (-1.7)	-11.2 (-2.2)	-11.4 (-2.3)	-11.5 (-2.3)
HM	-12.9 (-2.6)	-9.4 (-1.9)	-12.1 (-2.4)	-12.3 (-2.5)	-12.5 (-2.5)
HH	-15.1 (-3)	-11.3 (-2.3)	-14.3 (-2.9)	-14.6 (-2.9)	-14.6 (-2.9)

LM = lower warming-moderate U.S. growth; HL = high warming-low U.S. growth; HM = high warming-moderate U.S. growth; HH = high warming-high U.S. growth.

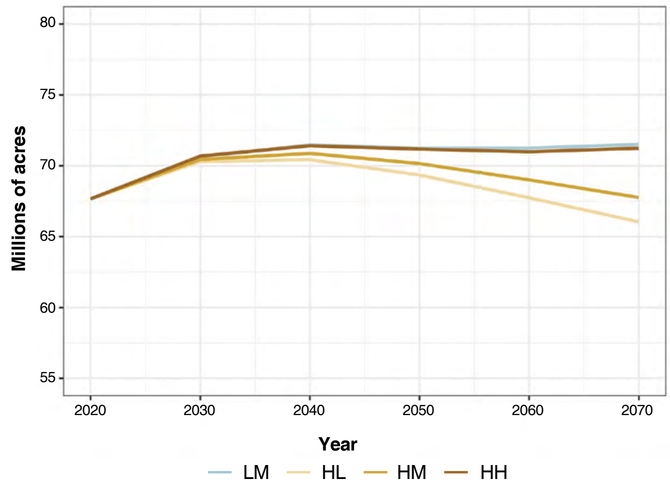
Timberland area projections differ by RPA region (figure 6-18). Most timberland loss is expected in the South, where between 5.7 (HL-hot) and 10.1 (HH-least warm) million acres are expected to be lost primarily to developed uses by 2070. The Pacific Coast Region is expected to lose between 1.6 and 2.5 million acres of timberland under HL-hot and HH-least warm, respectively. The projected range of timberland loss in the North Region is 0.9 (HL-hot) to 2.2 million acres (HH-wet). Timberland area in the Rocky Mountain Region is the most stable over the projection period, losing between 0.25 million acres (HL-hot) and 0.4 million acres (HH-dry). As with forest area, economic and population change is the primary driver differentiating future timberland area, with the largest loss of timberland projected under the high-growth HH RPA scenario, followed by the moderate-growth LM and HM scenarios, and then the low-growth HL RPA scenario (figure 6-18).

Forest Planting

While forest planting is a management tool used for forest restoration and to enhance or create wildlife habitat, a large majority of the Nation's planted forest is a timberland investment to produce roundwood for forest products. The decision to plant or replant after harvesting therefore depends on timber prices and expectations of those prices over time. Because projections of future planted forest area depend on timber prices, we review the roundwood price projections discussed in the Forest Products Chapter, which differ by RPA scenario and RPA region. Roundwood prices are expected to be lowest under the HL RPA scenario, where prices in 2070 are projected to be only slightly above 2015 prices. The LM and HM scenarios have similar price trajectories, where prices increase at a moderate rate from 2020 to 2070. The HH scenario has the largest price increase, where roundwood prices are expected to increase by 1.4 times for softwood and 2 times for hardwood from 2015 values. The different price paths for each RPA scenario lead to different forest planting and replanting rates over time.

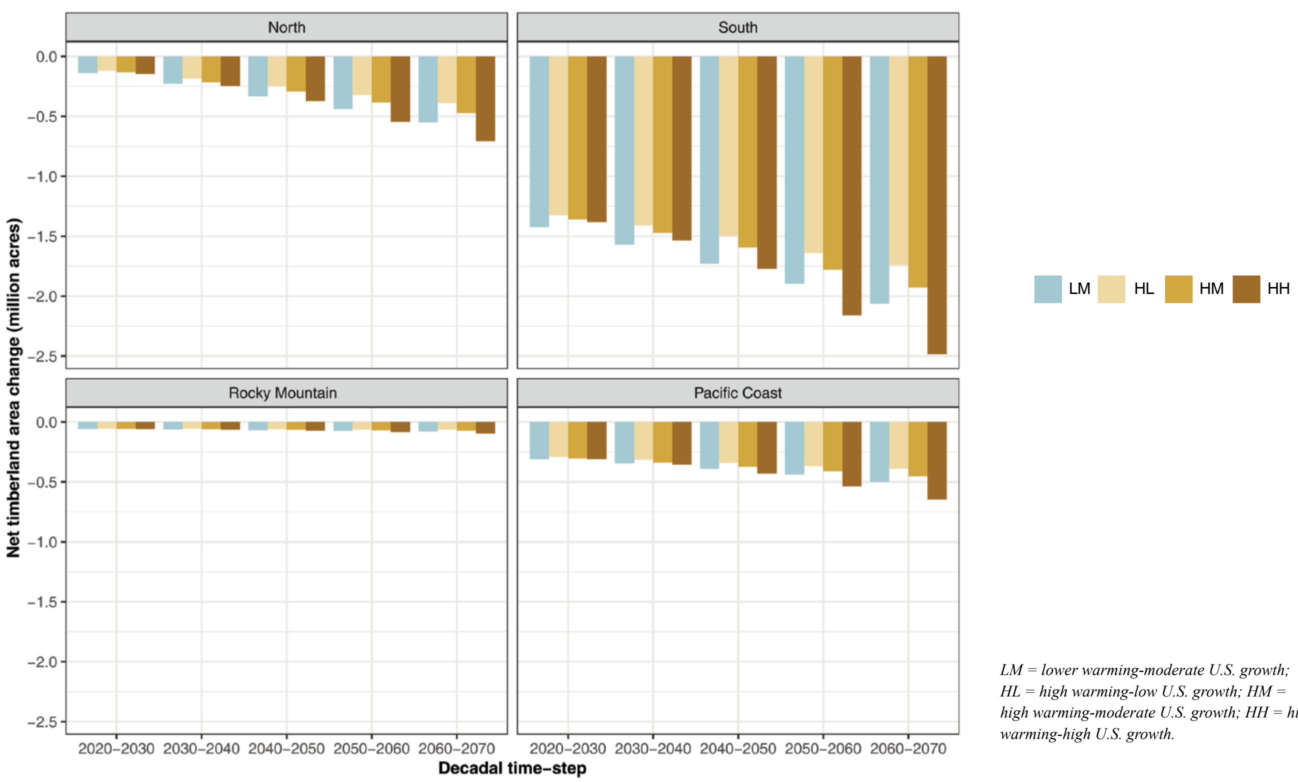
Under all RPA scenarios, planted forest area is projected to increase between 4 percent (HL) and 6 percent (LM) until 2040 (figure 6-19). From 2040 to 2070, planted area

Figure 6-19. Planted forest area in 2020 and projected to 2070 for the conterminous United States by RPA scenario. Projected planted area is based on averaging decadal projection results across climate projections within each RPA scenario.



LM = lower warming-moderate U.S. growth; HL = high warming-low U.S. growth; HM = high warming-moderate U.S. growth; HH = high warming-high U.S. growth.

Figure 6-18. Timberland area change per decade, starting from 2020 and projected out to 2070, by RPA region and RPA scenario. Projected timberland area is based on averaging decadal projection results across climate projections within each RPA scenario and RPA region.



LM = lower warming-moderate U.S. growth; HL = high warming-low U.S. growth; HM = high warming-moderate U.S. growth; HH = high warming-high U.S. growth.

is expected to decrease under the HL and HM scenarios and remain relatively constant under the LM and HH scenarios. The HL scenario leads to a projected loss of 1.7 million acres of planted forest between 2020 and 2070. The HM scenario projections suggest that the area of forest plantations in 2070 will be similar to the 2020 extent (67.7 million acres), while the LM and HH projections suggest an increase of 3.75 million acres and 3.5 million acres between 2020 and 2070, respectively. As discussed in the Forest Products Chapter, although the LM scenario has a medium economic growth view of the future, there is also greater demand for bioenergy; this leads to similar price trajectories for LM and HH. The LM scenario, however, has less land use change pressure than the HH scenario, which leads to slightly more investment in planted forests under LM. The higher timber prices under both LM and HH lead to sustained planting over the projection period as forest land uses are more competitive against other land use choices.

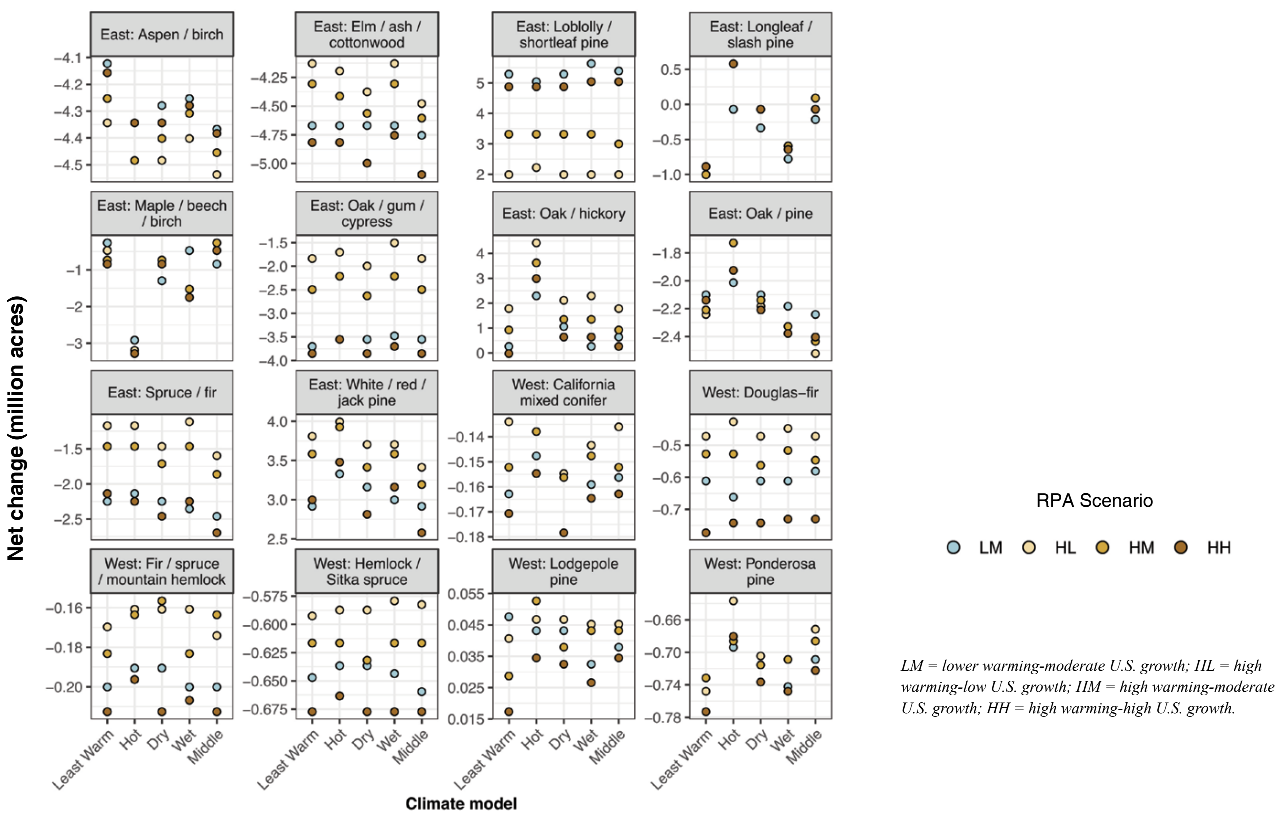
The national planted area projection trends are primarily driven by planting and replanting in the South Region, which contained 71 percent of planted forest in 2020. Planted area trends in the South therefore mirror the national trends. In the North and Rocky Mountain Regions, planted forest area is expected to decrease over the projection period, as opposed to the Pacific Coast Region where the planted forest area is expected to increase.

The loblolly/shortleaf, Douglas-fir, and white/red/jack pine forest type groups are important to softwood roundwood supply and therefore worth individual examination. Over the projection period, the proportion of the Douglas-fir group that is planted is projected to increase, while the planted proportion of the white/red/jack pine group is expected to decrease despite rising roundwood prices. The planted proportion of the loblolly/shortleaf group is projected to increase under the HH and LM scenarios but decrease under the HM and HL scenarios.

Timberland Area by Forest Type Group

Future extents of forest type groups are impacted by land use change, forest management, forest succession, and climate. We present projections of future timberland area by forest type group to be consistent with historic data presented in the section Historical Trends – Timberland Area by Forest Type Group. In general, the major FTGs in the western RPA regions are projected to change less in area between 2020 and 2070 than the major FTGs in the eastern RPA regions, which in some cases exceed 4 million acres of projected change (figure 6-20). Of the

Figure 6-20. Projected net change in timberland area from 2020 to 2070 for the forest type groups with the largest areal extent in 2020 by RPA scenario-climate future. Ten of the forest type groups primarily occur in the Eastern United States and six primarily occur in the Western United States. Net change is based on averaging projection results for each RPA scenario-climate future by forest type group.

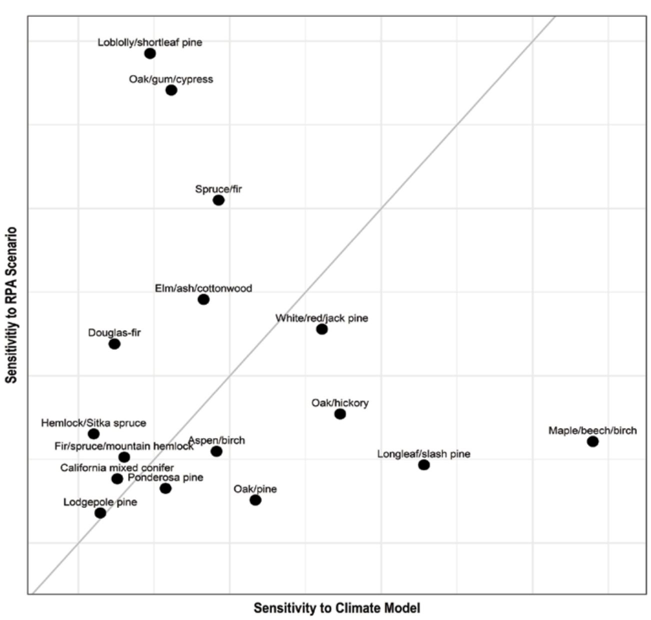


LM = lower warming-moderate U.S. growth; HL = high warming-low U.S. growth; HM = high warming-moderate U.S. growth; HH = high warming-high U.S. growth.

16 major forest type groups based on 2020 areal extent, only the loblolly/shortleaf, oak/hickory, and white/red/jack pine groups are projected to increase in area.

Many FTGs are expected to shift over time as part of normal successionary trends. However, both climatic and socioeconomic futures can alter or influence changes in the areal extent of each FTG over time. Here we examine the sensitivity of projected futures in FTG extent to the choice of RPA scenario versus the choice of climate projection, accounting for differing underlying successionary trends. In general, the sensitivity of changes in timberland area to RPA scenario and climate projection depends on the FTG (figure 6-21), with commercially important FTGs such as loblolly/shortleaf and Douglas-fir being more sensitive to RPA scenario, while others, such as longleaf/slash pine and maple/beech/birch, are more sensitive to climate projection. Sensitivity to RPA scenario and/or climate projection can lead to increases or decreases in timberland area: while the loblolly/shortleaf pine and oak/gum/cypress groups are both highly sensitive to RPA scenario, the high-economic-growth HH scenario leads to increased timberland area for loblolly/shortleaf pine but decreased timberland area for oak/gum/cypress. Similarly, the hot climate projection leads to less timberland area for the maple/beech/birch group but more timberland area for the longleaf/slash pine group. In general, economic growth reflected in the RPA scenarios promotes increases (or at least mitigates decreases) to timberland area for commercially important FTGs, while changes in climate reflected in the climate projections result in range shifts that vary across FTGs.

Figure 6-21. Sensitivity of timberland area projections to climate projection and RPA scenario for selected forest type groups. Sensitivity is calculated as a measure of separability between projections among different climate projections and RPA scenarios.



Timberland Volume

The future inventory in terms of volume is influenced by shifts in productivity, land use choices, management actions and objectives, and markets. Timberland growing stock volume is projected to increase until 2050 (figure 6-22). After 2050, growing stock volumes become more sensitive to RPA scenario, because they are influenced more by changes in land use and roundwood demand than by climate. For example, in 2070, the maximum volume difference among climate projections within a scenario is approximately 10.6 billion cubic feet, while the maximum difference among RPA scenarios (averaged across climate projections) is approximately 41.3 billion cubic feet. This suggests the choice of RPA scenario is about 3.9 times more influential than the choice of climate projection when projecting to the end of the period. Under the HL and HM RPA scenarios, which have less land use change and less harvest, growing stock volume is projected to increase to between 1,198 billion cubic feet (HM-middle) and 1,244 billion cubic feet (HL-least warm) in 2070. Under the HH and LM scenarios (more land use change and harvest), volume is expected to increase until mid-century, then decrease to between 1,136 billion cubic feet (HH-dry) and 1,161 billion cubic feet (LM-wet).

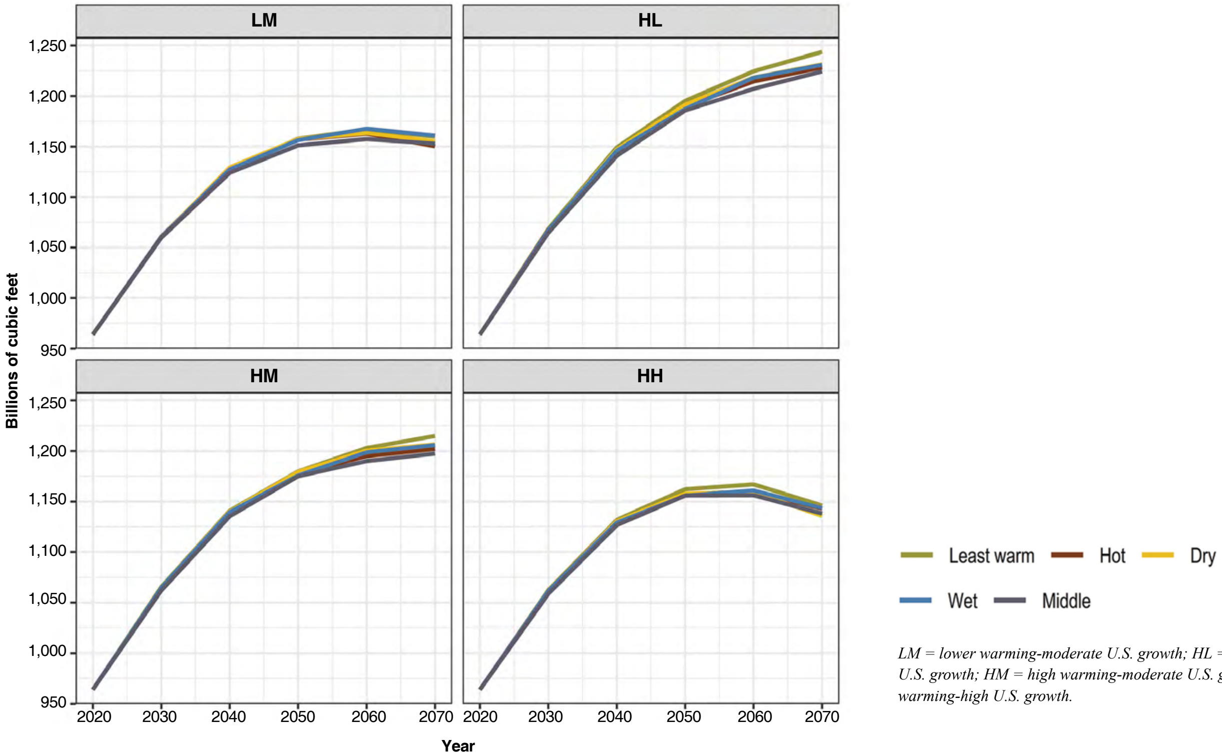
There are distinct regional patterns with respect to growing stock volume futures (figure 6-23). In the North, both hardwood and softwood growing stock inventories are projected to increase across RPA scenarios throughout the projection period. Hardwood inventory is more sensitive to demand because the North is projected to remain an important hardwood roundwood producer. Lower roundwood-demand RPA scenarios (HL, HM) lead to futures with more hardwood growing stock volume.

Growing stock volume in the South is more sensitive to RPA scenario than the other regions of the country. Projected softwood growing stock volume increases across RPA scenarios until 2050 and then declines, with the largest declines associated with the LM and HH scenarios. Projected hardwood growing stock volume increases across RPA scenarios until 2050 and continues to increase under HL and HM.

The Rocky Mountain Region is a softwood-dominated region, where future growing stock softwood volume is expected to decrease across RPA scenarios while hardwood volume is expected to remain relatively stable. The Rocky Mountain Region is rather insensitive to RPA scenario, in large part because roundwood demand in the region is significantly smaller than in the other regions.

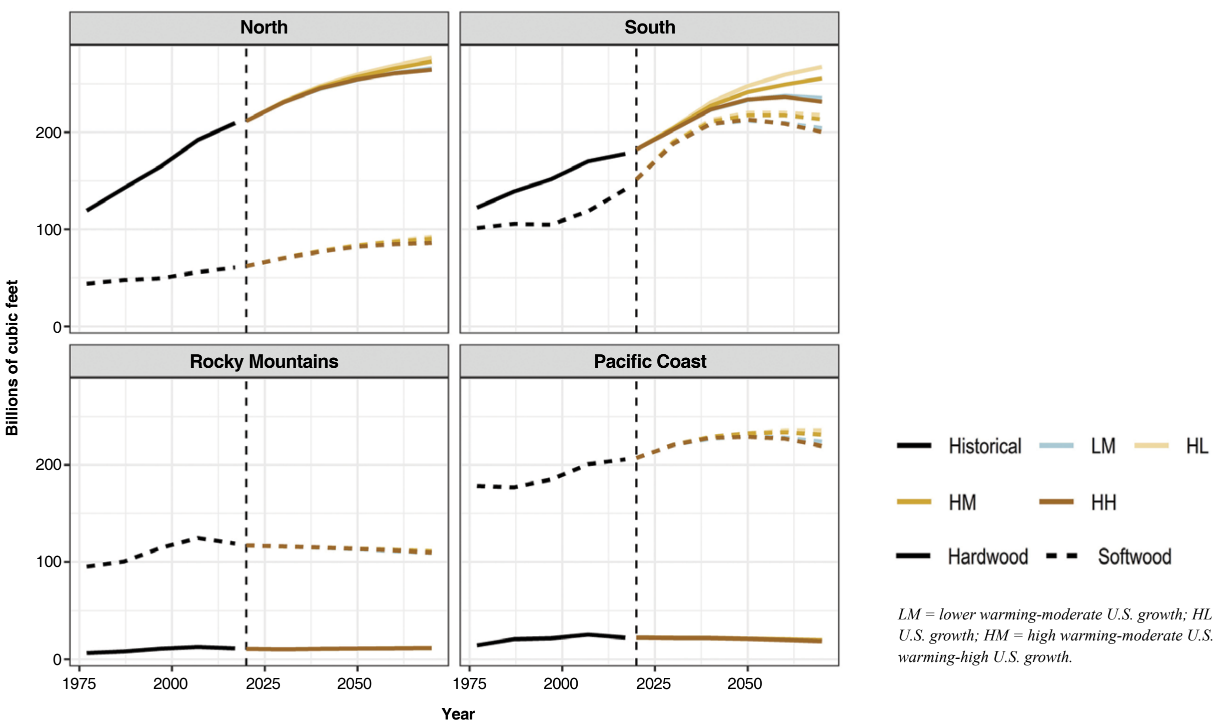
The Pacific Coast is also a softwood-dominated region, and softwood growing stock volume is projected to increase

Figure 6-22. Growing stock volume on timberland in 2020 and projected to 2070 for the conterminous United States by RPA scenario-climate future. Projected growing stock volume on timberland is based on averaging decadal projection results by RPA scenario-climate future.



LM = lower warming-moderate U.S. growth; HL = high warming-low U.S. growth; HM = high warming-moderate U.S. growth; HH = high warming-high U.S. growth.

Figure 6-23. Historical and projected growing stock volume for hardwood/softwood by RPA scenario and RPA region. Projected growing stock volume is based on averaging decadal projection results across climate projections within each RPA scenario, RPA region, and species group.



LM = lower warming-moderate U.S. growth; HL = high warming-low U.S. growth; HM = high warming-moderate U.S. growth; HH = high warming-high U.S. growth.

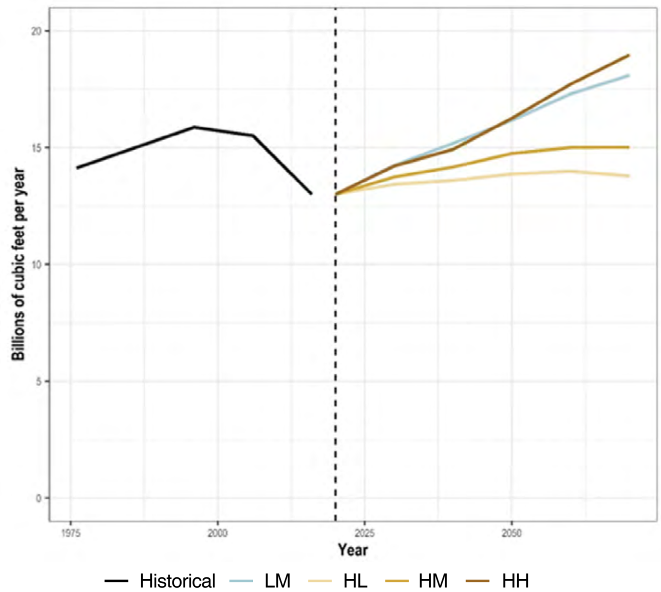
through 2050 across RPA scenarios, while hardwood growing stock volume is projected to decline slightly throughout the projection period. Similar to the South, post-2050 softwood growing stock futures depend on roundwood demand, where softwood growing stock volume are projected to decrease post-2050 under the LM and HH scenarios.

Removals

Projections of growing stock removals on timberland are strongly driven by the underlying market demand for roundwood associated with the RPA scenarios, where the high-growth HH RPA scenario in 2070 suggests substantially more growing stock removals (19 billion cubic feet per year) on timberland than the low-growth HL scenario (13.8 billion cubic feet per year; figure 6-24). Both the HH and LM scenarios suggest a recovery to pre-recession (2006 to 2007) levels by 2050 but the HL and HM scenarios do not recover to pre-recession levels. While both the LM and HM scenarios assume moderate growth, the LM scenario suggests a commitment toward sustainability and use of bioenergy, which increases forest removals over the HM scenario.

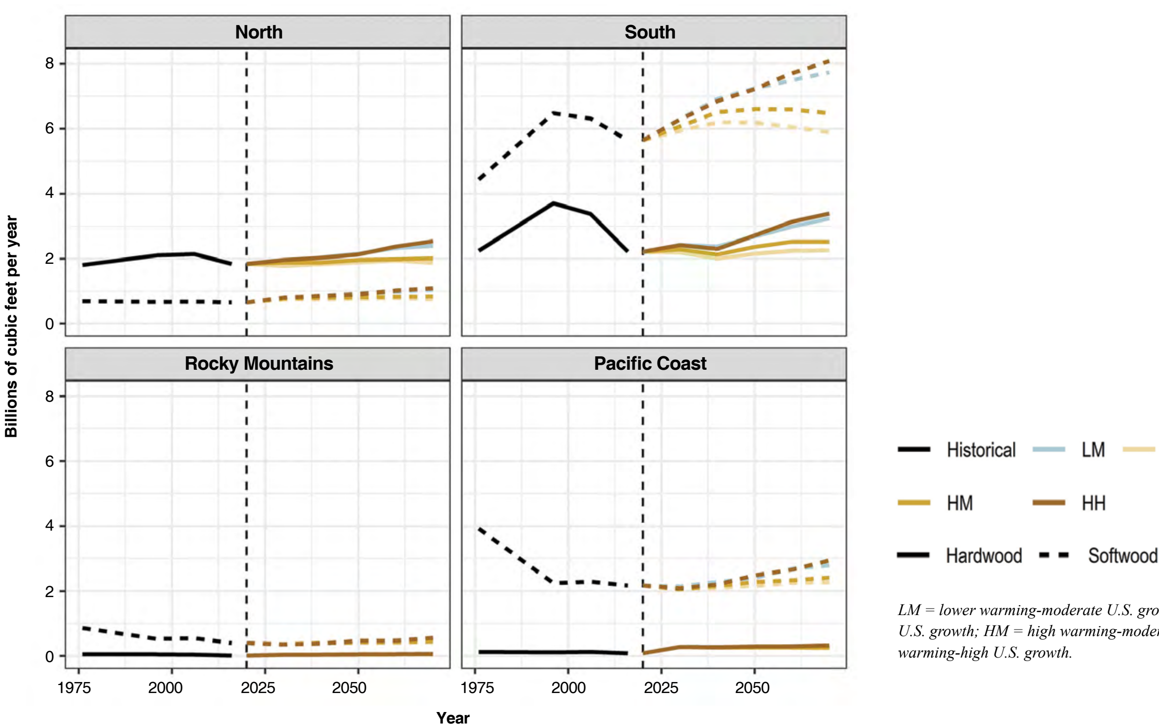
Hardwood and softwood removals are generally projected to recover from the lows that occurred in the 2000s in each region, but the North and South Regions are expected to show substantial increases in all removals by 2070 relative to 2020 removals (figure 6-25). These increases roughly mirror

Figure 6-24. Historical and projected annual removal volume on timberland across the conterminous United States, by RPA scenario. Projected annual removal volume is based on averaging decadal projection results across climate projections within each RPA scenario.



LM = lower warming-moderate U.S. growth; HL = high warming-low U.S. growth; HM = high warming-moderate U.S. growth; HH = high warming-high U.S. growth.

Figure 6-25. Historical and projected removal volume on timberland for hardwood/softwood by RPA scenario and RPA region. Projected removal volume is based on averaging decadal projection results across climate projections within each RPA scenario, RPA region, and species group.



LM = lower warming-moderate U.S. growth; HL = high warming-low U.S. growth; HM = high warming-moderate U.S. growth; HH = high warming-high U.S. growth.

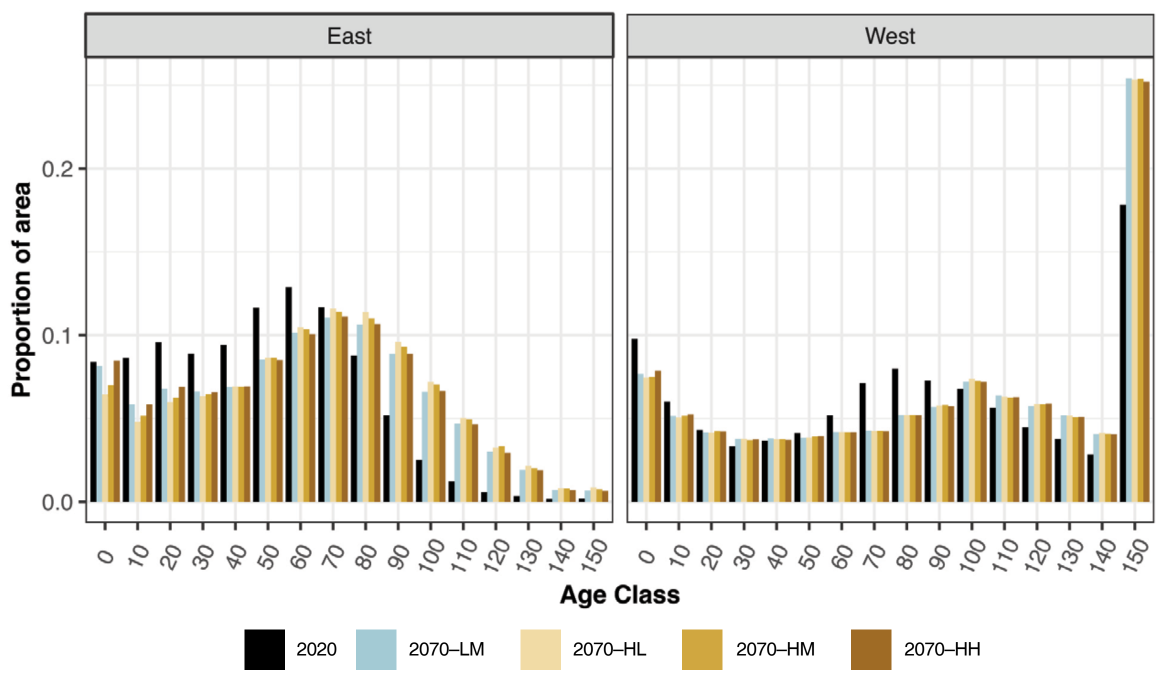
projected wood prices (see the Forest Products Chapter). As with trends across the conterminous United States, RPA scenario impacts the rate of this recovery, and in some cases, whether removals are expected to return to pre-2000s levels (e.g., softwoods in the Rocky Mountain and Pacific Coast Regions and hardwoods in the South Region). In the North, projections of hardwood removals vary from 1.88 billion cubic feet per year by 2070 under the HL scenario (5.0 percent above 2020 levels) to 2.54 billion cubic feet per year under the HH scenario (41.9 percent above 2020 levels), as driven by the economic growth assumptions inherent in these RPA scenarios and to a lesser extent by land use choices. Similarly, softwood removals in the South are projected to vary from 5.89 billion cubic feet per year in 2070 under the HL scenario (4.1 percent more than 2020 levels) to 8.08 billion cubic feet per year under the HH scenario (42.8 percent more than 2020 levels). In the Pacific Coast and Rocky Mountain Regions, softwood removals may return to 2006 levels, but no projection results in pre-2000s removal levels.

Forest Aging and Structure

Forests will age over the projection period; however, the impacts of forest management, disturbance, and forest succession can lead to a significant departure from linear aging. Under linear aging, all forest land would age 50 years over the 50-year projection period, but forest management, disturbance, and succession generally reduce the age of forests. In addition, the RPA scenarios have different assumptions with respect to forest investment, which leads to slightly different futures with respect to forest age distribution. Forest age distribution is important because it is correlated with forest structural components.

Across RPA scenarios, the average age of forest increases by 14 years in the East and 10 years in the West over the projection period. In the East, all projections suggest an increase in proportion of forest 80+ years old and a decrease in the proportion of forest less than 80 years old by 2070. However, the amount of forest management driven by timber prices associated with the LM and HH scenarios leads to less 80+ year old forest by 2070 than the other scenarios (figure 6-26), as well as young forests (0 to 9 years old) having a similar areal extent to the forests of 2020. In the West, the proportion of forest 100+ years old is projected to increase, with relatively large increases in the 150+ year age class. The projections also suggest an increase in 30- to 40-year-old forest as a result of forest management and disturbance. Like the East, projections for the 0- to 9-year age class are slightly higher under the LM and HH scenarios.

Figure 6-26. Forest age distribution in 2020 and projected forest age distribution in 2070 by RPA scenario for the Eastern and Western conterminous United States. The projected age distribution is based on averaging the 2070 projection results across climate projections within each RPA scenario for the Eastern and Western United States.



Note: 150-year age class represents age classes 150-years and older.

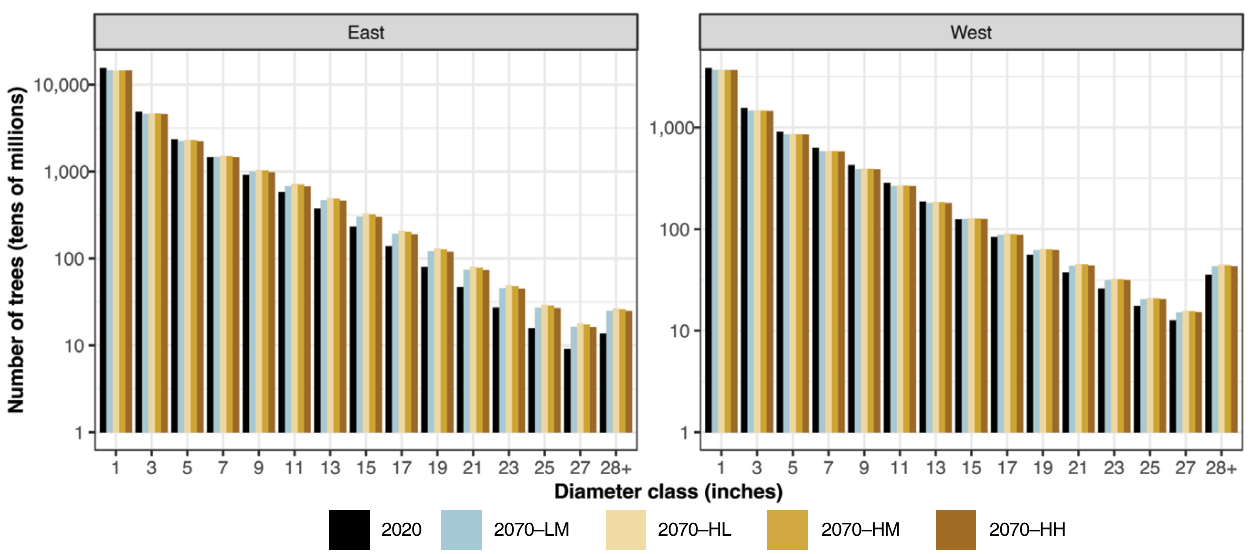
LM = lower warming-moderate U.S. growth; HL = high warming-low U.S. growth; HM = high warming-moderate U.S. growth; HH = high warming-high U.S. growth.

The combination of forest aging, forest disturbances, forest management, and land use change affects forest structure. One way to investigate shifts in forest structure is to examine how the number of trees by diameter class and tree volume by diameter class change over time. As forests age, the number of smaller trees typically decrease while the number of larger trees increase (Davis and Johnson 1987). Simultaneously, volume in the larger tree size classes increases. Projections in the East suggest a decrease in the number of saplings (small trees less than 5 inches in diameter) and the number of trees in the 5-inch diameter class (figure 6-27). In the West, this trend continues through the 13-inch diameter class. Increases in the number of trees (occurring for the 7+ inch classes in the East and the 15+ inch classes in the West) differed slightly by RPA scenario, where larger increases were generally projected for lower roundwood demand scenarios (HL and HM).

A decrease in the number of smaller diameter trees can occur for several reasons, including less afforestation (gross land use gains), less forest management, and less regeneration. Based on Domke et al. (2021), about 2.5 million acres of nonforest land transitioned to a forest land use in 2019, whereas land use change projections (see the Land Resources Chapter) suggest that on average from 2020 to 2070 about 0.5 million acres per year of land may be converted to a forest use. The projected decrease in afforestation does influence the number of small-diameter trees. Using forest removals as a proxy to indicate forest management, forest management is projected to remain relatively stable (HL) or increase (LM, HM, HH) from 2020 levels; however, forest management is more intensive in commercially important forest types that are commonly planted such as loblolly pine, Douglas-fir, and ponderosa pine. For example, projections suggest an increase in the number of trees across diameter classes for the loblolly/shortleaf pine group, with the largest increases seen for the 1- and 3-inch diameter classes under the high roundwood demand RPA scenarios (LM and HH). The Douglas-fir and ponderosa pine groups had similar projected trends for small-diameter trees. Other forest types that predominantly rely on natural regeneration showed a different pattern. The oak/hickory, oak/gum/cypress, and California mixed conifer groups are projected to decrease with respect to small-diameter trees. Oak regeneration has been an area of active research for decades due to the lack of both regeneration and advanced regeneration (Iverson et al. 2017), and the fact that California mixed-conifer regeneration is affected by fire suppression, harvesting, and other forest management activities (Welch et al. 2016). Projections for these forest type groups suggest continued decreases in the number of saplings in the 1- and 3-inch diameter classes across RPA scenarios.

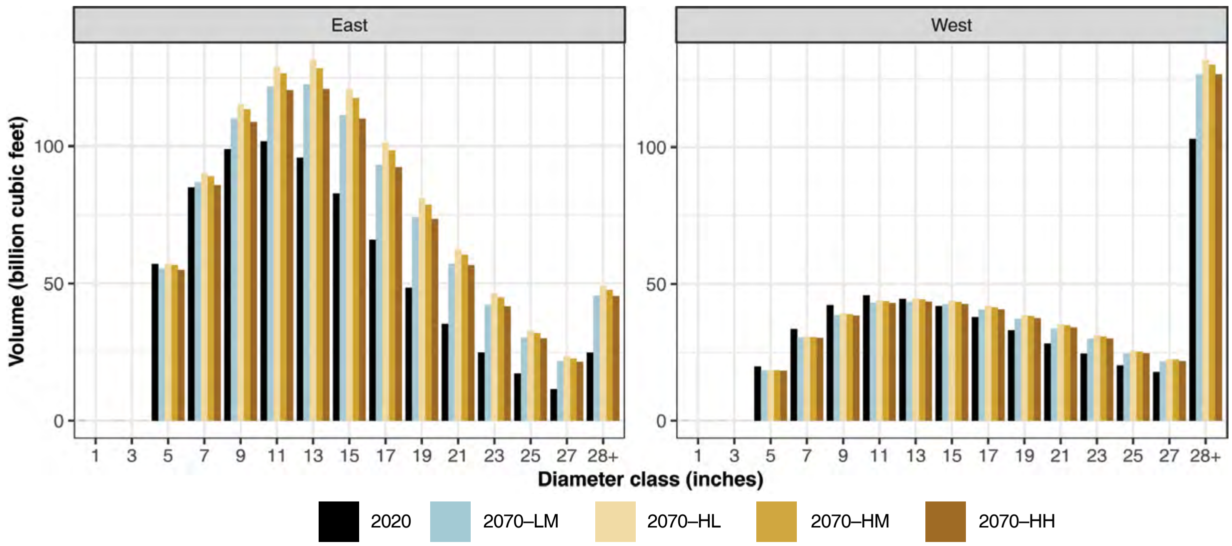
While the projected shifts in the number of trees by diameter class may appear subtle, these shifts have a large effect on the volume distribution by diameter class, particularly for diameter classes larger than 5 inches in the East and larger than 13 inches in the West (figure 6-28). The increase in the number of trees in larger diameter classes leads to an outward shift in the volume by diameter class distribution. In the East, large increases in volume are projected in 13+-inch diameter classes as compared to the West, where large

Figure 6-27. Forest tree distribution by diameter class in 2020 and projected forest tree distribution in 2070 by RPA scenario for the Eastern and Western conterminous United States. The projected tree distribution by diameter class is based on averaging the 2070 projection results across climate projections within each RPA scenario for the Eastern and Western United States.



LM = lower warming-moderate U.S. growth; HL = high warming-low U.S. growth; HM = high warming-moderate U.S. growth; HH = high warming-high U.S. growth.

Figure 6-28. Forest volume distribution by diameter class in 2020 and projected forest volume distribution in 2070 by RPA scenario for the Eastern and Western conterminous United States. The projected volume distribution by diameter class is based on averaging the 2070 projection results across climate projections within each RPA scenario for the Eastern and Western United States.



LM = lower warming-moderate U.S. growth; HL = high warming-low U.S. growth; HM = high warming-moderate U.S. growth; HH = high warming-high U.S. growth.

volume increases are projected for the 17+-inch diameter classes. The higher roundwood-demand RPA scenarios (LM and HH) are projected to have less volume in the larger-diameter classes because of increased harvest rates.

Forest Sector Carbon

The forests of the United States provide a suite of ecosystem services, including the storage and sequestration of carbon (C). Forest sector C includes C stored in forested ecosystems, C stored in new forest areas, and C stored in long-lived forest products. Within forests, C flows in from the atmosphere through photosynthesis and is stored in living trees, seedlings, and saplings. While forests are sequestering C, they are also emitting C through respiration, as well as cycling C through non-live pools such as dead wood, the litter layer, and soils. The amount of C stored in forests and the annual rate at which they sequester carbon are functions of biological processes (e.g., forest growth, aging), edaphic factors (e.g., site quality), human-mediated and natural disturbances (e.g., harvesting, wildfire), land use change (e.g., lands converted to forest, forest converted to other lands), and interactions among these drivers. Forests in the United States have historically offset a portion of C emissions from other sectors.

The United States, as a signatory of the United Nations Framework Convention on Climate Change, follows Intergovernmental Panel on Climate Change (IPCC) guidelines for C accounting (IPCC 2006). With respect to forests, there are three primary land use categories that are relevant to forest C accounting: forest remaining forest, lands converted to forest, and forest converted to other land (see the sidebar Definitions). The forest remaining forest land base is of particular interest, as carbon dynamics on that land represent interaction with the atmosphere. The lands converted to forest and forest converted to other land uses represent land use transfers of C, as well as sequestration and emissions. Under the IPCC guidelines, standard forest C pools used for reporting include C in aboveground biomass, belowground biomass, dead wood, litter, and soil.

There are two other pools of C relevant to forestry: harvested wood products (HWP) and HWP stored in solid waste disposal sites (SWDS). Harvested trees used for products are not a complete emission of C to the atmosphere, even though they are removed from forests, because a portion of the harvested roundwood is stored in long-lived wood products. For example, a portion of the softwood harvest in the United States is used to produce dimensional lumber (e.g., 2 x 4s): the sawtimber portion of the tree is used for dimensional lumber, while other portions of the tree are used for other products (e.g., the top may be chipped for pulp and residues from the sawing process may be used to generate electricity), and the unused portion of the tree remains onsite as logging residue. Wall et al. (2018) suggest that about 13 percent of a tree's volume is left as logging residue to decompose and emit C into the atmosphere. The C in long-lived wood products, however, remains stored while the products are in use. At the end of use, the products and the C they contain are discarded and moved to SWDS (Skog 2008).

Carbon remains an active topic in both science and policy as regional, national, and global emission reduction targets are identified. Forest sequestration of C in the United States is critical because it offsets approximately 11 percent of emissions from other sectors (Domke et al. 2021). Several policies are either in place or being considered to increase the sequestration rate of forests through natural climate solutions; these policies enable forests to offset a larger share of C emissions as emissions are reduced in other sectors. Griscom et al. (2017) examined the impacts of potential natural climate solutions—including reforestation, avoided forest conversion, natural forest management, improved plantations, avoided woodfuel, and fire management—to increase forest C sequestration, finding that reforestation and avoided forest conversion showed the greatest potential. Others have examined more specific forest management activities and options to increase forest C sequestration; for example, Fargoine et al. (2018) found that extending rotation lengths would increase forest C sequestration. While natural climate solutions offer approaches to increase the forest C sink strength, future climate and socioeconomic shifts create uncertainty in the long-term effectiveness of the potential approaches (Zhu et al. 2018, Tian et al. 2018). The first section presents historic forest C trends in the United States, while the Forest Sector Carbon Projections section describes the range of C outcomes across RPA scenario-climate futures and examines their relative sensitivity to these futures while accounting for the ecological processes that govern the forests of the United States.

Our presentation of historical trends and projections is based on the conterminous United States. We restrict our presentation to only those C pools described above and only consider soil C in mineral soils. Although not included here, the USDA Forest Service does provide contemporary estimates for Alaska, and for additional pools such as organic soil C, C emission from drained organic soils, and information on non-CO_2 emissions as part of the national greenhouse gas inventory report (US EPA 2021) and in analysis by Domke et al. (2021). We present our findings in metric units to facilitate comparisons to the literature and international comparisons.

Historical Forest Sector Carbon Trends

- ❖ Forest carbon stocks consistently increased from 1990 to 2019.
- ❖ Growth in the aboveground biomass carbon pool accounted for more than 67 percent of the increase in carbon stocks.
- ❖ Carbon storage in harvested wood products and solid waste disposal sites accounted for 14 percent of forest sector stock change in 2019.

Forest Ecosystem Carbon

Total forest remaining forest C in the conterminous United States increased from 40.6 billion metric tons C (BMT C) in 1990 to 45.5 BMT C in 2020 (table 6-3), an increase of 12.6 percent over that period. This increase was primarily driven by net afforestation and forest growth, exceeding the effects of disturbances (including forest harvesting). The annual C stock change ranged from 173 million metric tons C per year (MMT C yr^{-1}) in 1990 to 155 MMT C yr^{-1} in 2019. The average hectare of forest remaining forest land sequestered 0.6 megagrams per hectare per year in 2019 (Mg ha^{-1} yr^{-1}) (Domke et al. 2021). Annual C stock change was between 0.3 percent and 0.4 percent of the C stock amount, which suggests

Table 6-3. Carbon stocks (BMT) and stock changes (MMT yr^{-1}) from 1990 to 2020 in the conterminous United States for forest ecosystem pools and harvested wood pools. Stock changes are provided in parentheses.

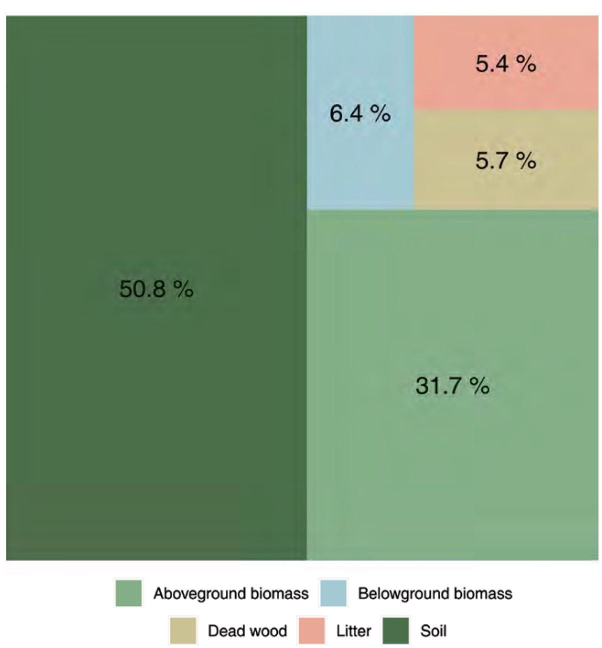
Carbon pool	1990	1995	2000	2010	2015	2019	2020
	Year						
	BMT C (MMT C yr^{-1})						
Forest ecosystem total	40.61 (173)	41.46 (168)	42.30 (164)	43.90 (161)	44.70 (166)	45.35 (155)	45.51 (--)
Aboveground biomass	11.08 (120)	11.67 (116)	12.25 (112)	13.35 (109)	13.89 (112)	14.33 (104)	14.43 (--)
Belowground biomass	2.23 (24)	2.35 (24)	2.47 (23)	2.69 (22)	2.80 (22)	2.89 (21)	2.91 (--)
Dead wood	1.78 (26)	1.91 (27)	2.05 (27)	2.32 (27)	2.45 (28)	2.56 (27)	2.59 (--)
Litter	2.42 (2)	2.43 (2)	2.44 (2)	2.46 (1)	2.46 (1)	2.47 (1)	2.47 (--)
Soil (mineral)	23.09 (0)	23.09 (0)	23.09 (0)	23.09 (1)	23.10 (2)	23.10 (2)	23.11 (--)
Land converted to forest	-- (27)	-- (27.1)	-- (27.1)	-- (27.2)	-- (27.2)	-- (27.3)	--
Harvested wood total	1.90 (34)	2.06 (31)	2.22 (26)	2.46 (19)	2.57 (24)	2.67 (30)	--
HWP	1.25 (15)	1.33 (14)	1.40 (9)	1.47 (2)	1.49 (7)	1.52 (11)	--
SWDS	0.65 (19)	0.74 (17)	0.82 (17)	0.99 (17)	1.08 (18)	1.15 (19)	--
Total	42.51 (234)	43.53 (226)	44.52 (217)	46.37 (206)	47.27 (216)	48.02 (213)	--

BMT = billion metric tons; C = carbon; HWP = harvested wood products; MMT = million metric tons; SWDS = solid waste disposal site; yr = year.

that relatively small changes over the entire forest remaining forest land base drive the stock change rates. Growth in the aboveground biomass pool accounted for 67 percent of the total C stock change in 1990 and 70 percent in 2019.

Carbon is distributed unevenly across pools. In 2020, for example, over 80 percent of C was stored in either aboveground biomass (31.7 percent) or soil pools (50.8 percent) (figure 6-29), with belowground biomass, dead wood, and litter combined making up the remaining 17.5 percent. The share of C that each pool contributes to the total has changed over time. For example, the aboveground biomass pool accounted for 27.3 percent of the total C for forests remaining forests in 1990, while it accounted for 31.7 percent in 2020. The belowground biomass, dead wood, and litter pools also showed an increase in their shares of the total between 1990 and 2020. The share of total C in the soil pool decreased from 56.9 percent in 1990 to 50.8 percent in 2020. The shifts in pool contributions to total forest ecosystem C were partially attributable to changes in land use, but they were even more strongly driven by biological forest growth. By examining stock densities—the size of a C pool per hectare of forest (Mg C ha^{-1})—we control for changes in the amount of forest land use and can examine changes due to forest growth. While soil is the largest C pool, it was also the most stable in terms of density, changing only slightly from 92.1 Mg C ha^{-1} to 92.2 Mg C ha^{-1} over the period 1990 to 2020. The density of C in aboveground and belowground biomass pools both increased by about 29 percent; however, the magnitude of the change was significantly larger for aboveground biomass, where the density increased from 44.2 Mg C ha^{-1} in 1990 to 57.6 Mg C ha^{-1} in 2020.

Figure 6-29. The share of total forest ecosystem carbon for each pool in 2020.



Other Land Converted to Forest Carbon

Changes in the forest land base have also influenced the amount of carbon stored and sequestered by forests (Woodall et al. 2015). Forests converted to other land uses and other lands converted to forests both constitute land use transfers. The total C stock on the forest land base in any given year is the C stock in forest remaining forest plus the C stock of other lands converted to forest. Since 1990, land use transfers of C have been relatively stable, where the C transferred from forest to other land uses ranged from 32 MMT C yr^{-1} to 34 MMT C yr^{-1} and the C gained by the forest land base from other land uses due to afforestation was about 27 MMT C yr^{-1} (table 6-3; Domke et al. 2021).

Harvested Wood Carbon and Total Carbon

Changes in C storage in HWP and SWDS accounted for approximately 16 percent of the total carbon stock change from 1990 to 2019. Carbon stocks in HWP and SWDS have continued to increase since 1990 despite episodic shifts in the demand for roundwood from the United States (table 6-3): the combined HWP and SWDS C stock grew from 1.9 BMT C in 1990 to 2.7 BMT C in 2019. Even with the shift away from newsprint since 1990, the HWP and SWDS pools continue to grow, albeit at considerably more variable rates than those for the forest ecosystem pools. The total stock change in forest remaining forest pools and harvested wood pools ranged from 206.7 MMT C yr^{-1} in 1990 to 184.6 MMT C yr^{-1} in 2019 (table 6-3). When including the C transferred from land-use change, the forest sector sequestered 212.9 MMT C yr^{-1} in 2019.

Forest Sector Carbon Projections

- ❖ Aboveground biomass carbon density is projected to increase by 17 to 25 percent from 2020 to 2070, while annual carbon sequestration is projected to decrease, indicating carbon saturation of U.S. forests.
- ❖ Forest ecosystem carbon futures are strongly driven by forest growth dynamics, roundwood demand, and to a lesser extent land use change. The amount of carbon sequestered by forests is projected to decline between 2020 and 2070 under all scenarios, with the forest ecosystem projected to be a net source of carbon in 2070 under the high roundwood demand RPA scenario (HH).
- ❖ Forests in the Rocky Mountain Region are expected to be the most sensitive to future climates and will remain a net carbon source through 2070.
- ❖ Conversion of forest to other uses results in between 194 MMT and 517 MMT of soil organic carbon being transferred to other land uses over the projection period. There is uncertainty regarding the portion of soil organic carbon that is emitted to the atmosphere in response to forest land conversion.
- ❖ Projections suggest that carbon stock change in harvested wood products and solid waste disposal sites will represent an increasing share of the forest sector's carbon stock change and eventually could be larger than forest ecosystem stock change

Without active management, significant disturbance, and land use change, forests approach a steady state in terms of C stock change over time. But management and disturbance do occur, along with changes in land use decisions, which affect forest C stocks and stock change. Forest C futures are driven by a suite of factors including climate, land use change, and disturbance, in addition to limiting factors that can impact forest growth when in short supply (e.g., light, nutrients, and water). As described in the Projected Futures of Forest and Timberland Area section of this chapter, forest area is expected to decrease between 2020 and 2070. At the same time, disturbances such as fire are expected to increase (see the Disturbance Chapter), and harvest for wood products is expected to either be relatively stable (HL scenario) or increase (LM, HM, and HH scenarios; see the Forest Products Chapter). These projected changes will affect forest C futures.

Forest Ecosystem Carbon Stocks and Changes

Forest Carbon Land Base

The amount of forest that has been in a continuous forest use over time ("forest remaining forest" – see the sidebar Definitions) is a critical factor in overall C sequestration because the total amount of C forests remove from the atmosphere is dependent on the size of the land base that has persisted in a forest use, in addition to forest conditions. In 2020, forest remaining forest land base across the conterminous United States was 619 million acres. As with forest land and timberland, the areal extent of forest remaining forest is expected to decline over the projection period. The pattern and timing of loss and general response to RPA scenario-climate futures is consistent with timberland projections (discussed in the section Future Projections – Forest Land and Timberland). Over the projection period, the amount of forest remaining forest is expected to decrease by 7.9 million acres (HL-hot) to 15.2 million acres (HH-least warm) (table 6-4).

Table 6-4. Projected net change and percent change in forest remaining forest area from 2020 to 2070 for the conterminous United States. Change and percent change are based on averaging projection results for each RPA scenario-climate future.

Climate model	2020 forest remaining forest	RPA scenario LM	RPA scenario HL	RPA scenario HM	RPA scenario HH
	million acres	million acres (percent)			
Least warm	619	-13.2 (-2.1)	-11.5 (-1.9)	-12.7 (-2)	-15.2 (-2.5)
Hot	619	-12.1 (-2.0)	-7.9 (-1.3)	-8.9 (-1.4)	-11.1 (-1.8)
Dry	619	-12.2 (-2.0)	-11.0 (-1.8)	-12.0 (-1.9)	-14.5 (-2.3)
Wet	619	-12.7 (-2.1)	-11.1 (-1.8)	-12.1 (-2)	-14.7 (-2.4)
Middle	619	-12.8 (-2.1)	-11.3 (-1.8)	-12.4 (-2)	-14.7 (-2.4)

LM = lower warming-moderate U.S. growth; HL = high warming-low U.S. growth; HM = high warming-moderate U.S. growth; HH = high warming-high U.S. growth.

Forest Ecosystem Carbon Pools

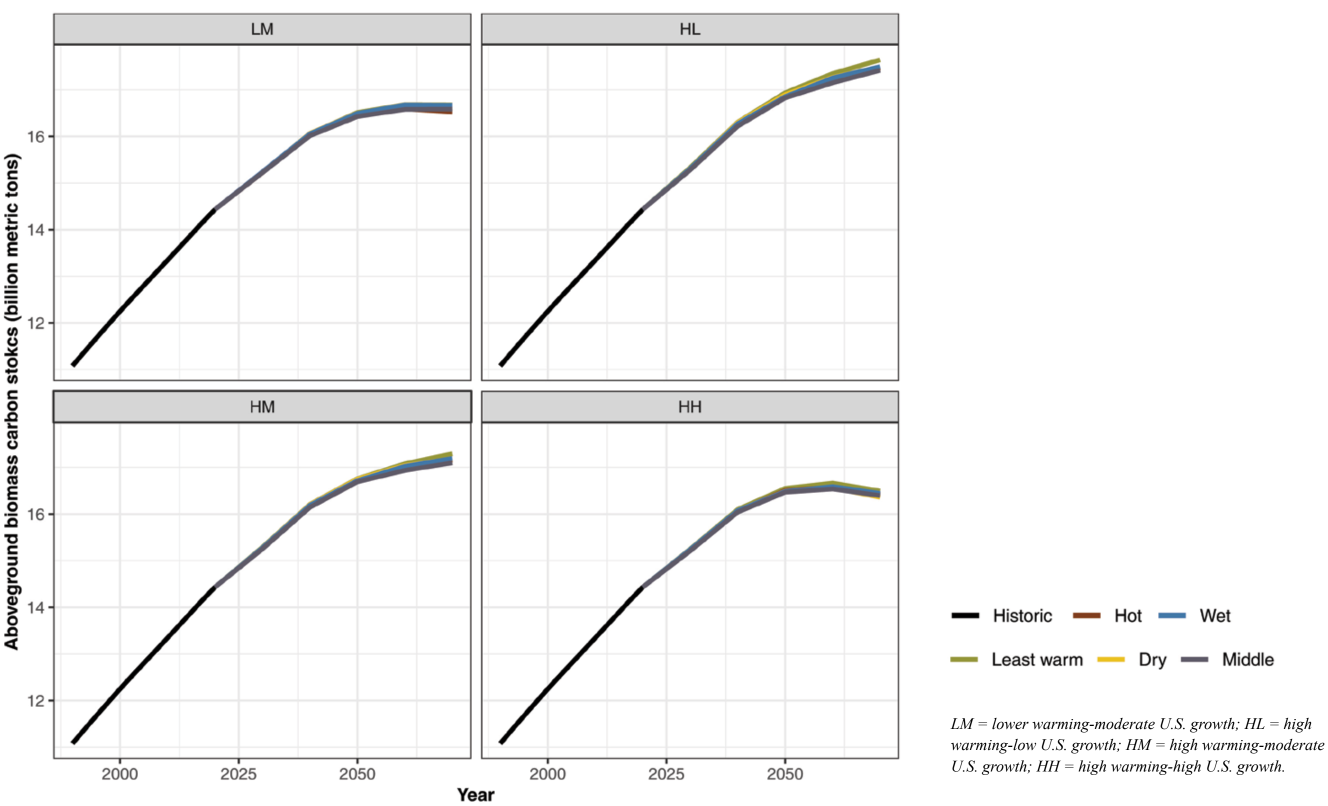
The aboveground biomass C pool is the primary driver of overall C sequestration (Pan et al. 2011). Our results suggest that this pool will increase at a decreasing rate from 2020 to 2070. While land use conversion and future disturbance play a role in reducing future sequestration rates, forest aging and senescence are also drivers of this trend. Aboveground biomass C is projected to increase across RPA scenario-climate futures to between 16.4 BMT C (HH-dry) and 17.6 BMT C (HL-warm) by 2070 (figure 6-30). The range of aboveground biomass C futures are more strongly driven by RPA scenario than by climate projection. The combination of increased land use pressure and roundwood demand under the LM and HH RPA scenarios leads to less aboveground biomass C stocks in 2070 than under the HL or HM scenarios.

The projected density of aboveground biomass C in 2070 is between 66.8 Mg C ha^{-1} (HH-dry) and 71.7 Mg C ha^{-1} (HL-warm). These projected density values are a 17- to 25-percent increase from 2020 and a 51- to 62-percent increase from 1990. In other words, the average hectare of forest in 2070 is projected to have 51 to 62 percent more C stored in aboveground biomass than the average forest hectare had in 1990. These findings are consistent with the hypothesis that the forest ecosystem C sink will saturate and are also consistent with the results of Zhu et al. (2018).

Soil organic C is the largest forest remaining forest pool. The total C content of the pool is related to the total forest remaining forest area; however, increased temperature and harvest can also influence the pool (Kirschbaum 2000, Mayer et al. 2020) through increased decay rates and reductions in the organic soil horizons (James and Harrison 2016). Our results suggest that soil C will remain the largest pool throughout the projection period, but we do project a net decrease in soil organic C over time. Specifically, projections suggest that soil organic C will remain relatively stable through 2030, and then decrease through 2070 by 0.8 percent (HL-hot) to 2.2 percent (HH-middle). While these decreases are small on a percentage basis, they equate to a transfer of between 194 MMT and 517 MMT of soil organic C over the projection period. The amount of soil organic carbon that is emitted back to the atmosphere during land use change is uncertain and depends on the specific land use forest is converted to. Conversion of forest to other uses is the main driver of loss in soil organic C, as soil organic C density remains relatively stable over the projection period (92 Mg C ha^{-1} to 93 Mg C ha^{-1}).

C in belowground biomass, dead wood, and litter accounts for a relatively small component of forest ecosystem C.

Figure 6-30. Historic and projected forest remaining forest aboveground biomass carbon stocks for each RPA scenario-climate future. Projected aboveground biomass is based on averaging decadal projection results by RPA scenario-climate future.

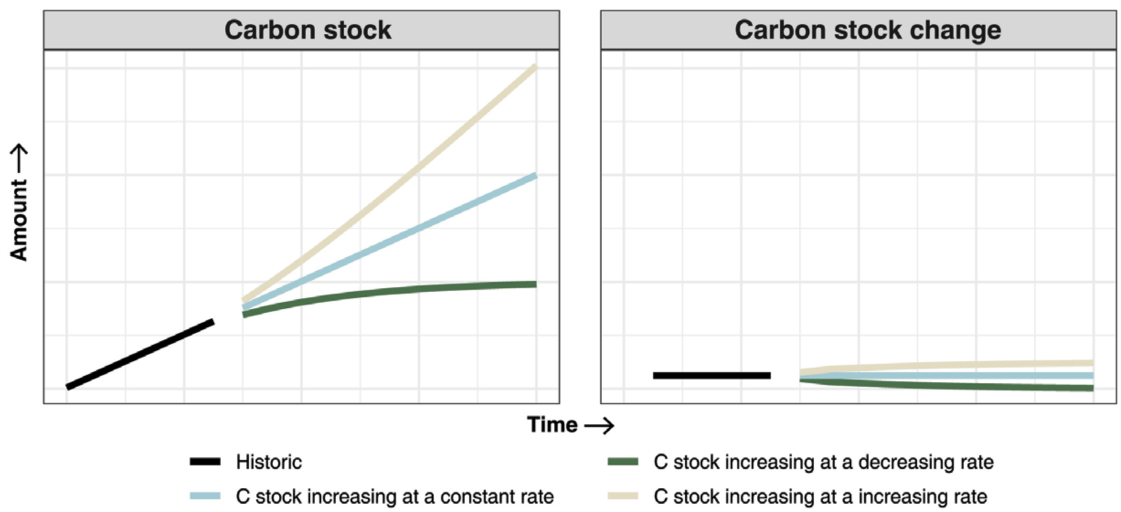


LM = lower warming-moderate U.S. growth; HL = high warming-low U.S. growth; HM = high warming-moderate U.S. growth; HH = high warming-high U.S. growth.

Forest Carbon Trajectories

Forest remaining forest C stocks increased at a relatively consistent rate from 1990 to 2020, but there are many potential future C stock trajectories. Three main alternative U.S. trajectories are suggested in the literature with respect to forest C futures, providing context for RPA projections: forest ecosystem C could increase at an increasing rate (exponential growth), increase at a constant rate (linear growth), or increase at a decreasing rate (logistic growth; figure 6-31). These three alternatives cover the range of potential forest C futures used in a U.S. government analysis identifying long-term strategies and pathways to net-zero greenhouse gas emissions by 2050 (U.S. State Department and Executive Office of the President 2021). Under exponential growth, C stocks increase at an increasing rate and resources are not limited over the time horizon. A linear trend implies that resources are sufficient to maintain sequestration over the time horizon, after accounting for disturbance and land use change. When C stocks increase at a decreasing rate, an asymptote is implied and the carrying capacity of the system is reached over the time horizon (growth approaches zero). Examining our results in the context of these three alternative trajectories can provide insights about the processes that lead to forest C stock change in the future.

Figure 6-31. Alternative future carbon stock (left) and stock change (right) trajectories.



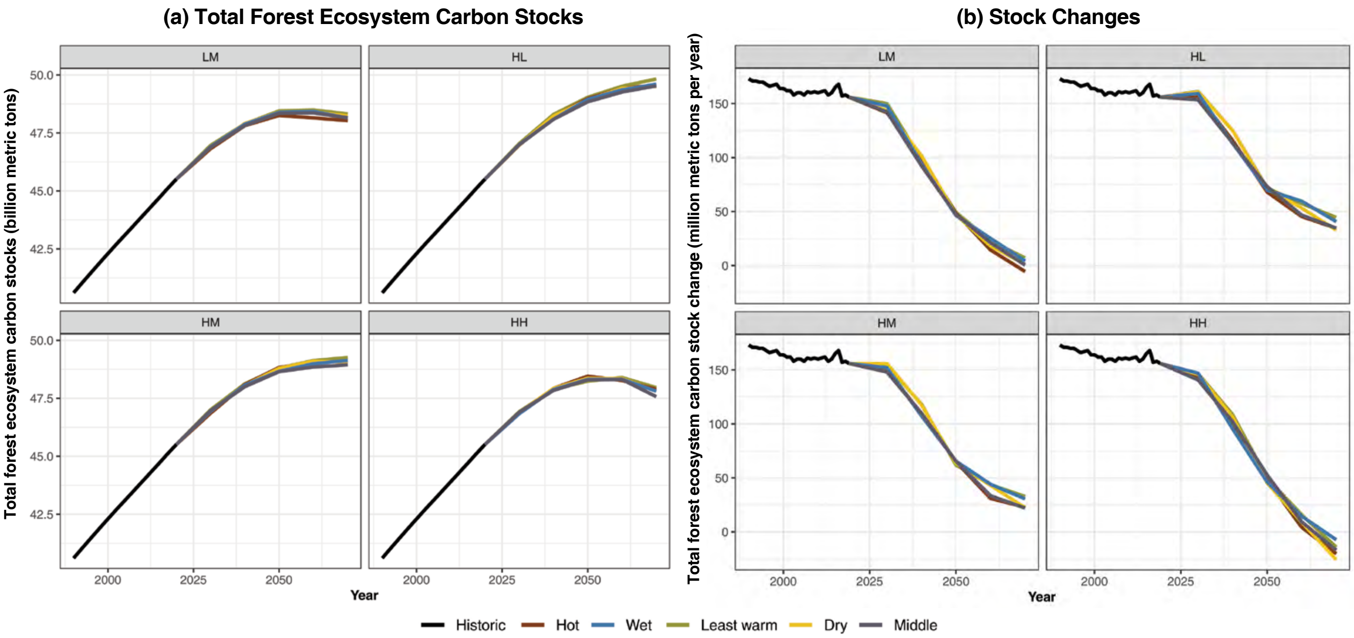
C = carbon.

While the belowground pool is smaller than the aboveground pool, projections of belowground biomass C follow a similar trajectory to aboveground biomass C in terms of the percentage change. C in belowground biomass is expected to increase from 2.9 BMT C in 2020 to 3.2 (HH-dry) to 3.5 (HL-least warm) BMT C in 2070. Litter C is projected to increase until 2050, and then decrease through 2070 with larger decreases associated with the hot climate projection. Dead wood C is expected to increase slightly over the projection period, with the largest increases under the HM and HL scenarios, suggesting that RPA scenarios with less forest removals lead to increased C in dead wood. Further, dead wood C is fuel for wildfires and our projections suggest a slower accumulation of dead wood C with the projected increase in wildfires (see the Disturbance Chapter).

Total Forest Ecosystem Carbon

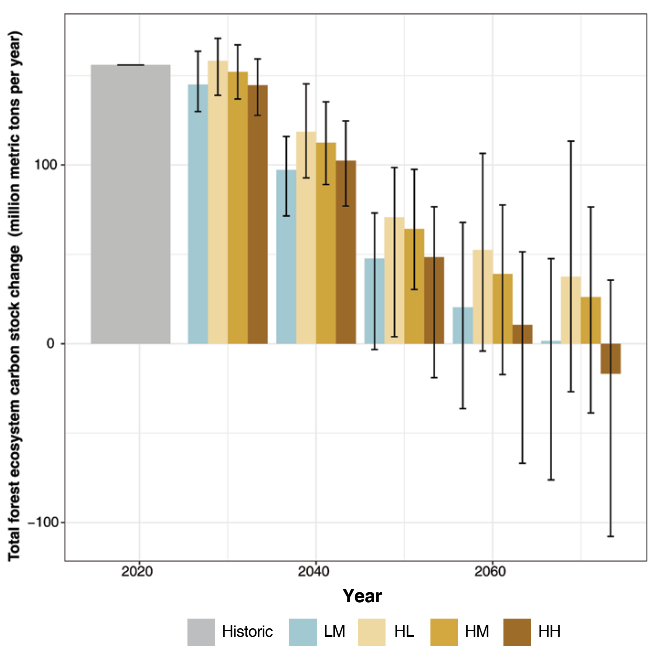
Total C stocks on forest remaining forest are projected to increase from 45.5 BMT C in 2020 to between 47.6 BMT C (HH-middle) and 49.8 BMT C (HL-least warm) in 2070 (figure 6-32a). C stock change in 2030 is projected to be relatively consistent with 2019 stock change estimates and then is projected to decrease across RPA scenario-climate futures from 2030 to 2040 (figure 6-32b). By 2070, whether the forest remaining forest land base continues to be a net C sink depends on the RPA scenario. The forest remaining forest land base is projected to remain a net C sink in 2070 under the HM and HL RPA scenarios, sequestering between 22 and 45 MMT C yr^{-1}, respectively. The 2070 forest remaining forest C stock change is projected to range from 6 MMT C yr^{-1} to -6 MMT C yr^{-1} under the LM scenario, while forest remaining forest is projected to be a net source

Figure 6-32. Historic and projected forest remaining forest (a) total forest ecosystem carbon stocks and (b) stock changes for each RPA scenario-climate future. Projected forest ecosystem carbon stock and stock change is based on averaging decadal projection results by RPA scenario-climate future.



LM = lower warming-moderate U.S. growth; HL = high warming-low U.S. growth; HM = high warming-moderate U.S. growth; HH = high warming-high U.S. growth.

Figure 6-33. Forest ecosystem total carbon stock change in 2019 (historic) and decadal projections for 2030 to 2070 by RPA scenario. Decadal projected values are the average of projection results by RPA scenario. Modeling uncertainty is denoted by the 99 percent projection intervals for 2030 to 2070 (black lines).



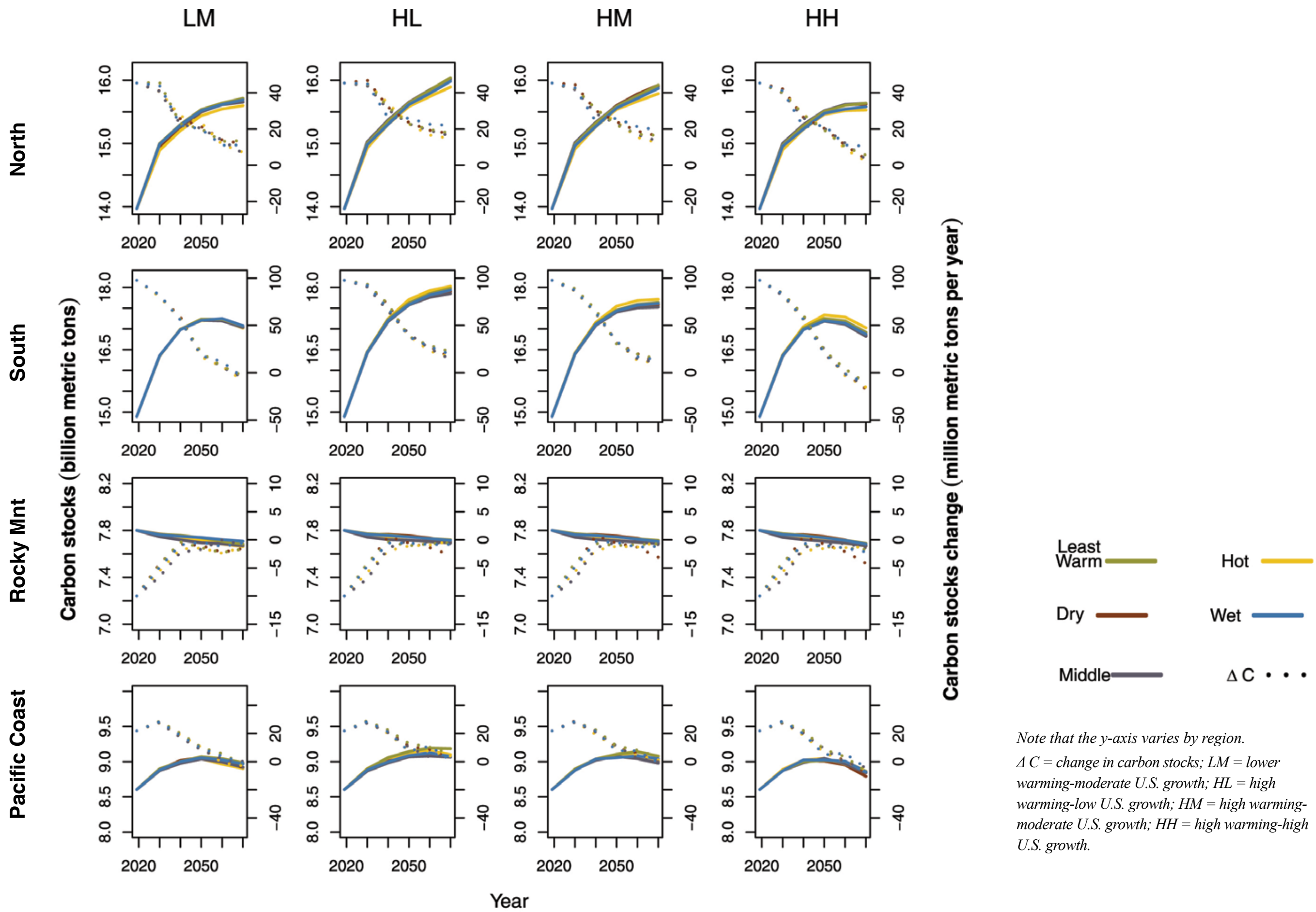
LM = lower warming-moderate U.S. growth; HL = high warming-low U.S. growth; HM = high warming-moderate U.S. growth; HH = high warming-high U.S. growth.

of C in 2070 under the HH scenario (-7 to -26 MMT C yr^{-1}). However, there is considerable modeling uncertainty in projected forest ecosystem C stock changes (figure 6-33). Based on projections from the Forest Dynamics Model, C stock change could be negative (net C source) under the LM and HH scenarios by 2050. The modeling uncertainty increases with the length of the projection period, leading to significant uncertainty by 2070, where the uncertainty envelope across RPA scenarios ranges from less than -100 MMT C yr^{-1} (substantial C source) to greater than 100 MMT C yr^{-1} (substantial C sink).

Regional Trends in Total Forest Ecosystem Carbon

Trends in forest ecosystem C stocks and stock changes differ by RPA region. The majority of C stocks were stored in the Eastern United States in 2019 and these regions were the primary force behind significant C accumulation since 1990. Forest growth, investments in forest management, and afforestation led to increasing C stocks at a consistent rate. In contrast, the forest ecosystems of the western RPA regions typically had slower growth rates and were subject to more severe disturbances, leading to only modest C accumulation since 1990. This was particularly evident in the Rocky Mountain Region, where forests were a C source (negative stock change) in 2019 (Domke et al. 2021).

Figure 6-34. Forest remaining forest total forest ecosystem carbon stocks and stock changes for 2019 and projections to 2070 for each RPA scenario-climate future, by RPA region. Projected forest ecosystem carbon stock and stock change are based on averaging decadal projection results by RPA scenario-climate future.



Note that the y-axis varies by region.
Δ C = change in carbon stocks; LM = lower warming-moderate U.S. growth; HL = high warming-low U.S. growth; HM = high warming-moderate U.S. growth; HH = high warming-high U.S. growth.

The Rocky Mountain Region is projected to remain a C source, with decreasing C stocks between 2019 and 2070 regardless of RPA scenario-climate future (figure 6-34). Conversely, the North Region is projected to continue to be a C sink throughout the projection period under all RPA scenario-climate futures. In the North, C stocks are projected to continue to increase through 2070, with annual stock change rates between 2.1 MMT C yr^{-1} (HH-hot) and 22 MMT C yr^{-1} (HL-wet). The RPA Pacific Coast and South Regions are both projected to experience C stock increases through mid-century across all RPA scenario-climate futures. C stocks are then generally projected to decrease under the HH and LM scenarios after 2050 in the Pacific Coast and after 2060 in the South, with both regions becoming a C source. Under the HL and HM scenarios, both regions continue to accumulate C but at reduced stock change rates compared to 2019.

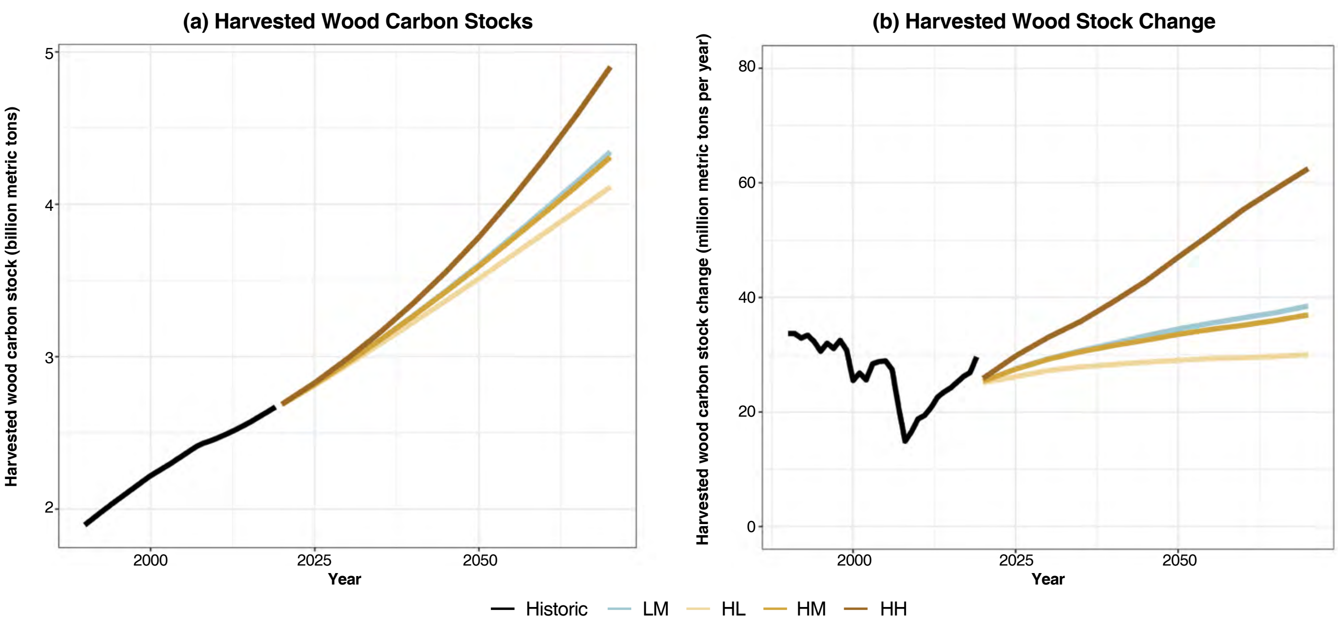
Other Land Converted to Forest

As presented in the Land Resources Chapter, forest land can be converted to other uses and other land uses can be converted to a forest land use. When land is converted to a forest use, the C on that land is transferred to the "other land converted to forest" category (IPCC 2006). The total forest land area at a given time is the sum of the forest remaining forest area and the other land converted to forest area. Historically, about 1 million hectares of other land converts to forest annually, transferring 27 MMT C yr^{-1} into the forest land base (Domke et al. 2021); however, forest area is projected to decrease (net forest loss) over the projection period, and the amount of land converted to forest (gross forest gains) is also projected to decrease due to the competition between economic returns to forest uses and economic returns to other land uses. The annual amount of C transferred through conversion to forest uses is projected to decrease by 25 to 28 percent between 2019 and 2070 under the HL and HH scenarios, respectively.

Harvested Wood Carbon

C stored in hardwood products (HWP) and solid waste disposal sites (SWDS) contributes significantly to the forest land sector sink (Johnston and Radeloff 2019). The trajectory of the HWP C pool in the United States is directly tied to the amount of domestic harvest and the types of products made from that harvest (see Forest Products Chapter). Similarly, SWDS C is tied to domestic harvest and products, but it reflects the C trends of products once discarded. C stored in HWP and SWDS (total harvested wood C) is projected to increase over the projection period (figure 6-35a). The stock change for HWP is projected to increase under the LM, HM, and HH RPA scenarios and projected to slightly decrease under the HL scenario due to the lower projected demand for roundwood products under this scenario (figure 6-35b). SWDS stock change is projected to increase across all RPA scenarios. Total harvested wood C is projected to remain small relative to the forest ecosystem pool from 2020 to 2070; however, global demand for wood products under all RPA scenarios except HL is projected to increase the stock change in harvested wood from 29.6 MMT C yr^{-1} in 2020 to between 36.9 MMT C yr^{-1} (HM) and 62.5 MMT C yr^{-1} (HH) in 2070. Under HL, C stock change in harvested wood is projected to decrease from 2020 to 2030, then slowly return to 2020 levels by 2070.

Figure 6-35. Historic and projected total harvested wood carbon (C in harvested wood products and solid waste disposal sites) for (a) stocks and (b) stock change from 1990 to 2070, by RPA scenario.



C = carbon; LM = lower warming-moderate U.S. growth; HL = high warming-low U.S. growth; HM = high warming-moderate U.S. growth; HH = high warming-high U.S. growth.

Sources: Projections for C in harvested wood products are based on the FOROM model (Forest Products Chapter, Johnston and Radeloff 2019). Projections for C in solid waste disposal sites are based on the model presented by Skog (2008).

Total Carbon

Total C includes stocks and stock changes from the forest ecosystem, harvested wood, and other land converted to forest categories. The forest ecosystem pool is projected to remain a C sink under all RPA scenarios except HH, where C stock change is projected to be -16.2 MMT C yr^{-1} in 2070 (negative stock change is a net emission of C). However, the C stock change in harvested wood is large enough to more than offset projected forest ecosystem C emissions under HH (table 6-5). When considering both the forest ecosystem and harvested wood pools, C stock change is projected to be positive across all RPA scenarios in 2070, although significantly lower than 2019. The HL scenario is projected to have the largest 2070 total C stock change, followed by HM, HH, and LM. While the LM scenario has a greater forest ecosystem C stock change than the HH scenario, the increased forest harvesting for products under HH is projected to be 1.6 times larger than under LM, leading to greater total C stock change. Based on the projections, harvested wood C stock change is expected to be larger than the forest ecosystem stock change under every RPA scenario except HL, and the contribution of the harvested wood pool to total C stock change is expected to increase over time.

Drivers of Change in Forest Ecosystem C

There are many drivers of change that influence trends in forest ecosystem C stocks, including biological, socioeconomic, and climate drivers. The goal of this section is to analyze the relative importance of these drivers in forest ecosystem C futures. Socioeconomic drivers affect the amount of harvest for products, land use change, and forest management. Land use choices are also sensitive to climate futures (see the Land Resources Chapter). In addition, forest ecosystem C trends are

Table 6-5. Forest ecosystem carbon, harvested wood carbon, and carbon from land use transfers to forest in 2019 and projected to 2070, by RPA scenario. Stock changes are provided in parentheses. Decadal projected values for the forest ecosystem and land use transfer to forest are the average of projection results by RPA scenario.

		Year					
Scenario	**Carbon pool**	**2019**	**2030**	**2040**	**2050**	**2060**	**2070**
		BMT C (MMT C yr^{-1})					
LM	**Forest ecosystem**	45.35 (155)	46.89 (145)	47.86 (97)	48.37 (48)	48.35 (20)	48.18 (1)
	Harvested wood	2.67 (30)	2.96 (29)	3.27 (32)	3.60 (35)	3.97 (36)	4.34 (39)
	Forest ecosystem+harvested wood	48.02 (186)	49.85 (174)	51.12 (129)	51.97 (82)	52.32 (57)	52.52 (40)
	Other land converted to forest	-- (27)	-- (24)	-- (23)	-- (22)	-- (21)	-- (20)
	Total	48.02 (213)	49.85 (198)	51.12 (152)	51.97 (105)	52.32 (78)	52.52 (60)
HL	**Forest ecosystem**	45.35 (155)	46.99 (158)	48.2 (118)	48.96 (71)	49.39 (52)	49.61 (37)
	Harvested wood	2.67 (30)	2.95 (27)	3.22 (28)	3.51 (29)	3.81 (30)	4.11 (30)
	Forest ecosystem+harvested wood	48.02 (186)	49.94 (186)	51.42 (147)	52.47 (100)	53.21 (82)	53.72 (67)
	Other land converted to forest	-- (27)	-- (25)	-- (24)	-- (23)	-- (22)	-- (21)
	Total	48.02 (213)	49.94 (210)	51.42 (170)	52.47 (123)	53.21 (104)	53.72 (88)
HM	**Forest ecosystem**	45.35 (155)	46.94 (152)	48.06 (113)	48.75 (64)	49.03 (40)	49.1 (26)
	Harvested wood	2.67 (30)	2.96 (29)	3.27 (32)	3.59 (34)	3.94 (35)	4.31 (37)
	Forest ecosystem+harvested wood	48.02 (186)	49.9 (181)	51.33 (144)	52.34 (98)	52.97 (75)	53.41 (63)
	Other land converted to forest	-- (27)	-- (24)	-- (24)	-- (23)	-- (22)	-- (20)
	Total	48.02 (213)	49.9 (206)	51.33 (168)	52.34 (121)	52.97 (96)	53.41 (83)
HH	**Forest ecosystem**	45.35 (155)	46.88 (145)	47.89 (102)	48.35 (48)	48.34 (11)	47.83 (-16)
	Harvested wood	2.67 (30)	2.99 (33)	3.35 (39)	3.78 (47)	4.3 (55)	4.9 (63)
	Forest ecosystem+harvested wood	48.02 (186)	49.87 (178)	51.24 (142)	52.13 (95)	52.65 (66)	52.74 (46)
	Other land converted to forest	-- (27)	-- (24)	-- (24)	-- (23)	-- (21)	-- (20)
	Total	48.02 (213)	49.87 (202)	51.24 (165)	52.13 (118)	52.65 (87)	52.74 (66)

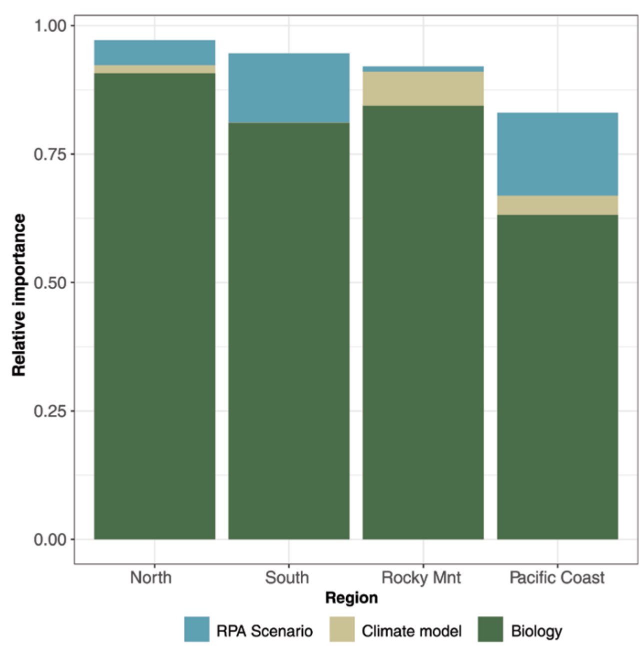
BMT = billion metric tons; C = carbon; MMT = million metric tons; yr = year; LM = lower warming-moderate U.S. growth; HL = high warming-low U.S. growth; HM = high warming-moderate U.S. growth; HH = high warming-high U.S. growth.

influenced by biological dynamics and their interaction with RPA scenarios and climate projections. Biological dynamics, including growth, aging, increased stocking, forest composition shifts, and other attributes, are simulated by the Forest Dynamics Model. We examine the effects of these various drivers on forest carbon stock futures, isolating the influence of scenario, climate model, and biological dynamics.

We examined the relative importance of RPA scenario (LM, HL, HM, HH), climate projection (least warm, hot, dry, wet, middle), and 'biological development' (biology) to the cumulative difference in forest ecosystem C over the projection period (i.e., the difference between 2019 C stock and C stock at each decadal time step). In this analysis, we used change in time as a surrogate for biology since the change in time reflects biological processes such as forest growth, aging, and disturbance effects not explained by the other factors. Performing a variance components analysis (McCulloch and Searle 2004) reveals how important the RPA scenario, climate future, climate projection, and biology each are in explaining the range of forest ecosystem C stock trends.

Across RPA regions, biology was the most important component in explaining the cumulative change in forest ecosystem C stocks (figure 6-36). This makes intuitive sense

Figure 6-36. Relative importance of RPA scenario, climate projection, and biology in explaining the difference in forest ecosystem C trends from 2019 to 2070 by RPA region.



C = carbon.

because forests have distinct growth patterns, successional trajectories, and disturbance regimes, all of which lead to predictable behavior over time in terms of C stocks. RPA scenario was the second most important driver in all regions except the Rocky Mountain Region, because land use change and roundwood harvest for products influences C stock trends in the North, South, and Pacific Coast Regions. The climate projection was more important than RPA scenario in the Rocky Mountain Region (although not necessarily a specific climate projection), partially because the Rocky Mountain Region is projected to have the smallest contribution to U.S. roundwood production among regions (and thus is less affected by roundwood demand), and partially due to the large proportion of public forest land in the region resulting in less projected loss of forest land use.

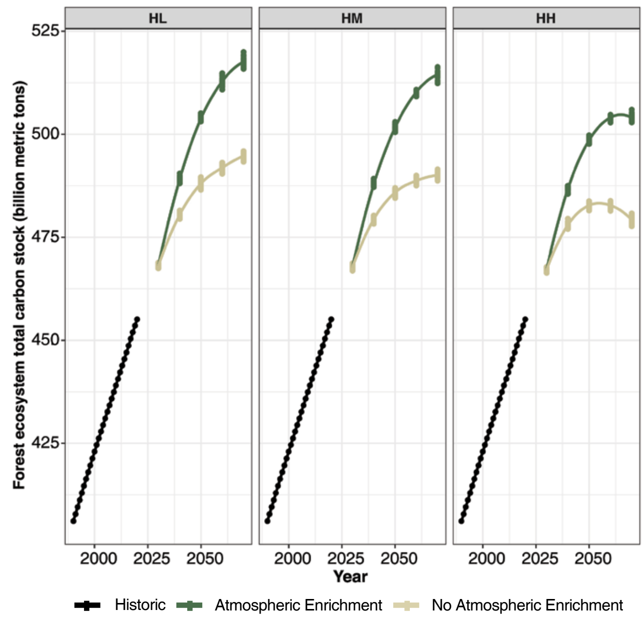
Atmospheric Enrichment

The Forest Dynamics Model uses historical biological growth patterns to simulate changes in the future. However, it is possible that biological growth patterns could be amplified or attenuated by changes in climate. Atmospheric enrichment is the process by which elevated levels of CO_2 and nitrogen effectively fertilize forests, resulting in increased growth (Fang et al. 2014, Hember et al. 2012). The scientific literature offers a range of growth enhancement rates due to atmospheric enrichment, ranging from 0 to 2 percent per year (Wear and Coulston 2015). Although Green and Keenan (2022), Jiang et al. (2020), Lo et al. (2019), and Wang et al. (2020) call atmospheric enrichment into question, suggesting that there are limits to the effect or that the fertilization effects are declining, the degree to which increased CO_2 influences C stocks and flux over the projection period is a source of uncertainty.

To examine the potential impacts of atmospheric enrichment, we assumed a 0.7 percent per year fertilization effect for the RCP 8.5 RPA scenarios (HL, HM, HH), and used the middle climate projection as a demonstration. A fertilization rate of 0.7 percent per year was chosen because preliminary analysis of the FIA data suggested an effect of this magnitude and 0.7 percent per year was in the range of the published literature. Because C stock change rates are projected to remain relatively constant until 2030, we applied the growth enhancement beginning in 2030. To impose the atmospheric enrichment assumption within the RPA Forest Dynamics Model, we artificially skewed modeled forest transitions over time towards denser and generally older stands. While the forest accumulates C at a faster rate with atmospheric enrichment, other processes such as disturbance, aging, and increased stocking continue to occur.

The growth enhancement increased projected C stocks across RPA scenarios, and the effect of the enhancement increased over time (figure 6-37). By 2070, C stock projections were

Figure 6-37. Historic and projected carbon stocks for the middle climate projection with and without an atmospheric enrichment assumption for the HL, HM, and HH RPA scenarios. Decadal projection results are based on average across the 100 realizations for the HL, HM, and HH scenarios for the middle climate projection.



LM = lower warming-moderate U.S. growth; HL = high warming-low U.S. growth; HM = high warming-moderate U.S. growth; HH = high warming-high U.S. growth.

about 5.6 percent larger than those projections without atmospheric enrichment. The cumulative effect of atmospheric enrichment on the total amount of C sequestered over the projection period ranged from 2.3 to 2.5 BMT C, where the largest cumulative effect was observed under the HH scenario.

With respect to C stock change, atmospheric enrichment does increase rates by about 22 MMT C yr^{-1} in 2070 and suggests a future where U.S. forest ecosystems within each RPA region are a C sink under the RPA scenarios. However, because C stock accumulation slows over time, annual C stock change rates continue to decrease over the projection period. Our results suggest that while atmospheric enrichment could lead to futures with greater forest ecosystem C stocks, stocks will increase at a decreasing rate.

Decadal projection results are based on average across the 100 realizations for the HL, HM, and HH scenarios for the middle climate projection.

Management Implications

The forests of the United States are managed for a range of objectives across a range of spatial scales. Management objectives include management for water quality and quantity, wildlife habitat, timber for products, recreation, and carbon. Over the next 50 years, managers will likely experience challenges with simultaneously managing for different ecosystem services and developing broad-scale management approaches in shifting forest landscapes.

At a fine-scale (stand-level), there are some ecosystem services that are difficult to manage for simultaneously. For example, management to optimize timber production may not optimize water quality and quantity. Similarly, management focused on maximizing carbon storage may not be optimal for wildlife habitat. Understanding and managing for ecosystem services over a broader spatial scale is required to develop and implement a suite of management approaches to increase net ecosystem services and decrease the potential effects of forest disturbance. This type of management has been contemplated through efforts such as the USDA Forest Service's Shared Stewardship strategy. However, approximately 60 percent of forests across the conterminous United States are privately owned. Most family-owned forests do not have a management plan and hence are passively managed. Further, U.S. forests exist in a mosaic of other land uses and land covers. Creating a mechanism to engage the disparate owners with diverse objectives to understand the potential opportunities of collaborative approaches, across landowners, to increase, or in some cases maintain, the services that forests provide is a management challenge.

The results presented in this chapter, coupled with results from the Land Resources Chapter, suggest the next 50 years will be dynamic. Land use choices are expected to change over the next 50 years. Net forest area loss is projected in all regions of the country; however, gross forest change (forest loss + forest gain) is projected to be substantially larger than net change. When considering gross forest change, it is important to understand that the combination of losses and gains means a shuffling of where forests exist on the landscape, who owns those forests, and of the structural and compositional makeup of those forest. Further, as forests shuffle on the landscape, the type and composition are likely to be different than the persistent forests in the landscape. Broad-scale management approaches aimed at improving forest ecosystem services will therefore need to anticipate a shifting forest landscape. This is particularly relevant to initiatives that aim for no net forest loss, because often the forests converted to other land uses are different from those areas that have afforested. The important consideration is whether the right forests are in the right places to meet broad-scale management objectives.

Increasing roundwood demand has historically led to increased roundwood prices, which have facilitated investments in forestry. Previous forestry investments included developing more effective silvicultural techniques and tree improvement, the adoption of which resulted in a management response that increased forest productivity. Our results suggest that demand for roundwood could lead to futures where harvest levels exceed those observed from 1976 to 2016 (LM and HH RPA scenarios). However, under those scenarios, our results do not show a management response where investments in forestry avoid declining growing stock volume at the end of the projection period. While our results do suggest an increase in planted forest under the LM and HH scenarios, the increase does not offset the influence of a 39- to 46-percent increase in forest harvested. Futures constructed with the Forest Dynamics Model account for contemporary management approaches (e.g., planting, thinning, fertilization, prescribed fire) commensurate with the forest types, stand ages, and owners that deploy them, but future improvements to management approaches are not incorporated in the modeling system. Increasing the effectiveness of the tools and approaches available to forest managers, which can be facilitated through increased investment in forestry, will help meet the increased roundwood demand under these futures. In addition, management tools and approaches can only benefit the forest land where they are deployed, but much of the Nation's forest land does not have a management plan. Increasing the area where effective forest management is deployed is a current and future management challenge.

Management choices have implications for carbon-neutrality efforts and natural climate solutions. C sequestration in the forest sector currently offsets approximately 11 percent of emissions from other sectors (Domke et al. 2021). Given that projected forest sector C sequestration in 2070 is expected to decrease by 59 to 72 percent, other sectors will need to decrease C emissions by 95 to 97 percent for the United States to achieve carbon neutrality. Natural climate solutions offer management approaches to enhance the forest sector C sink. These solutions generally fall in two categories: maintaining or increasing forest extent and increasing productivity though investments and changes in forest management. Given the areal extent of the forest land base (over 600 million acres for the conterminous United States), natural climate solutions will need to affect a significant amount of forest land to shift the projected C stock trajectory, which would have consequences for other ecosystem services when considering these broad-scale C objectives.

Conclusions

The extensive forest resources of the United States provide a wide range of goods and services to the American public. Since the late 1970s forest area has increased, as have growing stock volume and carbon stocks. Increases to the forest land base largely arose because forest gains from agricultural abandonment outpaced forest loss to developed uses over the last 50 years. Despite dynamic shifts in forest disturbance and their effects, the forests of the United States have continued to sequester C at rates sufficient to offset CO_2 emission from other sectors (e.g., energy), provided the raw material for traditional forest products (e.g., dimensional lumber), and provided the resources for emerging markets (e.g., pellets). At the same time, forests have been critical to water quality and quantity, providing wildlife habitat, and offering recreational opportunities.

The ability of forests to provide the goods and services that society depends upon will be challenged over the next 50 years. Global and national population and income trends will influence demand for forest products, and to a lesser extent expected climatic shifts will influence forest ecosystems in terms of their composition, structure, and productivity. In general, the forests of the United States are projected to decrease in area but increase in volume across RPA scenario-climate futures. Projections suggest the increase in volume will be driven by forest maturation outpacing the effects of disturbance and harvest pressure. Despite projected increases in forest volume, growth rates are projected to slow. The projected decrease in younger forests suggests much of the forested landscape will shift to an older age cohort where forest ecosystem C growth (stock change) will be less than current (2020) estimates. The disparity between actively growing younger forest and slower growing older forest is projected to impact the range of services forests provide, in some cases positively and in other cases negatively.

RPA scenarios, as driven by demand for roundwood and land use shifts, have been highlighted as more significant than alternative climate projections in defining future conditions throughout this chapter. This result does not suggest that climatic shifts are not important; rather, it highlights how the influence of forest management activities over broad spatial scales occurring over shorter timeframes outpaces the influence of climate. More simply, humans may impact the forests of the United States more quickly than climate shifts. However, there are regional differences in this pattern. The Rocky Mountain Region is the only region where the effects of climate projection overshadow the projected effects of RPA scenario. The Rocky Mountain Region currently produces, and is projected to continue producing, the smallest share of U.S. timber used for products, which suggests less forest management. The sensitivity of the Rocky Mountain Region to climate is driven by the interaction of future climates with the conditions, types of forest communities, and disturbances in the region. Our projections suggest the concurrent effects of these interactions is a stronger driver than demand for roundwood and land use change.

The results presented here represent a range of different projected trends. With respect to forest area, projections suggest a trend reversal from historic increases in forest area to a future with declining forest area. Growing stock volume and forest ecosystem C stocks are expected to follow current (increasing) trends through 2030. From 2030 to 2070, these increases to both volume and carbon occur at a decreasing (slower) rate. The slower rate of carbon accretion post-2030 leads to a shift from the relatively static 1990 to 2020 forest ecosystem C stock change rate trend to a decreasing trend in annual C stock change. While there are projected decreases in forest area, the projected extent of forest remains higher than observed in the 1980s. Further, growing stock volume, while projected to increase at a decreasing rate, is expected to be substantially larger in 2070 than it was in 2020 across the range of roundwood demand futures.

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Chapter 7

Forest Products

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The United States and the world have undergone immense economic, social, and economic change over the 10 years since the last Resources Planning Act (RPA) Assessment, all of which have impacts on production and consumption of forest products. This chapter describes recent trends in global and U.S. forest product consumption, production, and net trade and also explores economic projections of production, consumption, net trade, timber harvest levels, and timber prices, as influenced by four future scenarios regarding economic and population growth and changing biomass energy demand through 2070.

Key Findings

- The future of U.S. markets is shaped by strong growth in emerging economies, stable- to slightly-growing domestic demands, and by policy factors related to energy embedded in alternative scenarios. U.S. timber production and consumption are projected to remain strong with varying levels of growth across RPA scenarios, but with important changes in the product mix.
- U.S. industrial roundwood production is projected to rise faster than derived product manufacturing demand, resulting in the United States capturing a growing share of global industrial roundwood export markets.
- The U.S. South is projected to remain the dominant timber producing region in the world despite projected losses in forest area, producing around 10 percent of total industrial roundwood under all RPA scenarios.
- The U.S. paper sector has undergone a transition related to declining demand for graphics paper and the shift in global markets to overseas paper production in the last 20 years that is projected to continue into the foreseeable future.
- Overseas demand for hardwood roundwood and lumber provides a base of support for domestic U.S. production.
- Projected futures in the production and consumption of wood to generate energy depend on policy assumptions and consumer preferences and vary widely by RPA scenario.
- If current policies encouraging wood use in energy production are maintained in Europe, the United States is projected to have a durable and growing wood pellet export market through 2070. Across all RPA scenarios, future pellet production does not exceed 4.2 percent of total wood production.

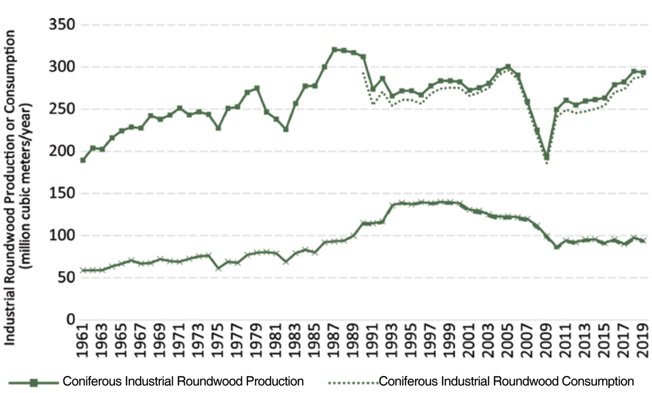
Historical Context

In 2009, the United States was emerging from a deep economic recession, the effects of which were evident in production of industrial roundwood (figure 7-1). The sharp contraction was due to substantial reductions in the demand for wood for the construction sector (Prestemon et al. 2018) and the diminished demand for paper for most end-uses (Wear et al. 2016). U.S. consumption of wood products, primarily from roundwood, rose during the recovery (Brandeis et al. 2021), while paper products consumption continued the trend of long-term decline evident since the late 1990s. The negative paper consumption trend was led by newsprint and printing and writing paper, due to substitution of electronic media (Latta et al. 2016). By 2019, total paper consumption levels still had not achieved rates observed in the late 1990s (Brandeis et al. 2021). Wear et al. (2016) attribute this weak growth to U.S. manufacturing overall, consistent with global findings (Hetemäki and Hurmekoski 2014).

From 2017 to 2020, the United States and its forest products sector were affected by increases in trade barriers, both on imports into the United States (particularly from Canada) and exports from this country to many of its major trading partners, such as Europe and China (Pan et al. 2021). Although there is uncertainty about the future evolution of trade frictions, the scenario-based approach used in this Assessment provides for a range of possible tariff environments, likely bracketing much of that uncertainty.

Today, the nation and the world are emerging from the sharpest economic contraction since the Great Depression, due to the SARS-CoV-2 global pandemic. The base year of our projection scenario falls before the pandemic and our focus is on long-run projections, so the results we present do not directly incorporate the sharp, short-term dynamics in the economy that buffeted the sector. However, a sidebar of this chapter does evaluate some of the dynamics and potential long-term implications of the pandemic on production, consumption, prices, and trade (see the sidebar A Short-Term Analysis of COVID-19 on the U.S. Forest Product Markets for more details). As the sidebar notes, the recovery from the spike-like economic contraction of mid-2020 has been sharp, in one way validating a perspective that short-run dynamics are usually subsumed in the secular trends that dominate in the long-run.

Figure 7-1. U.S. production and consumption of industrial roundwood, nationwide, 1961 to 2019.



Source: FAO 2021.

One dimension of market dynamics has been the evolving reliance on imports of forest products to meet domestic demands. The country has long been a net importer of wood products, particularly softwood lumber, softwood plywood, and oriented strand board for the construction sector (Brandeis et al. 2021). The sharp recessions observed from 2007 to 2009 and then in 2020 had little impact on U.S. import dependence in these products, with the Nation importing nearly one-third of its wood needs, particularly from Canada. In paper and paperboard, its import-dependence has receded along with demands for graphics paper (Brandeis et al. 2021).

Hardwood products also show temporal variations in production, consumption, and trade, related to the U.S. and global recessions, but secular trends in consumption and production have dominated. The United States is a net exporter of hardwood lumber, connected in part to the offshoring of furniture manufacturing in the 1990s and 2000s and corresponding growth in overseas furniture production (e.g., Grushecky et al. 2006, Schuler and Urs 2003). By 2019, consumption of hardwood lumber in the United States had declined by nearly 40 percent since its 1999 peak, a response to the disinvestment in the Nation's wood furniture manufacturing sector. U.S. hardwood industrial roundwood trends have been similarly impacted by the shifts in global wood furniture manufacture, particularly to Asia.

As Wear et al. (2016) point out, long-term trends in the U.S. forest sector are revealed not just in markets for forest products but also in its demands for inputs, including labor, capital, and wood. Employment in the wood products and paper sector has been trending downward for several decades (Wear et al. 2016). The employment trends accompany rising capital intensification and technology changes. The higher efficiencies in both labor and wood fiber use (Brandeis et al. 2021) have been enabled by innovations in manufacturing technology favoring capital over labor. The efficiency gains are further paired with the broad move away from paper as a medium for information delivery and the declining use of paper per unit of output by the U.S. manufacturing sector.

One feature of the U.S. forest product market, which can be described as an element of the sector's multiple trends but with an uncertain long-term trajectory, has been the rapid growth in the production and export of wood pellets for energy. Although pellets represent a small fraction (less than

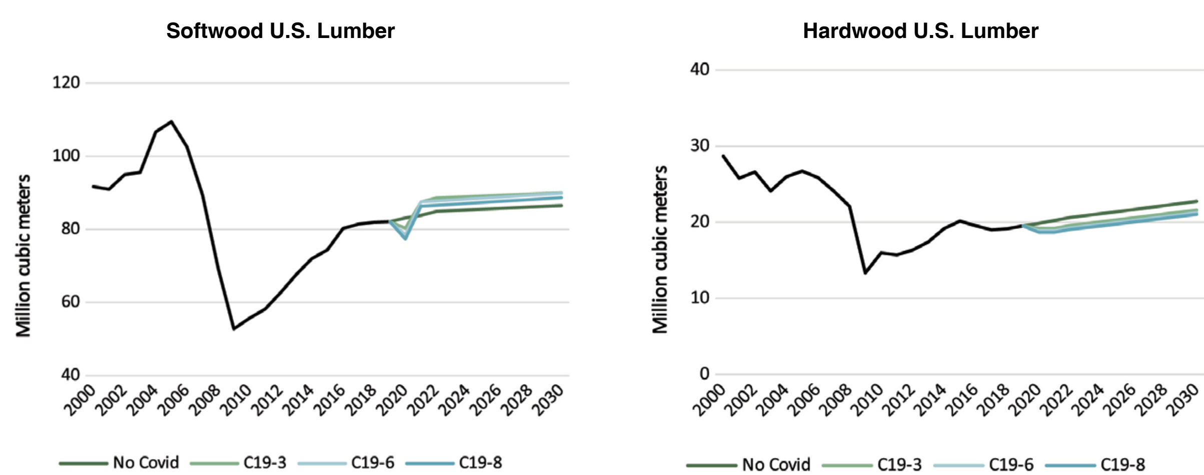
A Short-Term Analysis of COVID-19 on the U.S. Forest Product Markets

The second decade of the 21st century ended with a global pandemic caused by the SARS-CoV2 virus and the illness it produces, COVID-19. To contain the spread of the virus, governments implemented strict lockdown regulations which, along with fears of contracting the COVID-19 illness, shrank economic activity to lows not experienced in decades. Forest product markets were among those experiencing substantial disruptions early in the pandemic, ending a slow but steady rise in economic output in the United States and globally from the 2007 to 2009 global financial crisis. Despite experiencing some disruptions early on, the U.S. forest products sector rebounded quickly, yet the sector exhibited behaviors unique to the virus and differed from typical recessions. This sidebar places into context the scale of the pandemic's impacts on forest product markets and informs how such short-run market dynamics might be connected to the long-run dynamics described in the main part of the Forest Products Chapter.

To characterize the impacts of the pandemic on the sector, we applied an annualized version of the FOrest Resource Outlook Model (FOROM) model, which contains the essential features of the periodic FOROM model used in carrying out the long-run projections reported in the main body of the chapter. In carrying out what we label a COVID-19 scenario (abbreviated C19 in figure 7-2), a key modification has been made to accommodate a shorter run analysis compared to what was undertaken in the main chapter on forest products. To do this, we first updated the starting conditions of the projections to 2018 (rather than 2015, the starting point of the main chapter) and, in place of scenario-based projections, use the annual gross domestic product (GDP) forecasts of the Organization for Economic Cooperation and Development (OECD) for the world (OECD 2020) and U.S. Congressional Budget Office (CBO) for the United States (CBO 2020). The OECD and CBO forecasts for GDP envisioned a "V-shaped" recovery path. The modeling presented here also abstracts from the main chapter by not interacting (harmonizing) with the RPA Forest Dynamics Model in identifying model solutions. Variations on the scenario, C19-3, C19-6, and C19-8, quantify the effects under alternative 2020 U.S. GDP annual growth rates of -3 percent, -6 percent, and -8 percent, respectively. To identify the net effect of COVID-19 on the sector, we compared C19-3, C19-6, and C19-8 with a pre-COVID-19 projection of the U.S. and world economy made by CBO and OECD for 2020 and 2021. Assumed GDP growth from 2022 to 2030 stays the same for all the scenarios, corresponding to OECD's pre-pandemic projections (OECD 2020). Projections are to 2030, and our analysis focuses particularly on lumber markets.

According to the projections (figure 7-2), COVID-19 has time-varying impacts on lumber markets. Softwood lumber consumption, after an initial drop, quickly rebounds and exceeds what it would have been with no COVID-19. The difference increases to 2.2 to 3.5 million m^3 by 2030. Hardwood lumber consumption, in contrast, is projected to remain below the no-COVID-19 counterfactual level after its initial drop, 1.1 to 1.7 million m^3 less in 2030. The

Figure 7-2. Historic (1990 to 2019) and projected (2020 to 2030) U.S. lumber consumption, for softwood (left) and hardwood (right).



C19-3 = 2020 U.S. GDP annual growth rate of -3 percent; C19-6 = 2020 U.S. GDP annual growth rate of -6 percent; C19-8 = 2020 U.S. GDP annual growth rate of -8 percent.

combined effects of the changes in lumber consumption are to some extent consistent with Buongiorno (2021).

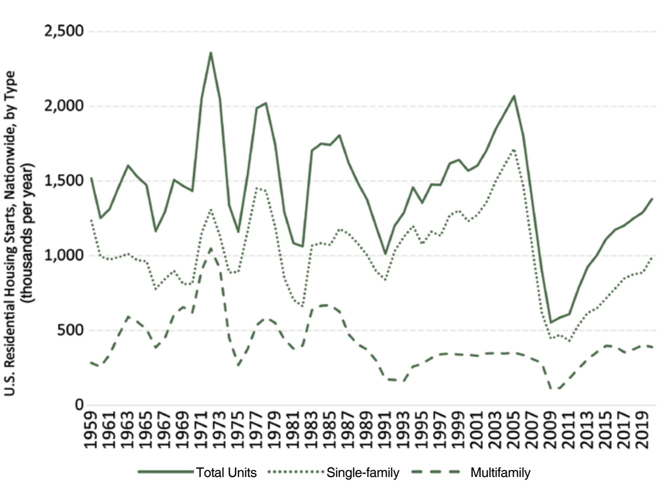
In line with the analysis in the Forest Products Chapter, the counterfactual analysis in this sidebar shows that the supply of and demand for forest products hinge on overall national economic growth. The rate of the economic growth following the 2020 nadir in consumption affects to what extent the forest product market may exhibit permanent impacts from the pandemic. A sharper but shorter "V-shaped" recovery makes up for the previous drop in growth and allows the production and consumption of forest products to return close to its long-run trend. In contrast, a longer period of U-shaped recovery reduces the production and consumption to a permanently lower level compared to the results based on the periodic FOROM.

This sidebar highlights the potential multi-year responses of forest product markets to COVID-19 disruptions. Evidence available today indicates that there were early significant disruptions in the wood products sector, but domestic U.S. production and imports slowly returned to near-normal levels 3 to 4 months after the United States first entered into a broad lock-down nationwide in March 2020 to limit virus spread (USDA FAS 2021). Despite the rapid increase in wood products demand following 3 to 4 months of subdued activity, the wood products sector has not proved immune to the multifaceted impacts of the pandemic. Producers were unable to respond to high demand promptly due to labor shortages and jumbled global supply chains (Riddle 2021), which constrained production combined with a relative abundance of standing timber volumes in much of the country—particularly in the Southern United States—and these factors combined to keep timber prices low (TimberMart-South 2021). We caution that this sidebar is not intended to be exhaustive of its effects of the pandemic on the sector; instead, it is provided to give a rough, first approximation of how it altered market conditions. Additionally, the simulation results are not intended to offer predictions of future market conditions but instead are offered to quantify how the pandemic affected markets.

2 percent) of all roundwood consumed, wood pellets have grown rapidly, destined for the European Union (EU) in support of that region's renewable energy policies.

The U.S. housing market (figure 7-3), a key component of wood products demand, has depended in part on a growing U.S. population and economy. Housing starts, in both single-family and multifamily units, have trended downward since World War II, although both categories are highly variable (U.S. Census Bureau 2021b). Prestemon et al. (2018) found a long-term trend downward in the number of housing units built, which could be connected to a slowing U.S. population (U.S. Census Bureau 2021a, Prestemon et al. 2022) and a slowing overall U.S. economy over time (e.g., Gordon 2016). To see how the projections in this chapter link to land use change, which embodies the new housing construction trends, see the sidebar The FOrest Resource Outlook Model (FOROM).

Figure 7-3. U.S. single-family and multifamily housing starts, 1959 to 2020.



Source: U.S. Bureau of the Census 2021.

A final long-term trend in the forest sector concerns climate (Tian et al. 2016). As greenhouse gases (GHGs) accumulate in the atmosphere, temperatures are rising and precipitation patterns are changing. Along with the higher GHG concentrations and higher temperatures is a general rise in net growth of forests, particularly when sufficient water is available to facilitate an acceleration in photosynthesis. Globally, forest productivity is expected to rise with altered GHG concentrations and higher temperatures. Such productivity rises could affect markets in diverse ways, including in the United States. With higher temperatures and the higher overall atmospheric water content that these higher temperatures enable, analysts expect changes in the frequency, intensity, spatial extent, and duration of natural disturbances, including from insects, diseases, tropical cyclones, wildfires, and droughts (see the Disturbance Chapter). Such disturbance changes may counter some of the climate forcing of forest productivity, and large-scale events can lead to market changes (e.g., Prestemon and Holmes 2000, 2004).

The future market outlook for forest products was projected from 2020 to 2070—based on a 2015 baseline—for the four future RPA scenarios (see the sidebar RPA Scenarios, as well as the Scenarios Chapter for more information), with the RPA climate projections incorporated through forest inputs from the Forest Dynamics Model (see the sidebar The FOrest Resource Outlook Model). These future scenarios provide a framework for describing a plausible range in the evolution of global forest product markets. When presenting the results, it is sometimes required to provide additional detail at the country/regional or product level. In these instances, the HM scenario (high warming-moderate U.S. growth) is used by default as it aligns closely with the SSP2 "middle-of-the-road" pathway, where many of the indicators broadly follow historical trends through 2070.

The future evolution of the U.S. and global forest products sector consistent with the RPA scenarios was modeled using the Forest Resource Outlook Model. FOROM incorporates various assumptions on socioeconomic developments consistent with the SSPs, and certain climatic influences on the global forest sector consistent with the RCPs. The sidebar FOrest Resource Outlook Model (FOROM) elaborates on how the four RPA scenarios were simulated within FOROM; those looking for more detailed information are encouraged to review Johnston et al. (2021).

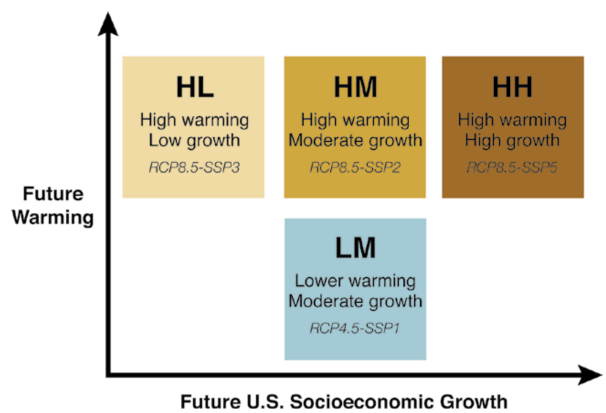
For a more in-depth overview of the state of the U.S. forest products sector, refer to other RPA products, including Status and Trends for the U.S. Forest Products Sector (Brandeis et al. 2021). Additional context about the United States as part of the global forest products sector is available from Wear et al. (2016) and Prestemon et al. (2015).

RPA Scenarios

The RPA Assessment uses a set of scenarios of coordinated future climate, population, and socioeconomic change to project resource availability and condition over the next 50 years. These scenarios provide a framework for objectively evaluating a plausible range of future resource outcomes.

The 2020 RPA Assessment draws from the global scenarios developed by the Intergovernmental Panel on Climate Change (IPCC) to examine the 2020 to 2070 time period (IPCC 2014). The RPA scenarios pair two alternative climate futures (Representative Concentration Pathways or RCPs) with four alternative socioeconomic futures (Shared Socioeconomic Pathways or SSPs) in the following combinations: RCP 4.5 and SSP1 (lower warming-moderate U.S. growth, LM), RCP 8.5 and SSP3 (high warming-low U.S. growth, HL), RCP 8.5 and SSP2 (high warming-moderate U.S. growth, HM), and RCP 8.5 and SSP5 (high warming-high U.S. growth, HH) (figure 7-4). The four 2020 RPA Assessment scenarios encompass the projected range of climate change from the RCPs and projected quantitative and qualitative range of socioeconomic change from the SSPs, resulting in four distinct futures that vary across a multitude of characteristics (figure 7-5), and providing a unifying framework that organizes the RPA Assessment natural resource sector analyses around a consistent set of possible world views. The Scenarios Chapter describes how these climate models were selected and paired; more details are provided in Langner et al. (2020).

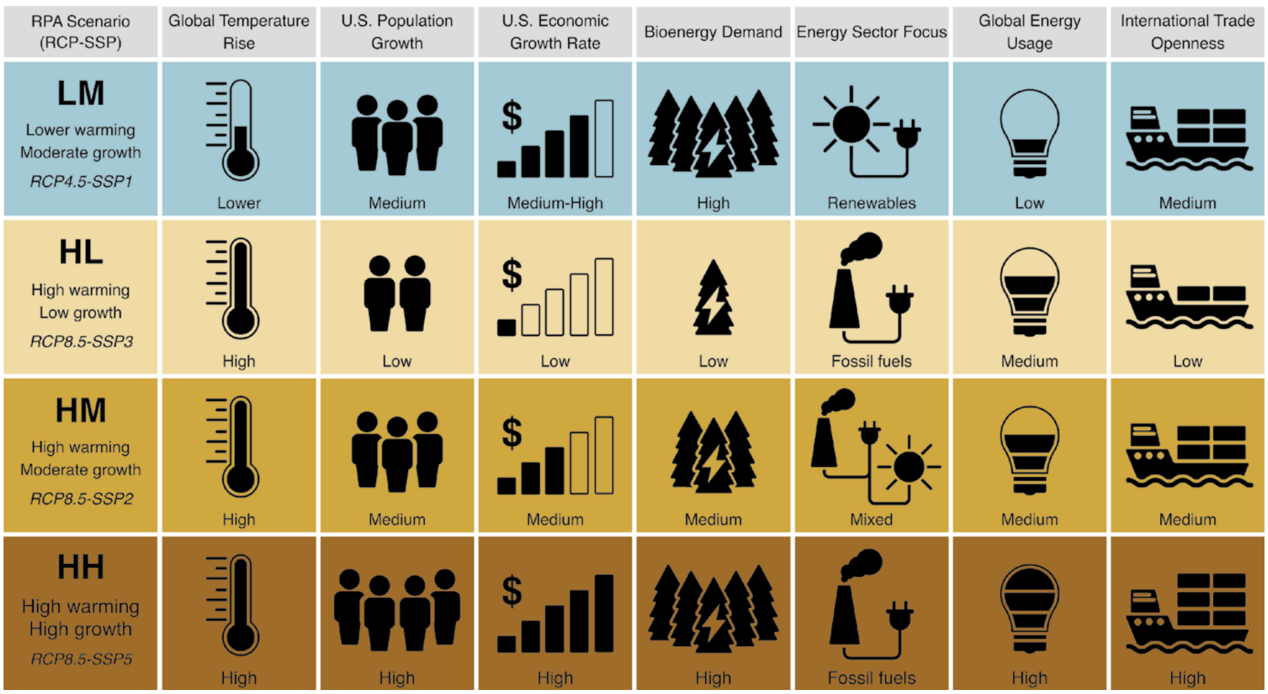
Figure 7-4. Characterization of the 2020 RPA Assessment scenarios in terms of future changes in atmospheric warming and U.S. socioeconomic growth. These characteristics are associated with the four underlying Representative Concentration Pathway (RCP) – Shared Socioeconomic Pathway (SSP) combinations.



Source: Langner et al. 2020.

The 2020 RPA Assessment pairs these four RPA scenarios with five different climate models that capture the wide range of projected future temperature and precipitation across the conterminous United States. An ensemble climate projection that averages across the multiple model projections is not used because of the importance of preserving individual model variability for resource modeling efforts. The five climate models selected by RPA represent least warm (MRI-CGCM3), hot (HadGEM2-ES), dry (IPSL-CM5A-MR), wet (CNRM-CM5), and middle-of-the-road (NorESM1-M) climate futures for the conterminous United States; however, characteristics can vary at finer spatial scales. Although the same models were selected to develop climate projections for both lower and high-warming futures, distinct climate projections for each model are associated with RCP 4.5 and RCP 8.5. The Scenarios Chapter describes how these climate models were selected. Joyce and Coulson (2020) give a more extensive explanation. An explanation of how the FOROM incorporated the effects of climate on forests globally is shown in the sidebar FOrest Resource Outlook Model (FOROM) and more extensively in Johnston et al. (2021).

Figure 7-5. Characteristics differentiating the 2020 RPA Assessment scenarios. These characteristics are associated with the four underlying Representative Concentration Pathway (RCP) – Shared Socioeconomic Pathway (SSP) combinations.



FOrest Resource Outlook Model (FOROM)

The FOrest Resource Outlook Model (FOROM) is a partial equilibrium model of the world's forest sector that includes forest resources, timber supply, demand for intermediate and final products, and international trade. The model is calibrated primarily to the FAOSTAT (FAO Stat 2021) 2015 base year information, supplemented with information from the U.S. Department of Agriculture, Forest Service's Timber Product Output (TPO) program and the United States International Trade Commission. The main function of this model is to analyze whether and to what extent production, consumption, trade, and prices of raw material, intermediates, and final products, as well as forest land area and forest standing stock, might change in response to external shocks such as economic growth, climate change, trade liberalization, or forest management.

FOROM incorporates various assumptions to help shape future conditions. The main drivers of the evolution of the global forest sector include exogenous trends in gross domestic product (GDP) and population. Market demand is assumed to change over time through exogenous shifts in GDP per capita, while changes in per capita GDP affect the marginal cost of production arising through changes in forest area and standing inventory.

Other exogenous assumptions, including technological development, provide the degree with which the global forest sector becomes efficient in transforming raw materials into finished products. Trade openness describes the frictions embedded in the model relating to the movement of goods between foreign regions of the model. In addition, the demand for bioenergy is calibrated to projections of primary and secondary biomass energy from the International Institute for Applied Systems Analysis Integrated Assessment Modeling framework, reflecting plausible differences in the future evolution of preferences (see Bauer et al. 2017).

To evaluate the forest sector impacts of climate change, exogenously projected changes in net primary productivity (NPP) were used in the FOROM to adjust the endogenous supply costs of each country/region outside the United States. Changes in NPP were simulated to 2070 at 0.5 degree-resolution globally by the dynamic global vegetation model MC2 (Kim et al. 2017), based on climate change (precipitation and temperature) and CO_2 (atmospheric forcing) change inputs. Climate and CO_2 change inputs to MC2 in Kim et al. (2017) were obtained from the MIT Integrated Global System Model-Community Atmosphere Model (IGSM-CAM) for RCP 4.5 (corresponding to the LM scenario) and RCP 8.5 (HL, HM, and HH RPA scenarios). MC2 projections under RCP 8.5 were averaged across all seven ensemble members (seven climate simulations) reported by Kim et al. (2017), while RCP 4.5 was projected with a single climate simulation from that study. NPP projections made by MC2 were aggregated to 16 global land units (countries or regions), and their average annual trends were converted to changes in forest productivity above base rates of growth for each country assigned to one of the global land units.

When solving for global forest sector solutions of the FOROM, however, climate-induced productivity change projections made by MC2 for the United States were replaced by those made by the RPA Forest Dynamics Model (FDM). FDM projections were averaged across the RPA climate projections (least warm, hot, dry, wet, middle) for each RPA scenario and each projection time-step. Projections of the U.S. forest sector made jointly with FOROM and the FDM were harmonized on inventory (volume) and removals (roundwood production) to find a roundwood price path where the inventory and removals for the United States aligned over the projection period. In each 5-year time step of FOROM, the FDM was used to calibrate inventory growth rates across the RPA regions, which were an exogenous input into FOROM. Then, FOROM projected an endogenous path of removals and roundwood prices. The roundwood prices were then used in the FDM harvest choice and timber supply models to project removals. The projected removals from FOROM and the FDM were then compared to ensure alignment.

Table 7-1 provides an overview of the defining characteristics of the RPA scenarios.

As GDP and population are key to the evolution of market projections in FOROM, they received special attention in the 2020 RPA Assessment. First, Wear and Prestemon (2019) developed a method to jointly downscale national-scale income and population projections to counties nationwide. This method was designed through statistical estimation of the relationships between historical personal income per capita at the county scale and population at the county scale. Downscaling was done such that the sum of income and the sum of population across counties matched the national level income and population projections,

Table 7-1. Key exogenous drivers of global trends in the RPA scenarios.

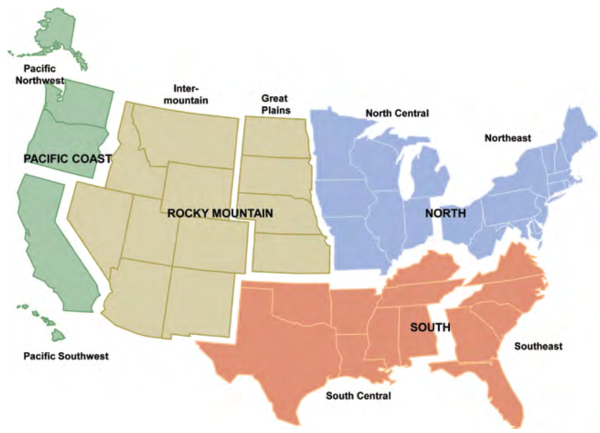
	RPA scenarios			
Exogenous driver	**LM**	**HM**	**HL**	**HH**
Socioeconomic				
GDP	High in LICs, MICs; moderate in HICs	Moderate	Low	High
Population	Relatively low	Moderate	Low in OECD, high in other countries	High in OECD, low in other countries
Technological change	High	Moderate	Low	High
Trade openness	Moderate	Moderate	Low	High
Bioenergy preferences	High	Moderate	Low	High
Climatic				
Atmospheric warming	Low	High	High	High
Motivated by the following IPCC scenarios				
SSP	SSP1	SSP2	SSP3	SSP5
RCP	RCP 4.5	RCP 8.5	RCP 8.5	RCP 8.5

GDP = gross domestic product; HIC = high income country; LIC = low income country; MIC = middle income country; OECD = Organization for Economic Cooperation and Development; RCP = Representative Concentration Pathway; SSP = Shared Socioeconomic Pathway; LM = lower warming-moderate U.S. growth; HL = high warming-low U.S. growth; HM = high warming-moderate U.S. growth; HH = high warming-high U.S. growth.

respectively, for each of the five Shared Socioeconomic Pathways; archived datasets are available from Wear and Prestemon (2019). Next, to generate projections of GDP and population at the RPA region level, a simple aggregation was done by summing projected personal income and projected population across all counties assigned to each RPA region.

FOROM explicitly recognizes the United States as six distinct RPA regions, separating the RPA North and South Regions into their component subregions for added specificity (see figure 7-6). The regional detail allows the model to directly account for changes in forest conditions and land uses and associated differences in regional production and demand conditions, including those emerging from independent projections of GDP and population from Wear and Prestemon (2019). For more detailed information on FOROM, see Johnston et al. (2021).

Figure 7-6. Resources Planning Act regions and subregions.



It is important to note that models like FOROM are calibrated to existing data, and parameterized based on historical relationships with existing product markets. Thus, as a limitation, these models cannot predict the invention of new products, or products that may be in their early stages of development (e.g., mass timber). Research on new products is ongoing, and some are considering how these new products may enter into models like FOROM (for an example, see Nepal et al. 2021 who explore various scenarios of integrating mass timber into FOROM).

Global Trends and Projections

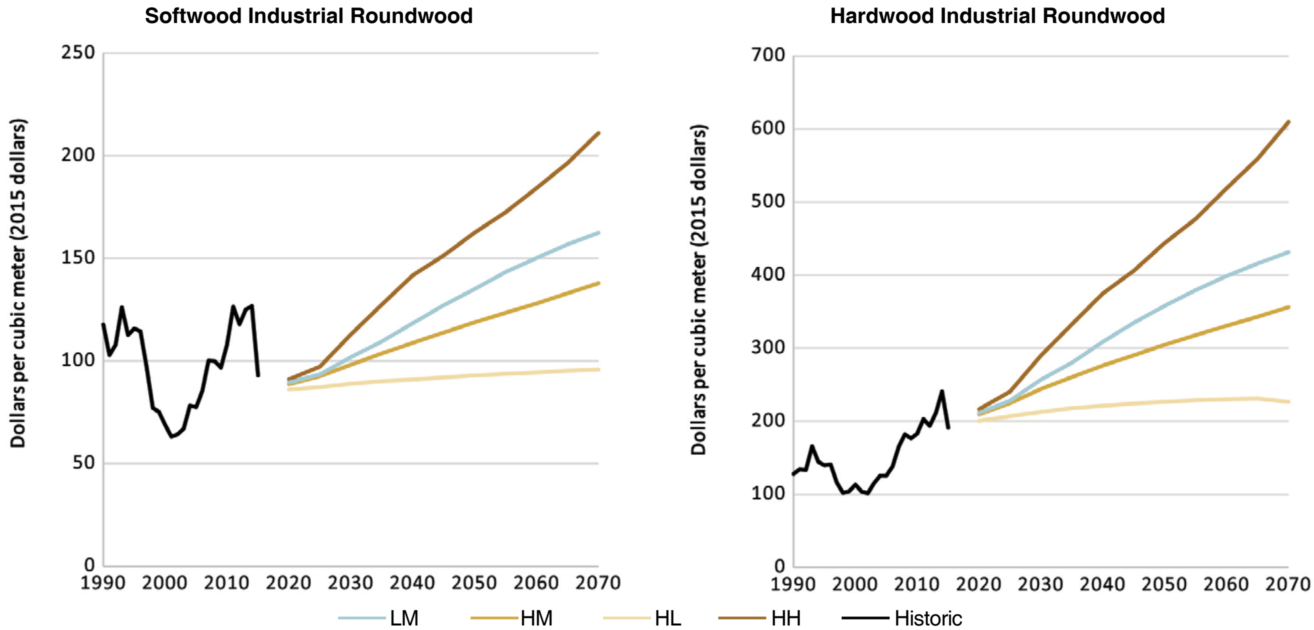
- ❖ Global forest products markets have been gradually recovering from the deep recession of 2007 to 2009. FOROM projects that global softwood roundwood consumption returns to pre-recession levels by 2020 and continues to grow thereafter. The hardwood industrial roundwood consumption trend resembles that of softwood but with a higher growth rate.
- ❖ Economic growth in emerging economies such as China and India drive much of the overall growth in demand for industrial roundwood across the scenarios.
- ❖ The consumption and production of new products such as wood pellets have the potential to increase significantly over the projection horizon under some scenarios but are contingent upon policy assumptions.
- ❖ There have been major structural changes in markets for some wood product categories since the deep recession of 2007 to 2009, including markets for newsprint and printing and writing paper which have experienced erosion in demand because of the growth in digital alternatives.

This section summarizes the market trends and FOROM-based global modeling results for major forest products (e.g., fuelwood and industrial roundwood) under the RPA scenarios. Historical data on the quantities of production, imports, exports, and unit values of products are available from Brandeis et al. (2021) for the United States and from FAO Stat (2021), which provided the input data for the global market model, FOROM. Global and U.S. projection data for this assessment are available from Johnston et al. (2022).

The real prices for softwood and hardwood industrial roundwood are projected to increase from 2020 to 2070 (figure 7-7). The prices exhibit large variations across the RPA scenarios, which are mostly driven by differences in the GDP developments. The price of softwood industrial roundwood products is expected to see the largest growth under the RPA HH scenario, rising from \$90.91 per m^3 to \$210.63 per m^3. In contrast, the HL scenario, which features a low GDP growth rate, is expected to see the lowest levels of price growth. Price elasticities of demand for hardwood are, on average, relatively smaller than that of softwood; therefore, a larger price rise is needed to satisfy the demand for hardwood industrial roundwood. Socioeconomic conditions, however, lead to the same general pattern of hardwood industrial roundwood price growth, with HH generating the highest and HL the lowest.

The demand for bioenergy in the form of fuelwood as well as wood pellets in FOROM are assumed to be driven not

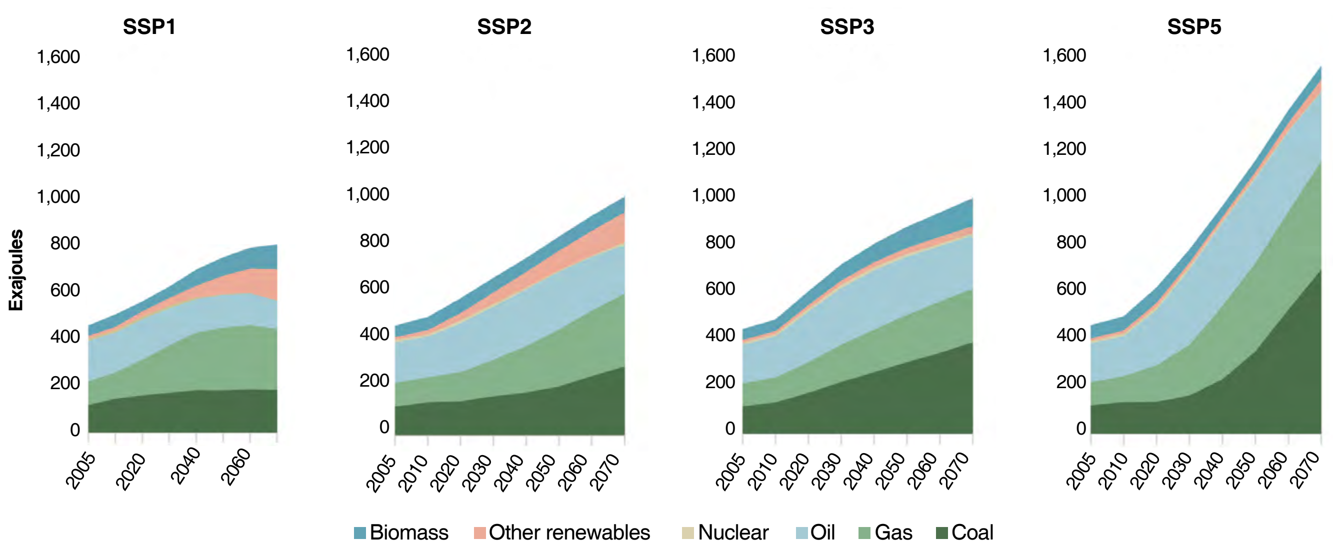
Figure 7-7. Projected average prices for global softwood industrial roundwood (left) and hardwood industrial roundwood (right) by RPA scenario, 2020 to 2070, relative to 2015 average prices.



LM = lower warming-moderate U.S. growth; HL = high warming-low U.S. growth; HM = high warming-moderate U.S. growth; HH = high warming-high U.S. growth.

only by economic development assumptions, but also by differences in consumer preference and policy assumptions underpinning the IPCC's Shared Socioeconomic Pathways (Bauer et al. 2017). For fuelwood demand, FOROM incorporates trends consistent with global primary energy from biomass from the IPCC SSP scenarios (figure 7-8). Similarly, the evolution of wood pellet consumption in FOROM is driven not only by changes in GDP per capita, but is also constrained using trends in global secondary biomass energy production to capture SSP-related preference and policy differences (figure 7-9). Global growth rates of secondary energy were used to scale recent regional growth rates. Secondary energy is energy that has been converted, and in the case of bioenergy, this could represent energy sourced from biomass including wood pellets.

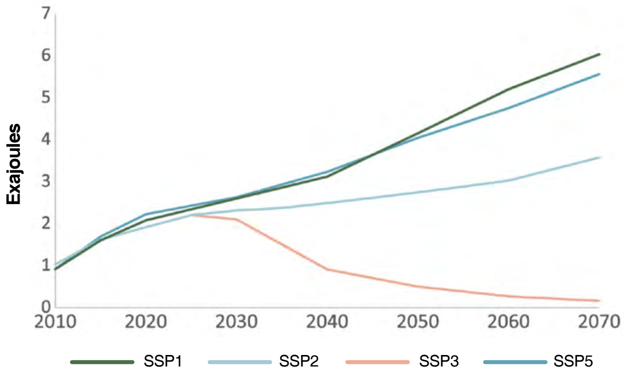
Figure 7-8. Global primary energy production for the IPCC Shared Socioeconomic Pathways used in the RPA Assessment.



IPCC = Intergovernmental Panel on Climate Change; SSP = Shared Socioeconomic Pathway.

Source: Riahi et al. 2017.

Figure 7-9. Global secondary energy production for the IPCC Shared Socioeconomic Pathways used in the RPA Assessment.



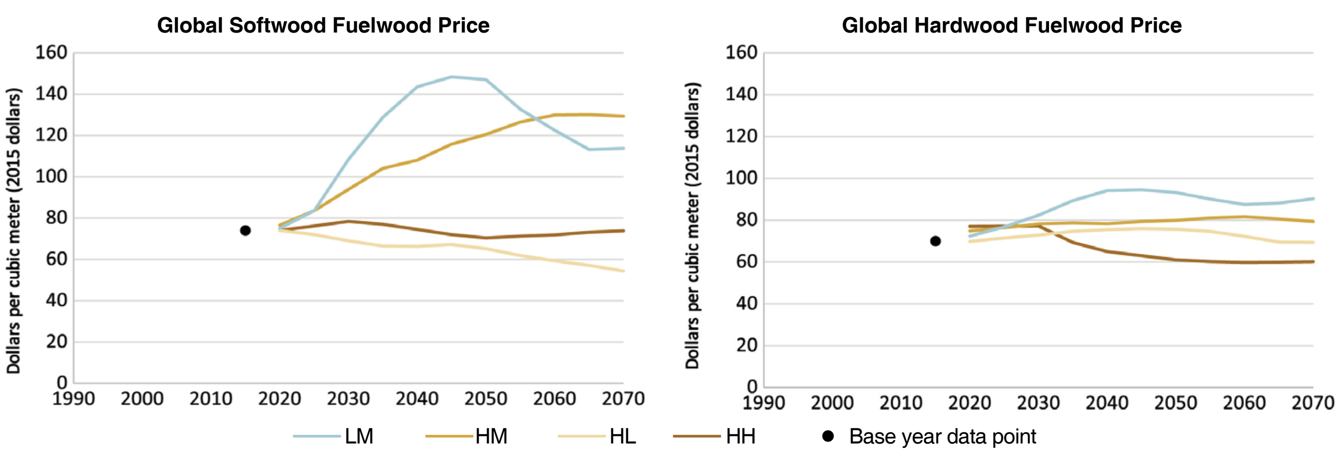
IPCC = Intergovernmental Panel on Climate Change; SSP = Shared Socioeconomic Pathway.
Source: Riahi et al. 2017.

To illustrate the projections of bioenergy demand under the RPA scenarios, consider the sustainability-minded SSP1 scenario that underpins the RPA LM scenario. Here, global average fuelwood consumption reaches its highest levels, driven in part by strong economic growth, but also from implied environmental and policy support. Correspondingly, we can see that in the LM scenario, the price of fuelwood rises rapidly and peaks in 2050 (figure 7-10). As preferences tend to shift more toward wood pellets, demand for fuelwood is gradually decreasing, resulting in a price drop. In contrast, the global average softwood fuelwood price in the HH scenario—a fossil fuel-dominated world—is expected to remain relatively unchanged. Even though there is a negative demand growth in the early period, the negative impact is mitigated by relatively high economic growth, leading to a relatively constant low fuelwood demand and price level throughout the simulation. The future price projection of hardwood fuelwood does not quite resemble the trends of softwood fuelwood because its positive income effect on demand is mitigated, to some extent. Thus, the growth rate of global average hardwood fuelwood price is smaller than that of softwood fuelwood price for the same scenario.

Over the past decade, the world has experienced a boom in wood pellets markets. Global wood pellet consumption reached 35.4 million metric tons (mt) in 2018, more than double its 2010 levels of 13.5 million mt. Europe is the world's largest wood pellet producer and consumer, mainly owing to EU's binding renewable energy targets for 2020 and 2030, and other environmental legislation. In 2018, the EU consumed 26.1 million mt of wood pellets but produced only 20.1 million mt. The gap between the supply and demand within the EU is contributing to the increasing importance of global wood pellet trade. In 2018, intercontinental trade in wood pellets amounted to 29 million mt, of which more than half (17 million mt) was imported from the United States by the United Kingdom.

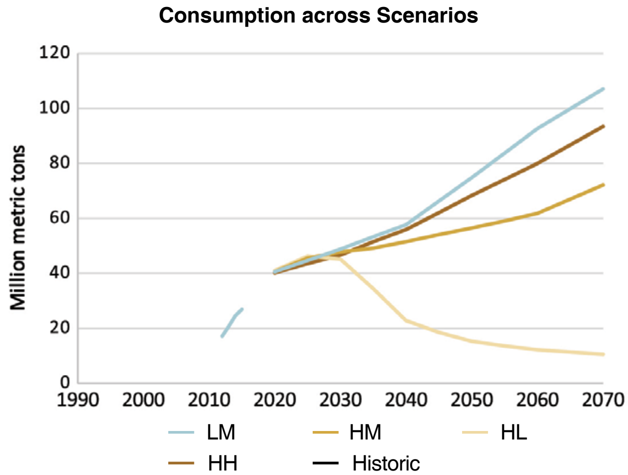
The RPA HL scenario is the only scenario in which global wood pellet consumption is projected to decrease (figure 7-11, left), which is primarily a result of projected expansion in fuelwood consumption and limited increase in industrial roundwood consumption. The other three scenarios exhibit a steady increase in the final consumption, ranging from 72 to 107 million mt across the RPA scenarios by 2070. Europe is undoubtedly the largest wood pellet consumer (figure 7-11, right), followed by North America. The growing trend continues throughout the simulation and the total consumption of wood pellets in these two regions reaches 53.2 million mt and 9.6 million mt by 2070, respectively (from 31.4 million mt and 4.8 million mt in 2020, respectively). However, it is important to note that future

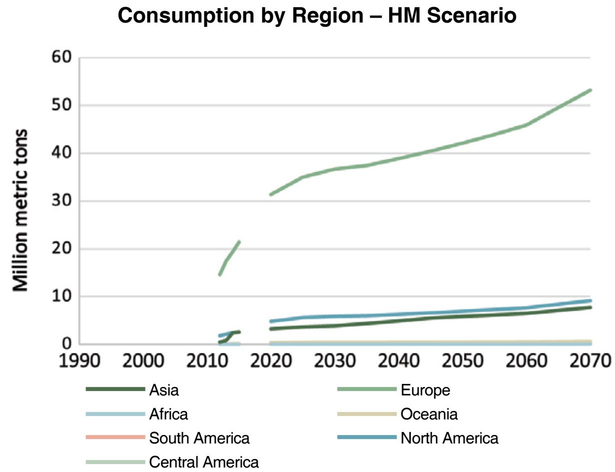
Figure 7-10. Projected average prices for global softwood fuelwood (left) and hardwood fuelwood (right) by RPA scenario, 2020 to 2070, relative to 2015 average prices.



LM = lower warming-moderate U.S. growth; HL = high warming-low U.S. growth; HM = high warming-moderate U.S. growth; HH = high warming-high U.S. growth.

Figure 7-11. Historic (2012 to 2015) and projected (2020 to 2070) global wood pellet consumption across RPA scenarios (left) and by region within the RPA HM scenario (right).



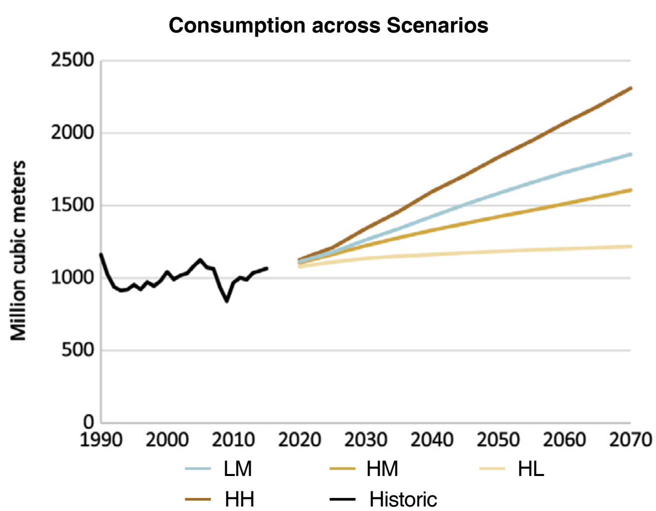


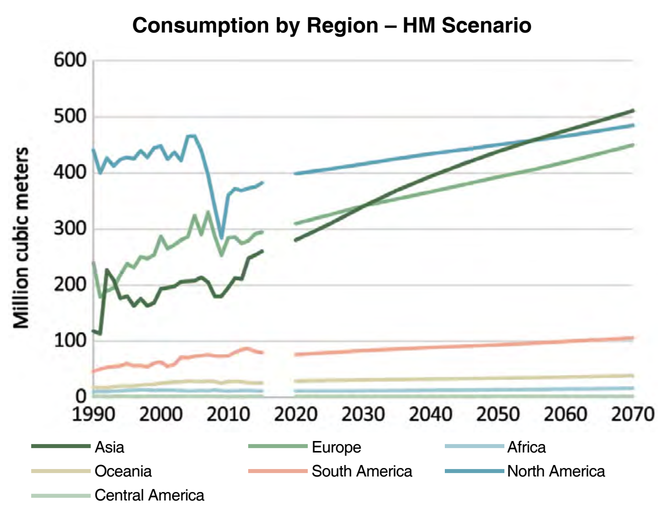
LM = lower warming-moderate U.S. growth; HL = high warming-low U.S. growth; HM = high warming-moderate U.S. growth; HH = high warming-high U.S. growth.

wood pellet markets have an additional layer of uncertainty compared to other products given the strong dependence on foreign policy and the treatment of wood in renewable energy targets.

Between 1990 and 2015, the global softwood industrial roundwood consumption fluctuated greatly, especially during the deep recession of 2007 to 2009 (sometimes referred to as the Great Financial Crisis, or GFC). After the U.S. housing bubble burst in 2008, softwood industrial roundwood consumption fell sharply. North America and Europe experienced the most severe consumption drop. With new housing construction rising since 2009, softwood lumber prices have risen, and softwood lumber and timber outputs have been gradually rising (Brandeis et al. 2021). Consumption will likely surpass the GFC level in 2020 and is projected to continue to grow by 2070 in all four RPA scenarios (figure 7-12, left). The projected global roundwood consumption trends directly hinge on assumptions about future economic growth. The consumption of softwood industrial roundwood more than doubles in the RPA HH scenario but only increases by 8 percent above its 2020 level in the RPA HL scenario. Regionally, the highest consumption growth is found in Asia, with China and India propelling the growth (figure 7-12, right). It is projected that industrial roundwood consumption in Asian markets will exceed that of the North American market in 2050 under the HM scenario and reach 511 million m^3 in 2070.

Figure 7-12. Historic (1990 to 2015) and projected (2020 to 2070) global softwood industrial roundwood consumption across RPA scenarios (left) and by region within the RPA HM scenario (right).





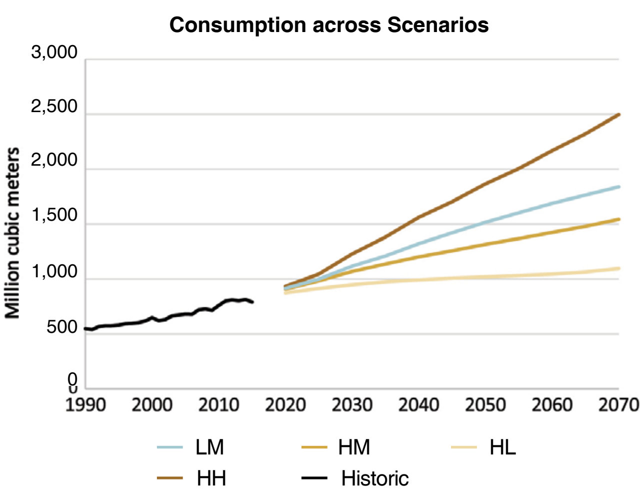
LM = lower warming-moderate U.S. growth; HL = high warming-low U.S. growth; HM = high warming-moderate U.S. growth; HH = high warming-high U.S. growth.

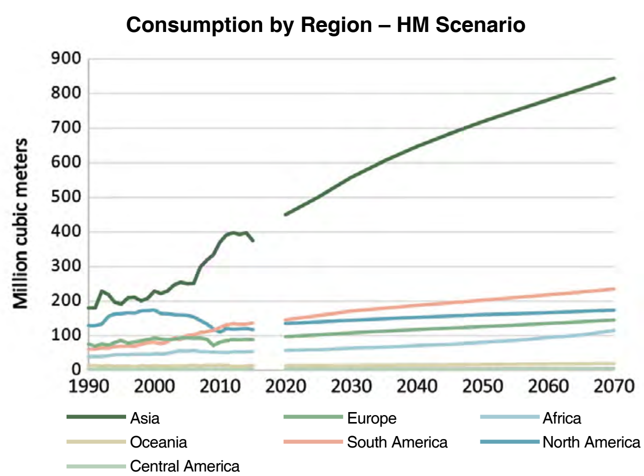
The lowest consumption growth occurs in Central America, where economic development is assumed to be slow and fragmented. North America has been, and is expected to continue to be, the highest per capita consumer of softwood roundwood with 798 m^3 per capita in 2020 and remain around this level through 2070. Asia is expected to increase its per capita consumption of softwood roundwood from 61 m^3 per capita in 2020 to 100 m^3 per capita in 2070.

Similarly, for hardwood industrial roundwood consumption, the largest increase occurs in the HH scenario and the smallest in the HL scenario (figure 7-13, left). The difference between the two scenarios reaches 1400 million m^3 in 2070. Global hardwood industrial roundwood consumption for scenarios HM and LM fall between HH and HL consumption levels throughout the projection period, largely because economic growth assumptions for these scenarios also fall between HH and HL. At the regional level, Asia is projected to continue to dominate hardwood industrial roundwood consumption (figure 7-13, right). Their share of global consumption is projected to increase from 48.2 percent in 2020 to 54.7 percent in 2070, reaching 844.5 million m^3 under the HM scenario. In contrast, other regional markets only experience minor additions to their roundwood use. South America is the highest per capita consumer of hardwood roundwood, consuming 340 and 487 m^3 per capita in 2020 and 2070 respectively. Meanwhile, Europe is projected to increase its consumption of hardwood roundwood from 97 to 165 m^3 per capita from 2020 to 2070.

The historical data indicate that a structural shift had been taking place in printing and writing paper markets since the beginning of the GFC. As the digital age matures, demand for printing and writing papers is expected to continue its trend of consumption decline throughout the projections (figure 7-14, left). In FOROM, the level of digital maturity is represented by GDP per capita. With the rapid growth in real GDP per capita, the LM scenario sees the largest reductions in the consumption of newsprint and printing and writing paper, to slightly more than one-fourth (26.12 percent) of its 2020 level by 2070. The decline is moderate in the HL scenario, where final consumption by 2070 amounts to 65 percent of 2020 global consumption levels (106.68 million mt in 2020). Figure 7-14 (right) shows a consistent negative trend in the consumption of newsprint and printing and writing paper across regions under the HM scenario. Asia accounts for the largest proportion of reduction, falling from 38 million mt to 11 million mt by 2070, followed by Europe and North America. Others have also highlighted this inverse relationship between economic growth and paper consumption, where economic development accelerates digitalization, and consumption patterns more rapidly shift away from hard print to digital alternatives (see Johnston 2016).

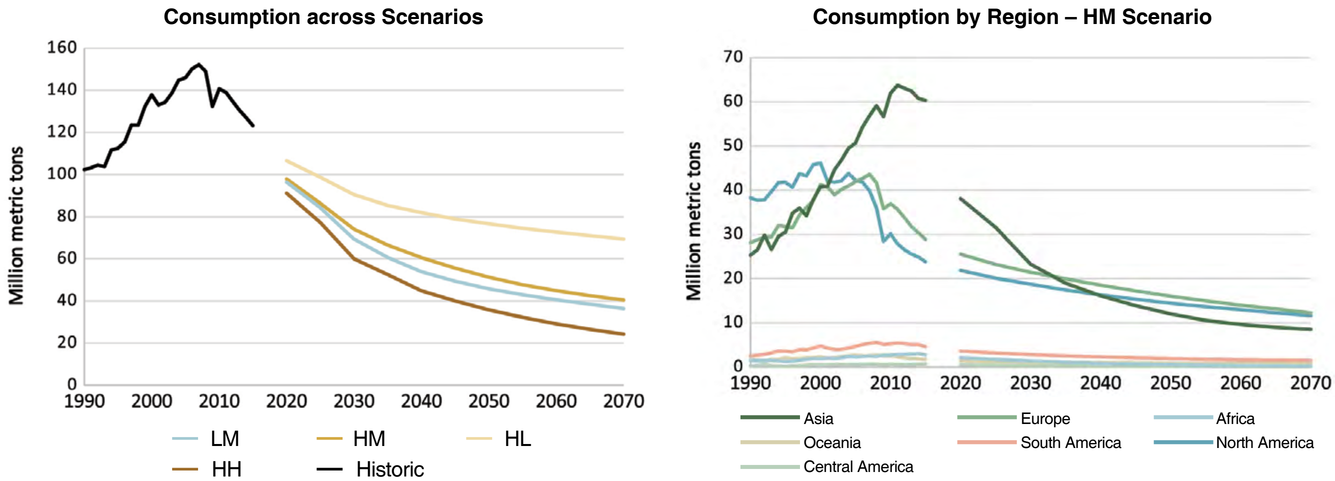
Figure 7-13. Historic (1990 to 2015) and projected (2020 to 2070) global hardwood industrial roundwood consumption across RPA scenarios (left) and by region within the RPA HM scenario (right).





LM = lower warming-moderate U.S. growth; HL = high warming-low U.S. growth; HM = high warming-moderate U.S. growth; HH = high warming-high U.S. growth.

Figure 7-14. Historic (1990 to 2015) and projected (2020 to 2070) global newsprint and printing and writing paper consumption across RPA scenarios (left) and by region within the RPA HM scenario (right).



LM = lower warming-moderate U.S. growth; HL = high warming-low U.S. growth; HM = high warming-moderate U.S. growth; HH = high warming-high U.S. growth.

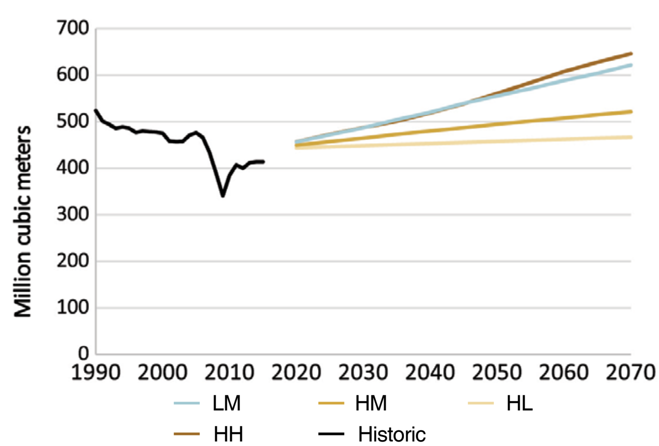
U.S. Trends and Projections

- ❖ U.S. roundwood production and prices are projected to trend upward across all scenarios, as wood product demand increases through 2070. Most projected production growth emerges from the RPA South Region, despite projected forest area shrinkage.
- ❖ Overseas markets are projected to support increasing net exports of hardwood lumber, and the United States is projected to become increasingly dependent on softwood lumber imports.
- ❖ Because of projected continued shrinkage in the demand for graphics paper and modest increases in the demand for other paper products, pulp production is projected to only increase slightly over the next 50 years. Two RPA scenarios (LM and HH) project a near doubling in the net export of non-graphics paper over this period.
- ❖ The RPA Southeast and South Central Subregions are projected to continue to supply the vast majority of wood pellets within the United States and remain the primary U.S. source of pellet exports through 2070.

Roundwood Production and Prices

Historical data and projections of U.S. roundwood production by RPA scenario are provided in figure 7-15. The production of roundwood in the United States trended downwards from the 1990s until the late 2000s. The global financial crisis in 2007 to 2009 saw a sharp reduction in roundwood production in the United States, falling from 466 million m^3 in 2007 to 341 million m^3 by 2009. A significant driver of this decline was the fall in residential housing construction, which dropped by about 75 percent between 2007 and 2009 (figure 7-3). Associated with this drop was a fall in the demand for building materials, particularly affecting softwood lumber and structural panel markets.

Figure 7-15. Historic (1990 to 2015) and projected (2020 to 2070) U.S. roundwood production by RPA scenario.



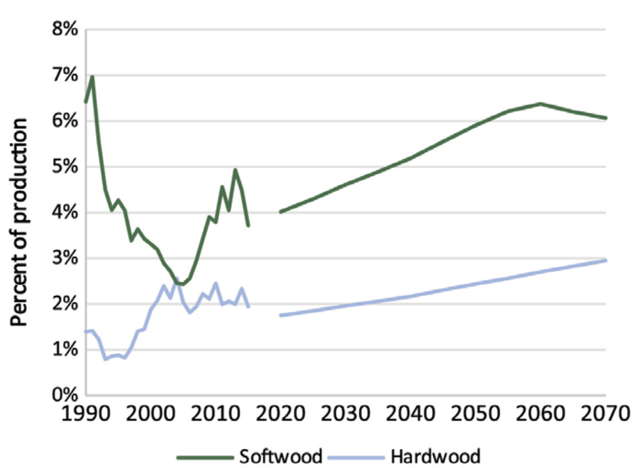
LM = lower warming-moderate U.S. growth; HL = high warming-low U.S. growth; HM = high warming-moderate U.S. growth; HH = high warming-high U.S. growth.

Since then, residential home construction and industrial roundwood production continue to rebound, with industrial roundwood production rising by roughly 20 percent between 2009 and 2015.

Projections of roundwood production across scenarios reach between an estimated 467 to 646 million m^3 by 2070 (figure 7-15). The production of roundwood is determined largely by the evolution of GDP, which varies from low under the HL scenario, to high under the HH scenario. Consumer preferences for fuelwood also impact the level of roundwood production. While the LM scenario is associated with only moderate growth in real GDP per capita, it relies on the socioeconomic developments under SSP1 which is grounded on strong sustainability preferences favoring bioenergy (see figures 7-8 and 7-9). Consequently, the LM scenario produces a similarly high level of roundwood. U.S. (and global) projection data for this assessment are available from Johnston et al. (2022).

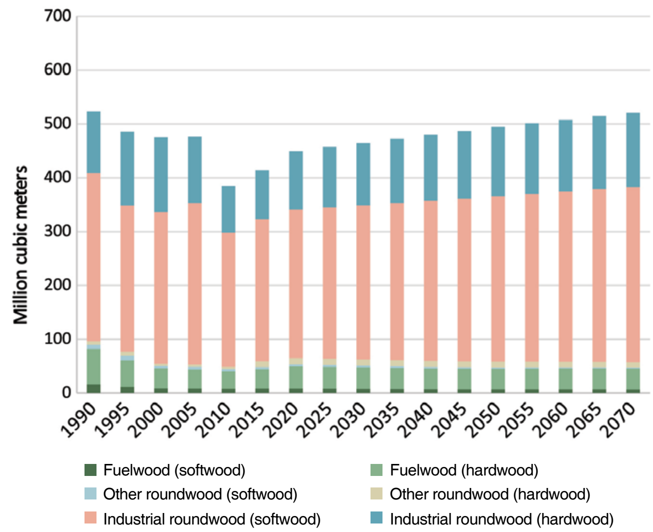
Figure 7-16 shows the export share of industrial roundwood production for softwood and hardwood roundwood. The GDP impacts of the GFC were pronounced within the United States, leading to sharp reductions in the demand for building materials. While similar effects were being felt in foreign economies, they tended to be less severe on average. As a result, this led to a reversal of the trend of a declining share of softwood roundwood production being exported observed in the 1990s for softwood roundwood, as domestic markets began to seek foreign buyers to compensate for reduced domestic demand. Markets for hardwood roundwood depend less on growth in residential housing, and export shares of production remained stable through the GFC period. Looking forward, FOROM projects an increase in the share of roundwood production exported for both hardwood and softwood under the HM scenario over the next 50 years, driven largely through the rapid consumption expansion of developing economies such as China and India.

Figure 7-16. Historic (1990 to 2015) and projected (2020 to 2070) U.S. industrial roundwood exports as share of production for the RPA HM scenario.



HM = high warming-moderate U.S. growth.

Figure 7-17. Historic (1990 to 2015) and projected (2020 to 2070) U.S. roundwood production by type for the RPA HM scenario.

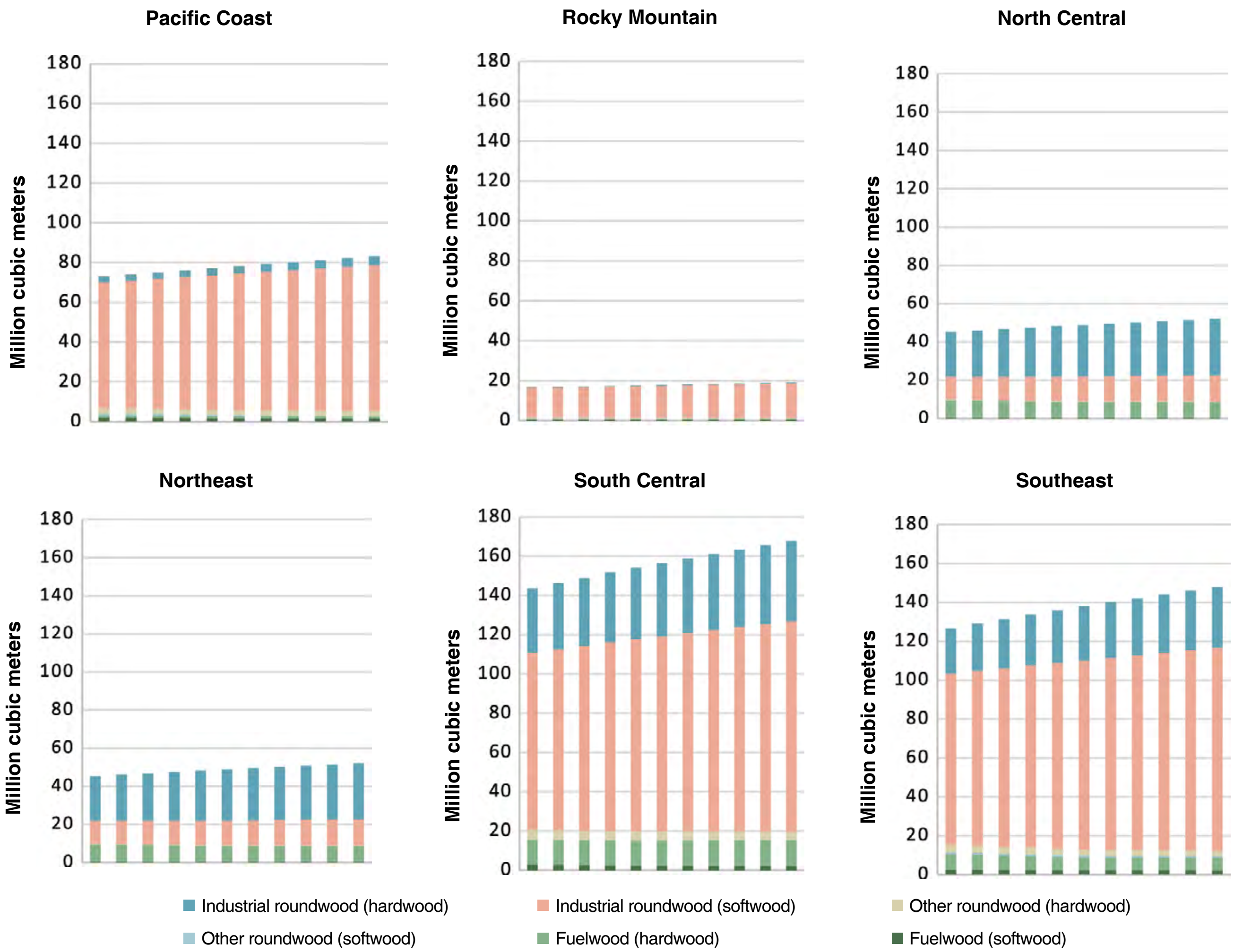


HM = high warming-moderate U.S. growth.

Since 1990, industrial roundwood from softwood and hardwood species composed over 80 percent of total roundwood production (figure 7-17). Before the GFC, the declines in roundwood production came predominantly from fuelwood and other roundwood categories, while softwood and hardwood industrial roundwood was more stable. However, during the GFC, the largest impacts were in the softwood industrial roundwood sector, driven through sharp GDP impacts affecting residential housing and other softwood-demanding sectors. FOROM projects the production of softwood industrial roundwood will return to pre-GFC levels in the coming decades, and mild growth in hardwood industrial roundwood production will materialize, driven largely through increased demand for hardwood fiber from emerging economies like India and China.

The FOROM model recognizes RPA Assessment regions as separate producing, consuming, and trading regions within a complete global market and can capture market dynamics by region across scenarios. Figure 7-18 depicts roundwood production projections by RPA region and by type, for the HM scenario. The classification of forest products used in this chapter is described in detail in Johnston et al. (2021, table A-3). Most of the growth across regions is projected to come from increased production of industrial roundwood, while other roundwood and fuelwood, regardless of species, is expected to remain constant. Most of the softwood industrial roundwood production is projected to continue to come out of the RPA South and Pacific Coast Regions, with the largest growth in softwood industrial roundwood

Figure 7-18. Projected roundwood production by RPA region for the RPA HM scenario, 2020 to 2070. The RPA North and South Regions are broken into subregions to provide additional information.



HM = high warming-moderate U.S. growth.

production coming out of the South Central and Southeast Subregions despite projected losses in forest area (see the Forest Resources Chapter). Meanwhile, the two RPA northern subregions rely more on hardwood industrial roundwood production. Despite this, the largest growth in hardwood production is projected to come out of the South Central Subregion.

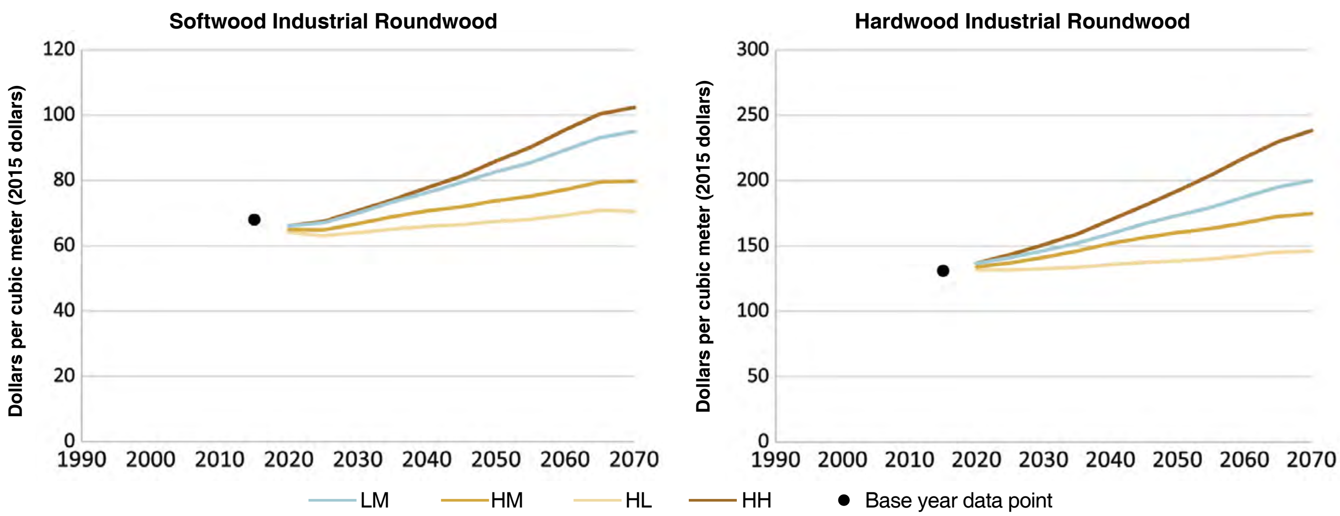
The average price of softwood industrial roundwood has been on a declining trend in recent years, which is projected to continue in the short run (figure 7-19, left). This trend could reverse quickly under a high-growth future scenario. The highest GDP scenario—the HH scenario—elicits the greatest demand for wood products, increasing the price of industrial roundwood the most relative to today's levels. Conversely, the lower growth HL scenario puts minimal pressure on the forest sector to meet demand, yielding, on average, an almost-stagnant path in the United States. Similar trends are projected for average U.S. hardwood industrial roundwood prices (figure 7-19, right).

Solid Wood Products

Lumber

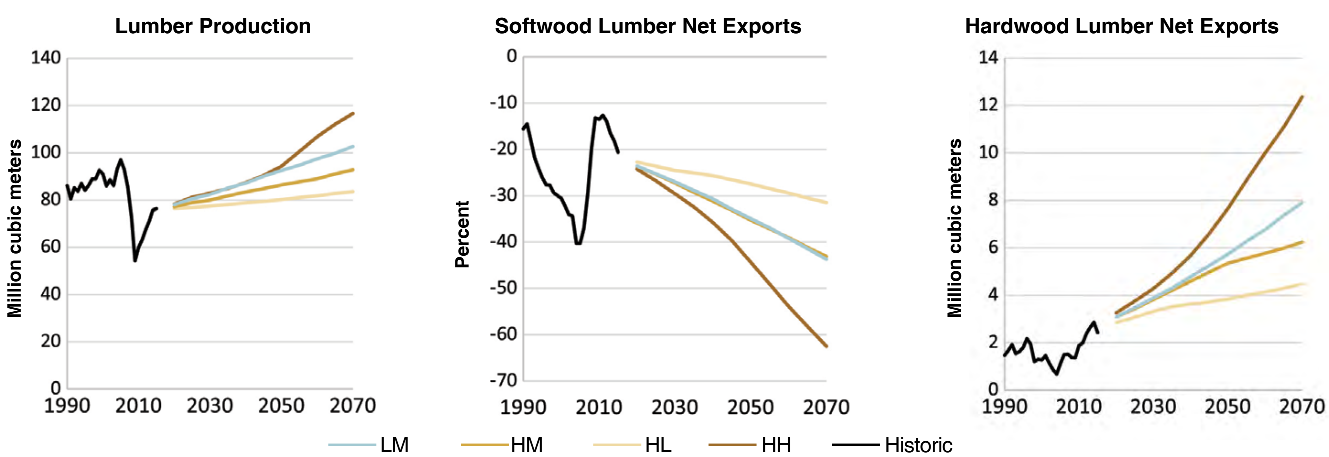
The production of lumber in the United States had been on an increasing trend before the GFC (figure 7-20, left), dominated by the production of softwood lumber—representing about 70 percent of total annual lumber production during this time.

Figure 7-19. Projected average prices for U.S. softwood industrial roundwood (left) and hardwood industrial roundwood (right) by RPA scenario, 2020 to 2070, relative to 2015 average prices.



LM = lower warming-moderate U.S. growth; HL = high warming-low U.S. growth; HM = high warming-moderate U.S. growth; HH = high warming-high U.S. growth.

Figure 7-20. Historic (1990 to 2015) and projected U.S (2020 to 2070): lumber production (left), softwood lumber net exports (middle), and hardwood lumber net exports (right), by RPA scenario.



LM = lower warming-moderate U.S. growth; HL = high warming-low U.S. growth; HM = high warming-moderate U.S. growth; HH = high warming-high U.S. growth.

The lumber sector experienced a sharp reduction in production in 2008 to 2009, brought about through reduced demand for residential home building materials. During this time, total lumber production fell from 93 million m³ in 2007 to 54 million m³ by 2009. Historically, the United States consumed more than it produced, making its net exports (exports minus imports) negative for softwood lumber, sourcing lumber primarily from Canada. During the GFC, net exports contracted towards zero (figure 7-20, middle), driven largely through a sharp reduction in the import of lumber, as the demand for this product eroded with reduced residential home construction. In contrast, the United States has historically been a positive net exporter of hardwood lumber (figure 7-20, right). Net exports of U.S. hardwood lumber were relatively unaffected by the GFC, because demand for hardwood lumber is less sensitive to fluctuations in residential construction, and being a net exporter of hardwood lumber meant this trade pattern was less sensitive to the domestic economic impacts of the GFC.

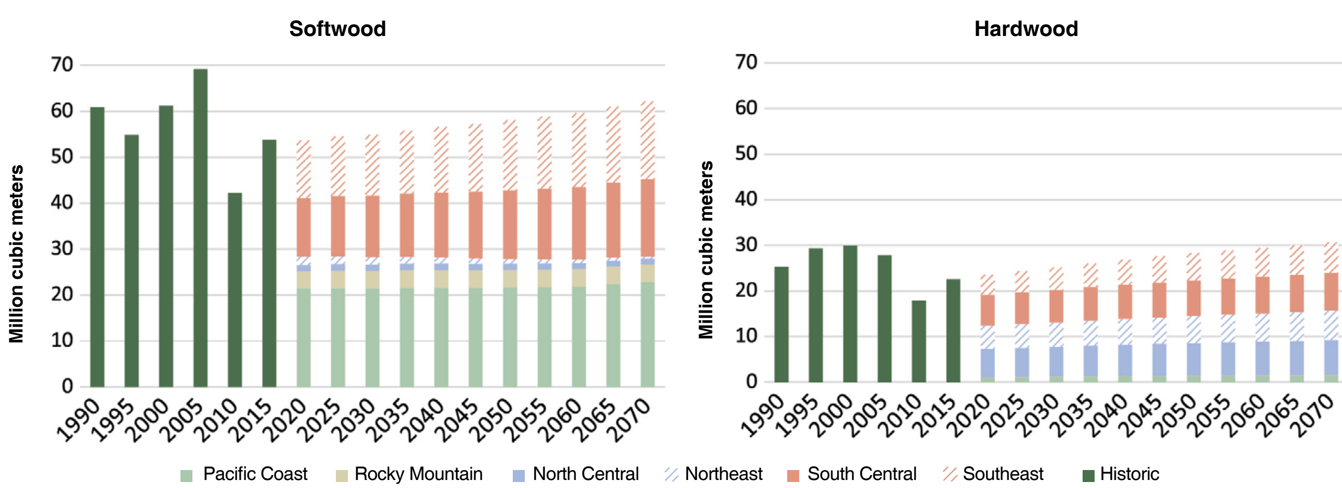
The future of lumber production in the United States is projected to be largely driven by the evolution of GDP assumed in the RPA scenarios. The high-income HH scenario sees the largest increase in the production of lumber, rising from 76 million m³ in 2015 to 117 million m³ by 2070 (figure 7-20, left). Meanwhile, the low-income HL scenario projects U.S. lumber production to reach only 84 million m³ by 2070. The scenarios project a continued trend of net softwood imports (negative net exports) under all scenarios (figure 7-20, middle). It is projected that net imports of softwood lumber in the United States will increase to 31 million m³ by 2070 under the low-income HL scenario, and as much as 62 million m³ by 2070 under the HH scenario. Meanwhile, the scenarios project a continued trend of net exports of hardwood lumber exports from the United States, ranging from at least 5 million m³ by 2070 under the HL scenario to as much as 12 million m³ by 2070 under the HH scenario (figure 7-20, right).

U.S. lumber production is projected to continue to be dominated by the production of softwood lumber, coming primarily out of the RPA South and Pacific Coast Regions (figure 7-21, left). While the Pacific Coast is currently the largest producer of softwood lumber, the model predicts only a 7-percent increase in production in the region between 2020 and 2070. Meanwhile, investments in planting and plantation forests have the South Central and Southeast Subregions increasing production by 32 and 36 percent during this period, respectively. Alternatively, production of hardwood lumber is concentrated in the four RPA South and North subregions, representing 95 percent of total hardwood lumber production combined (figure 7-21, right). Growth in production of hardwood lumber is projected to be distributed approximately evenly across these major producing subregions, driven in large part through increased foreign demand for these products from emerging markets.

Wood-Based Panels

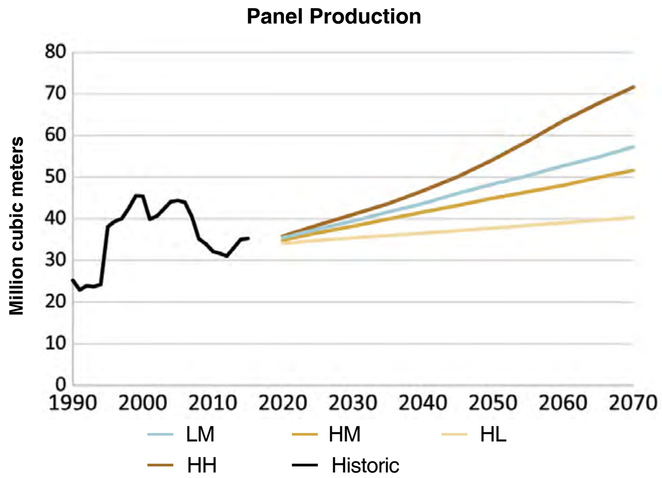
The production of wood-based panels in the United States experienced a similar adverse effect from the GFC and had yet to return to pre-GFC levels as of 2015 (figure 7-22). This is due, in part, to the slow rebound in U.S. residential home construction (figure 7-3), and the continued rise of China as the dominant wood-based panel supplier. Despite producing 35 million m³ in 2015, the United States has most recently been a net importer of wood-based panels (figure 7-22), again due in part to the low-cost alternatives coming

Figure 7-21. Historic (1990 to 2015) and projected (2020 to 2070) U.S. production of softwood lumber (left) and hardwood lumber (right) for the RPA HM scenario.



HM = high warming-moderate U.S. growth.

Figure 7-22. Historic (1990 to 2015) and projected (2020 to 2070) U.S. wood-based panels production (left) and net exports (right) by RPA scenario.



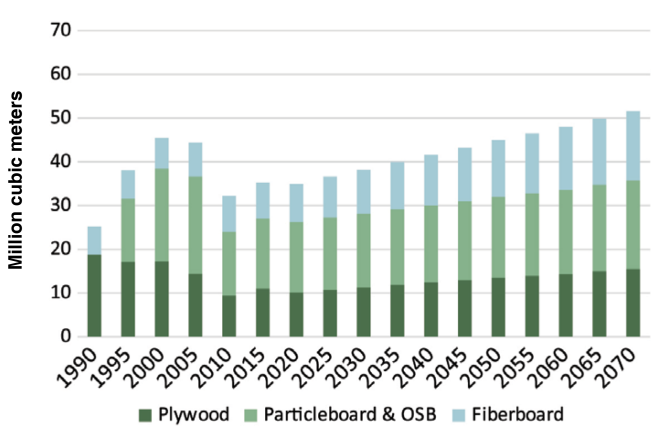
LM = lower warming-moderate U.S. growth; HL = high warming-low U.S. growth; HM = high warming-moderate U.S. growth; HH = high warming-high U.S. growth.

from foreign markets such as China. While production of panels has historically been dominated by the production of plywood and veneer (figure 7-23), the share of production from particleboard and oriented strand board (OSB) and fiberboard has been increasing since the 1990s. In 2020, about 70 percent of total wood-based panel production originated in the RPA South Region (figure 7-24).

The production of wood-based panels in the United States is projected to continue to increase under all scenarios (figure 7-22). The low-income HL scenario has production rising from 36 million m³ in 2015 to 40 million m³ by 2070. Production is projected to increase to as high as 72 million m³ in 2070 under the HH scenario. The country is projected to become an even larger net importer of panels under the HL scenario, as the low-income path provides less foreign demand competing for these products (figure 7-22). Conversely, the opposite is true for the HH scenario, where high income growth around the world creates more competition for panels, raising prices and pushing the United States to reduce its imports.

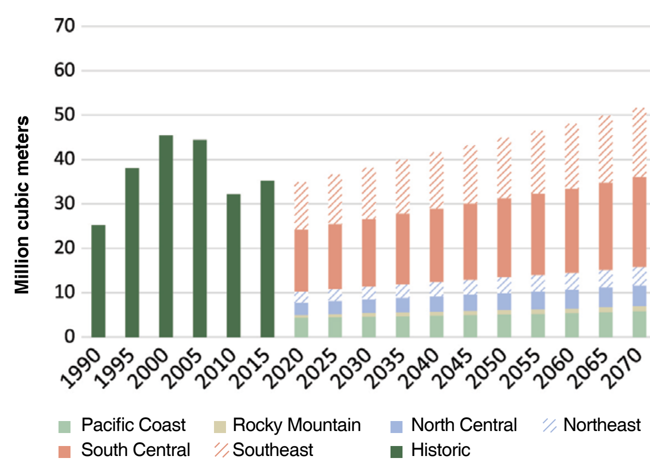
Production of panels is projected to continue to rely heavily on the South Central and Southeast Subregions through 2070 (figure 7-24). Under the HM scenario, it is projected that while plywood and veneer production will continue to rise modestly,

Figure 7-23. Historic (1990 to 2015) and projected (2020 to 2070) U.S. wood-based panels production by type for the RPA HM scenario.



HM = high warming-moderate U.S. growth; OSB = oriented strand board.

Figure 7-24. Historic (1990 to 2015) and projected (2020 to 2070) U.S. wood-based panels production by region for the RPA HM scenario.



HM = high warming-moderate U.S. growth.

much of the growth will come from fiberboard, and to a lesser extent from particleboard and OSB (figure 7-23). In 1990, plywood and veneer production comprised 74 percent of all wood-based panels production in the United States. By 2015, this number had declined to 31 percent. Fiberboard is expected to increase its relative importance in U.S. panel production, rising from 26 percent of all production in 1990 to 31 percent by 2070 in the HM scenario. The aggregate of particleboard and OSB production, meanwhile, has grown from a negligible amount in 1990 to the largest share of total panels production by volume by 2070.

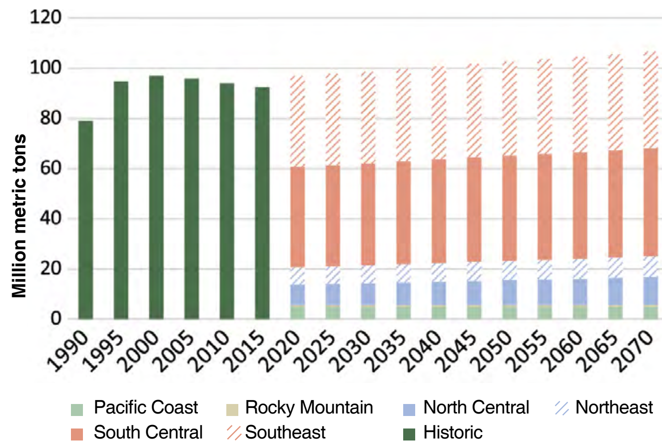
Pulp and Paper

Pulp production in the United States increased from 82 million metric tons in 1990 to 92 million metric tons by 2015 (figure 7-25). Given the projected declines in consumption of newsprint and printing and writing paper across all scenarios, it follows that only modest growth in pulp production is projected. For example, U.S. pulp production reaches an estimated 99 million metric tons in 2070 under the HL scenario, while it is projected to reach 128 million metric tons in 2070 under the HH scenario. The Southeast and South Central Subregions dominate other regions in pulp production currently, representing about 78 percent of all pulp output in 2020. It is projected that much of the growth in pulp production will come from the Southeast, South Central, and to a lesser extent, the North Central Subregions between 2020 and 2070 (figure 7-26).

Most of the pulp produced in the United States is waste (i.e., pulp made from recycled paper) and chemical forms. Mechanical pulp has historically represented a small share of total production and has been decreasing further since the 1990s. Meanwhile, waste pulp has been increasing its share of total pulp production since the 1990s, rising from 33 percent to about 50 percent of total pulp production by 2015 (figure 7-27). The U.S. production of pulp is projected to continue to be dominated by waste and chemical types.

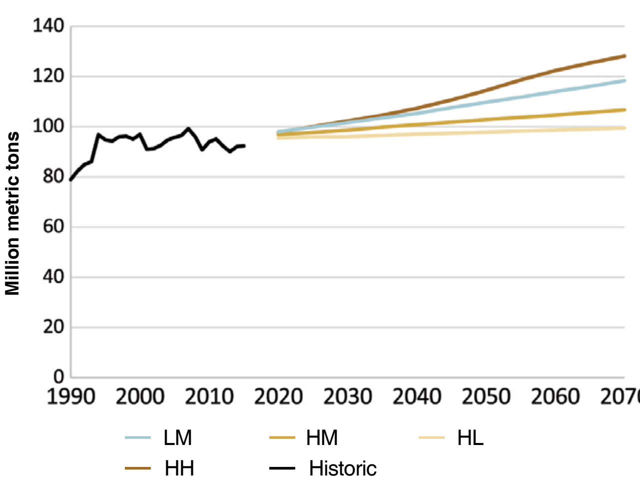
The demand for pulp is derived through the demand for final paper products (newsprint, printing and writing paper, and other paper and paperboard). As described earlier (see figure 7-14), the last decade has seen a structural break in the demand for newsprint and printing and writing paper, as consumers switch toward digital substitutes. In the United

Figure 7-26. Historic (1990 to 2015) and projected (2020 to 2070) U.S. pulp production by region for the RPA HM scenario.



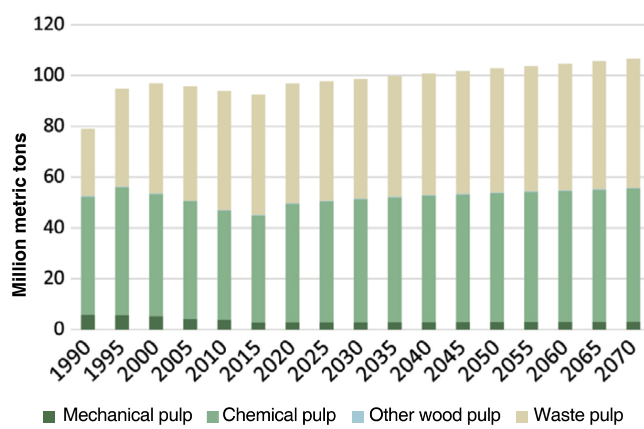
HM = high warming-moderate U.S. growth.

Figure 7-25. Historic (1990 to 2015) and projected (2020 to 2070) U.S. pulp production by RPA scenario.



LM = lower warming-moderate U.S. growth; HL = high warming-low U.S. growth; HM = high warming-moderate U.S. growth; HH = high warming-high U.S. growth.

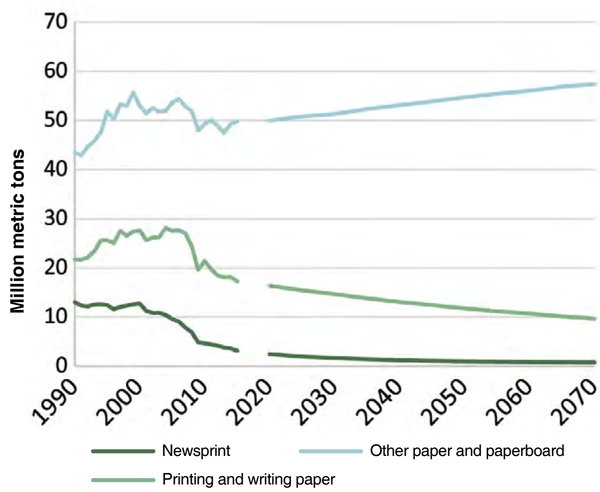
Figure 7-27. Historic (1990 to 2015) and projected (2020 to 2070) U.S. pulp production by type for the RPA HM scenario.



HM = high warming-moderate U.S. growth.

States, the consumption of these products peaked in the early 2000s and has since been on a steady decline (figure 7-28). Meanwhile, the demand for other paper and paperboard has been relatively stable in the United States during this time, driven in large part by increased demand for packaging materials to support online shopping and the robust demand for tissue papers, which rises with GDP. Consumption of newsprint and printing and writing paper were 75 and 38 percent below their 2000 levels by 2015, respectively. The consumption levels for other paper and paperboard were relatively unaffected during this period despite the impacts of the GFC. It is projected that newsprint, and printing and writing paper, will continue this trend through 2070, declining to 94 and 65 percent below their 2000 levels by 2070, respectively, under the HM scenario. Other paper and paperboard is projected to continue stable growth, growing 9 percent above its 2000 levels by 2070, under the HM scenario.

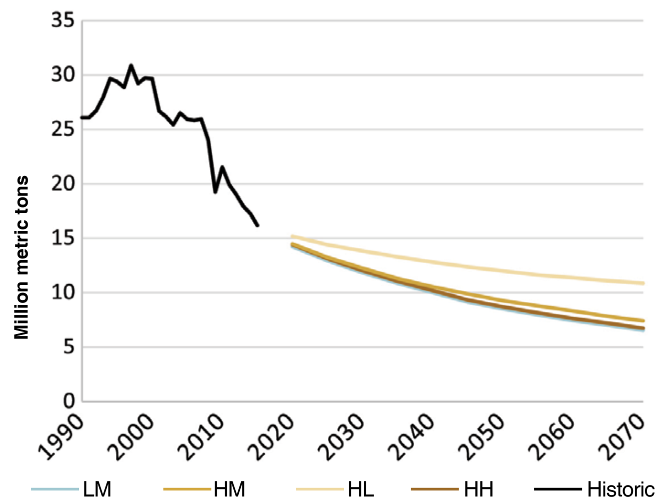
Figure 7-28. Historic (1990 to 2015) and projected (2020 to 2070) U.S. paper consumption by type for the RPA HM scenario.



HM = high warming-moderate U.S. growth.

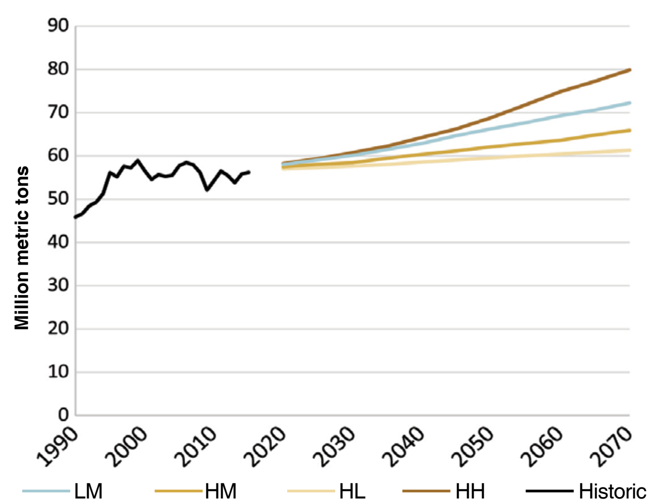
The sensitivity of these sectors to the path of GDP is highlighted in figures 7-29 and 7-30 showing diverging patterns. For newsprint and printing and writing paper, low economic growth in the HL scenario yields a slower path of digitalization, and therefore a slower path for substituting away from these paper products (figure 7-29). As a result, it is projected that production of the combined newsprint and printing and writing paper products will be 63 percent below 2000 levels by 2070 under the low-income HL scenario, and as much as 77 percent below 2000 levels under

Figure 7-29. Historic (1990 to 2015) and projected (2020 to 2070) U.S. production of newsprint and printing and writing paper by RPA scenario.



LM = lower warming-moderate U.S. growth; HL = high warming-low U.S. growth; HM = high warming-moderate U.S. growth; HH = high warming-high U.S. growth.

Figure 7-30. Historic (1990 to 2015) and projected (2020 to 2070) U.S. production of other paper and paperboard by RPA scenario.



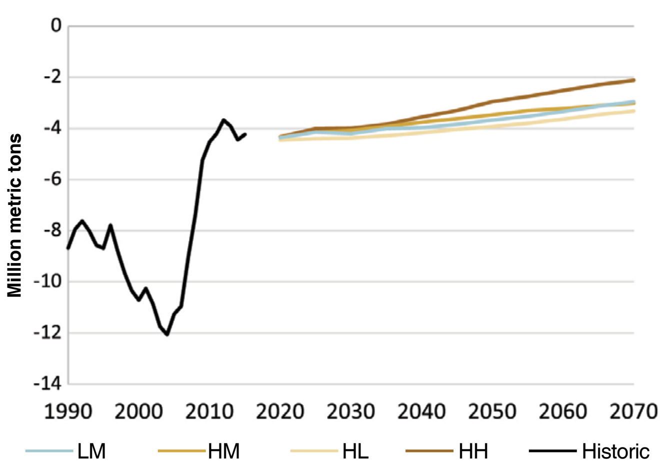
LM = lower warming-moderate U.S. growth; HL = high warming-low U.S. growth; HM = high warming-moderate U.S. growth; HH = high warming-high U.S. growth.

the higher income HH scenario. Conversely, other paper and paperboard production—which is complementary to digitalization as it supports packaging for online order shipments—yields as much as a 28-percent increase over 2000 levels by 2070 under the high-income HH scenario. The HL scenario yields a mere 8 percent growth in U.S. production of other paper and paperboard from 2000 levels by 2070, because low economic growth is related to lower manufacturing growth and connected to a slower rate of growth in online purchases and the packaging needed for deliveries to consumers.

The U.S. has historically been a net importer of newsprint and other printing and paper products (figure 7-31). The trend of decreasing demand for these products, as well as the economic impacts associated with the GFC, cut net imports to nearly 1/3 relative to pre-GFC levels. This trend is expected to continue as the U.S. and other economies continue to digitalize and is relatively insensitive to the degree of economic growth under the various scenarios. On the other hand, the United States has historically been a net exporter of other paper and paperboard products (figure 7-32), brought on by the move towards online shopping. Exports of these products are sensitive to assumptions about future economic growth, as the demand for shipping materials depends largely on the development of emerging markets like India and China. It is projected that exports of U.S. other paper and paperboard products will remain stagnant or even decline slightly under the HL scenario yet continue to increase sharply under the higher income HH scenario.

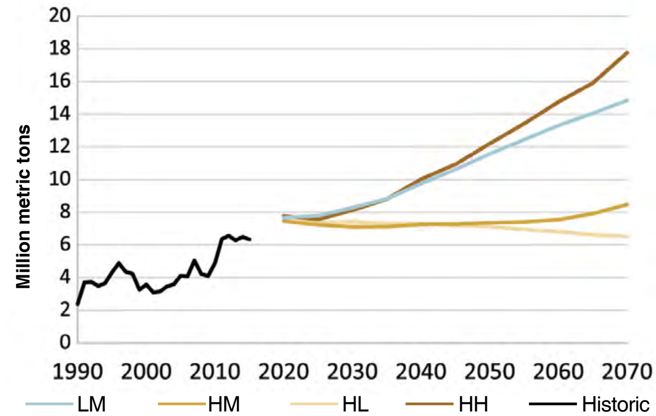
Production of newsprint is concentrated within the Southeast and South Central Subregions, representing a combined 77 percent of total U.S. production in 2020. Under the HM scenario, it is projected that these subregions will lose about 50 percent of their production of newsprint by 2070 (figure 7-33). Yet, this is lower than the proportional impact in some other U.S. regions. While the Pacific Coast is a minor player in the production of newsprint, it is expected this region will lose about 84 percent of its production during the same period.

Figure 7-31. Historic (1990 to 2015) and projected (2020 to 2070) U.S. net exports of newsprint and printing and writing paper by RPA scenario.



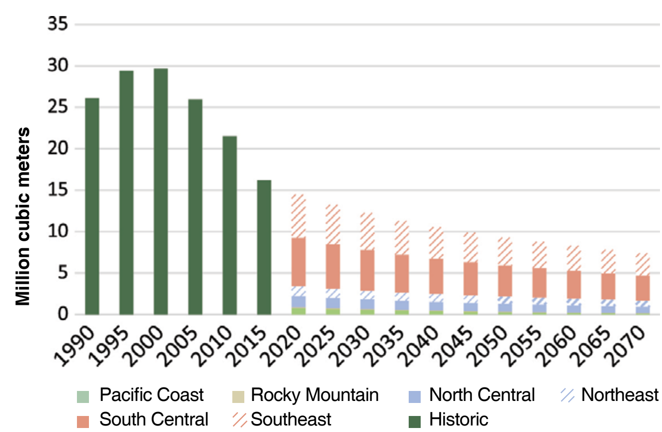
LM = lower warming-moderate U.S. growth; HL = high warming-low U.S. growth; HM = high warming-moderate U.S. growth; HH = high warming-high U.S. growth.

Figure 7-32. Historic (1990 to 2015) and projected (2020 to 2070) U.S. net exports of other paper and paperboard by RPA scenario.



LM = lower warming-moderate U.S. growth; HL = high warming-low U.S. growth; HM = high warming-moderate U.S. growth; HH = high warming-high U.S. growth.

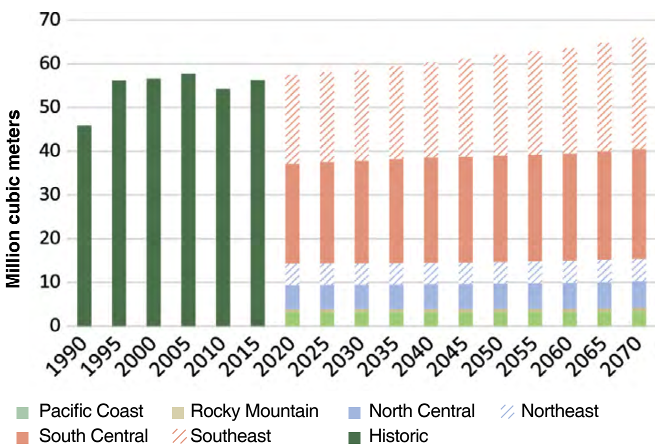
Figure 7-33. Historic (1990 to 2015) and projected (2020 to 2070) U.S. production of newsprint and printing and writing paper by region for the RPA HM scenario.



HM = high warming-moderate U.S. growth.

The U.S. production of other paper and paperboard under the HM scenario is provided in figure 7-34, where production is concentrated again in the South, and to a lesser degree in the North. Growth in the production of these products is projected to be concentrated in the South, with the Southeast and South Central growing nearly 25 and 10 percent respectively from 2020 to 2070. Other regions experience more modest gains of below 10 percent.

Figure 7-34. Historic (1990 to 2015) and projected (2020 to 2070) U.S. production of other paper and paperboard by region for the RPA HM scenario.



HM = high warming-moderate U.S. growth.

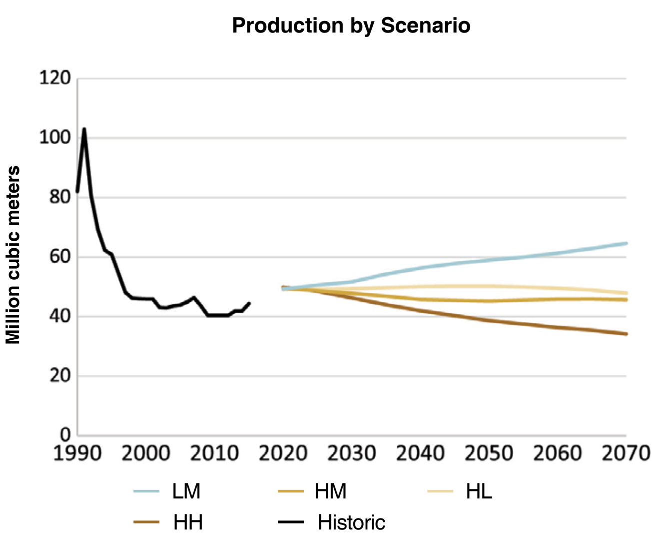
Wood Energy

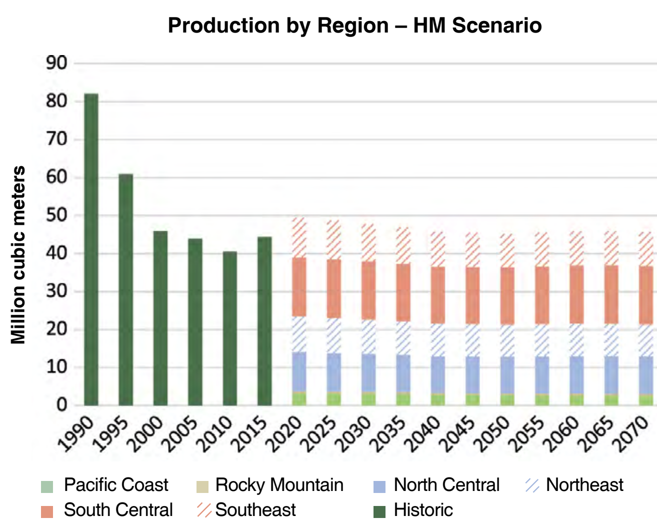
The production of fuelwood within the United States has been relatively constant over the last couple decades, after a period of significant declines (figure 7-35, left). As of 2015, the U.S. produced about 44 million m^3 of fuelwood. The RPA scenarios project modest variation in the production of fuelwood through 2070. Looking at the two most extreme pathways, the lowest levels are reached under the high economic growth HH scenario (34 million m^3 by 2070), while the sustainably minded LM scenario yields the highest levels (65 million m^3 by 2070).

The production of fuelwood is distributed across the four RPA regions, with the South Central Subregion contributing the largest share (figure 7-35, right). FOROM estimates that 31 percent of fuelwood was produced in the South Central in 2020, followed by 21 percent in both the Southeast and North Central. These shares do not change markedly throughout the HM scenario projection.

This assessment treats wood pellets as a unique product, independent from fuelwood, yet wood pellets may use industrial roundwood, fuelwood, and/or wood processing residuals as feedstock. This relationship is calibrated at the regional level to recent reported feedstock utilization outlined in the 2013 UNECE/FAO Joint Wood Energy Enquiry. As mentioned in the global section, the wood

Figure 7-35. Historic (1990 to 2015) and projected (2020 to 2070) U.S. fuelwood production by RPA scenario (left) and by region for the RPA HM scenario (right).



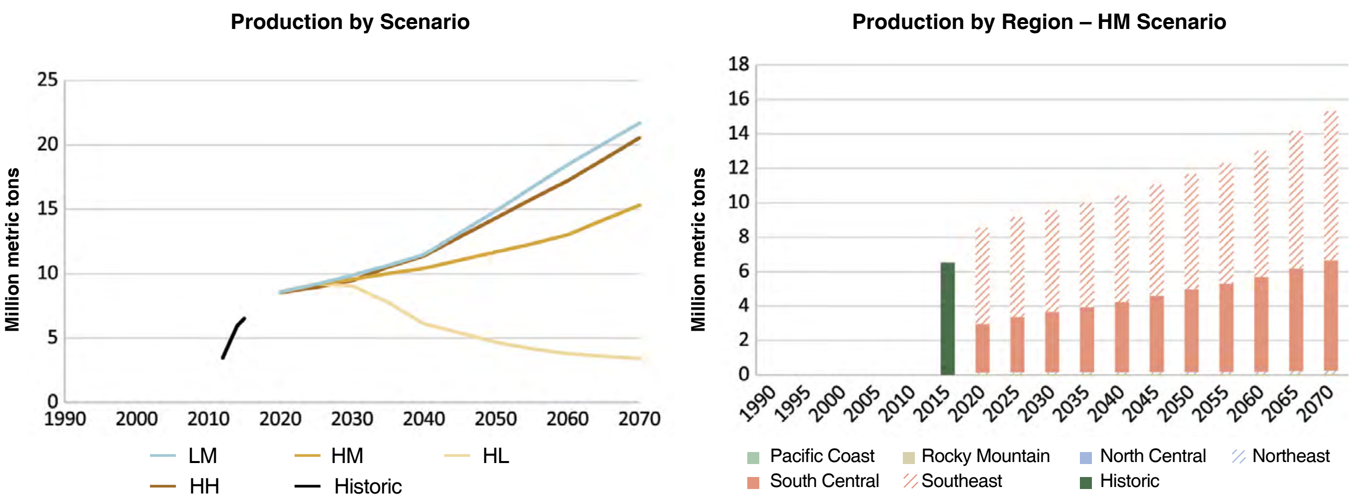


LM = lower warming-moderate U.S. growth; HL = high warming-low U.S. growth; HM = high warming-moderate U.S. growth; HH = high warming-high U.S. growth.

pellet market has experienced significant growth in the last number of years, with Europe emerging as the dominant consumer, relying significantly on the import of wood pellets from the U.S. Accordingly, the production of wood pellets in the United States has also exhibited strong growth in recent years, reaching nearly 9 million mt by 2020. Projections are highly sensitive to the RPA scenario and the underlying SSP related assumptions on preferences and policies (figure 7-36, left). The HL scenario is a low-growth scenario, where little preference is given to sustainability goals to promote the use of wood pellets in energy production. Accordingly, U.S. pellet production plateaus around current levels before shifting to a declining trend, reaching about 4 million mt by 2070. Alternatively, the more sustainability-oriented LM scenario assumes high growth in wood pellets around the world, leading to continued growth in U.S. production for export and, ultimately, a projection that wood pellet consumption increases to over 20 million mt by 2070, representing close to 4.2 percent of total annual removals.

Within the United States, wood pellet production has been overwhelmingly focused in the South (figure 7-36, right). In 2020, it is estimated that 65 percent of all wood pellets produced in the country were produced in the Southeast, followed by 33 percent in the South Central Subregion. Under the HM scenario, both subregions continue to produce the vast majority of wood pellets, with the highest growth rates observed in the South Central Subregion. Part of the South's continued dominance in wood pellet production relates not only to its high quantity of available timber, but also its relative proximity as a trading partner to supply the EU's continued demand for the product as a carbon-beneficial source of energy.

Figure 7-36. Historic (1990 to 2015) and projected (2020 to 2070) U.S. wood pellet production by RPA scenario (left) and by region for the RPA HM scenario (right).



LM = lower warming-moderate U.S. growth; HL = high warming-low U.S. growth; HM = high warming-moderate U.S. growth; HH = high warming-high U.S. growth.

Management Implications

Global production of both hardwood and softwood roundwood are projected to rise into the future, and the scenarios we report support the idea that these markets would be maintained in the coming 5 decades. For hardwood in the United States, a strong overseas market for roundwood and lumber imply likely steady to growing opportunities for exports. Such strength in hardwood markets translates into generally unchanged to rising prices in both hardwood roundwood and hardwood lumber. In contrast, the United States has long been a net importer of softwood lumber and wood-based panels, and most of the projected growth in U.S. softwood roundwood is used to produce lumber, softwood plywood, and OSB for domestic consumption. However, growth in roundwood production is projected to exceed growth in domestic consumption across most scenarios, the difference adding to U.S. net exports. Managers could therefore expect growing opportunities for exports. From this outlook, managers might expect markets to be maintained or strengthened across the United States where markets currently exist.

Although U.S. lumber production is projected to rise to 2070, projections also indicate a growing dependence on softwood lumber net imports and rising hardwood lumber net exports. Both results highlight the likely steady to strengthening markets for both kinds of lumber. Producers and consumers of lumber would therefore expect rising prices, on average, in the coming decades. Scenarios also show that the Southeast and South Central Subregions. would experience the most robust growth in softwood lumber production, with the Pacific Coast Region not increasing significantly. Growth in hardwood lumber production is more broad-based, across all regions of the country.

Although wood-based panel (plywood, OSB, fiberboard) production is projected to increase throughout the projection under most scenarios, the Nation is projected to maintain its import-dependence. Low economic growth leads to more negative net exports under the HL scenario, while high growth leads to less negative net exports under the HH scenario. Fiberboard production is projected to experience vigorous production growth to 2070 under the HM scenario, an indication of the effects of sustained U.S. economic growth and export demand.

Pulp production is expected to remain either unchanged or to grow, depending on the scenarios, and the South Central and Southeast Subregions are projected to continue to dominate the market. However, continuing a long-run trend, consumption of newsprint and printing and writing paper is projected to decline for both products, across all scenarios: in the HM scenario, newsprint declines to near zero by 2040, while printing and writing paper drops by half by 2070, compared to 2015 levels. A lesson for investors is that the trends observed in consumption since the 1990s are likely to continue, implying steady disinvestment in graphics paper manufacturing capacity. Other paper and paperboard consumption, in contrast, generally increases across all scenarios. The United States is projected to either maintain its positive net export status (HL and HM scenarios) or increase its net exports (LM and HH scenarios) in other paper and paperboard. The South Central and Southeast are projected to continue to dominate domestic paper production, highlighting likely geographic regions where steady to higher output of that aggregate category of paper would be expected.

For fuelwood, the future depends heavily on income growth, and consumption could rise or fall to 2070. For wood pellets, on the other hand, only under the HL scenario is production projected to decline after 2030, while output rises by three to five times by 2070 under the HM, HH, and LM scenarios. Nearly all production of wood pellets is expected to come from the U.S. South. Prospects for domestic production and export of wood pellets depends in large part on strong overseas markets, however, which currently are largely maintained by European Union policies fostering their consumption.

Conclusions

The U.S. forest sector has undergone wide swings in production and consumption, due to widely varying rates of economic growth over time and to secular trends in demand. High economic growth corresponds with increased residential construction and higher demand for wood-based building products, such as softwood lumber and wood-based structural panels. Therefore, vigorous economic growth raises industrial roundwood production, particularly softwood. Such vigorous growth, however, also drives demands for imports, with the United States remaining a net importer of softwood lumber and structural panels. In contrast, hardwood timber harvests are connected to not only U.S. economic growth but also to overseas economic growth and investment in furniture manufacturing. Overseas demand for hardwood roundwood and lumber provides a base of support for domestic production. All scenarios project stable export markets for hardwood industrial roundwood and lumber.

The U.S. paper sector has undergone a transition in the last 20 years that is projected to continue into the foreseeable future. In all scenarios, newsprint production and consumption decline to historically low levels by 2070, while printing and writing paper also declines, but at a slower rate. Such declines translate into lower total quantities of their imports since the United States is a net importer of both categories. The future of the remaining part of the paper sector, embodied in the aggregate category of "other paper and paperboard," however, is tied more closely to economic growth and rising overall global demand for paper for packaging and other human needs. U.S. and global consumers are projected to continue to demand those categories of paper for packaging and for sanitary purposes.

Projected futures in the production and consumption of wood to generate energy vary widely by scenario, adhering to the storylines embodied in the RPA scenarios. A future in which the United States and the world use wood to manufacture wood pellets for energy under a sustainability-oriented LM scenario leads to high growth in wood pellet demand and U.S. exports. Nevertheless, wood pellet manufacture consumes less than 2 percent of all roundwood consumption today and would not rise to much more than 4.2 percent by 2070 under LM and remain less than 1 percent under HL. Concerns about the sustainability and carbon implications of wood pellets as an energy source would therefore be most pronounced under the LM and least under the HL scenarios, but in both cases would not define substantial changes in overall production/carbon at the sector level.

The role of global markets is undeniable in the projections made not only for wood pellets but also for all other products, as the United States is among the top national producers and consumers of most broad categories of forest products. It is for that reason that U.S. projections are made in the context of a global market model. At the same time, the global market model used here allows for detailed analysis of the relative roles of the regions within the United States. Providing such regional detail in the market model allows for the full effects of global phenomena to be accounted for in regional markets and in the projected future of forest conditions. The regional detail additionally offers insights on how regions are projected to individually contribute to global markets and whether their contributions to the global position of the U.S. forest sector will endure. For example, the South (South Central plus Southeast), already the single largest producing region in the world, is projected to remain the dominant producing region for the foreseeable future, producing 10 percent of the world's total industrial roundwood by 2070 under all scenarios. The relative position of the Pacific Coast also remains steady throughout the projections, providing 3 percent of the world's total industrial roundwood by 2070.

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Chapter 8

Rangeland Resources

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Rangelands are areas where the natural vegetation is comprised principally of grasses, forbs, grass-like plants, and shrubs that are suitable for browsing or grazing, but the presence of herbivory is not a prerequisite for rangeland classification. In this chapter, we evaluate the nature of rangeland resources across the conterminous United States and provide projections of future rangeland resources. One of the main changes since the 2010 Resources Planning Act (RPA) Assessment has been the dramatic increase in computational power and remotely sensed data describing the biophysical properties of the Earth's surface, allowing us to characterize trends in rangeland vegetation not previously possible (Reeves et al. 2014b). Increased computational capacity also offers an improved ability to evaluate the role and effect of climate change on the potential future of rangelands. We begin this chapter by evaluating recent trends in rangeland extent, health, vegetation ground cover, aboveground net primary productivity (NPP), and livestock numbers. We then examine the potential impacts of climate change on U.S. rangelands by using the RPA scenarios and climate models to project future changes in rangeland phenology, vegetation productivity, and land use.

Key Findings

- ❖ Rangeland health is relatively unchanged since the 2010 RPA Assessment. The greatest overall impacts to rangeland health have been observed in the RPA Pacific Coast Region and in the southwestern part of the United States due to increases in invasive annual grasses and drought.
- ❖ Rangeland production is increasing in the northern parts of the rangeland extent and decreasing in the South, with corresponding changes in bare ground. Interannual variability in productivity is increasing in most areas at the same time, with the largest changes since 2000 having occurred in the Southwestern United States. Current production trends are projected to intensify in the future and become more variable on an interannual basis.
- ❖ Rangelands have been steadily converted to developed and agricultural land uses. Urbanization is projected to be responsible for most of the future reduction in rangeland extent, especially in the Pacific Coast Region.

Rangeland Extent

- The non-Federal rangeland base declined by 6 million hectares (ha; 3.6 percent) from 1982 to 2017, primarily driven by net movement of 2.3 million ha to developed uses (urban and rural transportation infrastructure) and 1.2 million ha to cropland.
- Land area enrolled in the Conservation Reserve Program (CRP) reached a national peak in 2007 of about 14.7 million ha, followed by a steady decline to 9.1 million ha in 2018, representing a loss of 38 percent.

Most of the rangeland area in the conterminous United States exists west of the 97th meridian (Reeves and Mitchell 2011). Although not part of the conterminous United States and not discussed in this report, rangelands also occur in Alaska, Hawaii, and several of the U.S. protectorates and territories. The composition and distribution of rangelands are described in Reeves and Mitchell (2011, 2012), while rangeland transitions to and from other land uses are described in the Land Resources Chapter of this Assessment. Highlights from those sources are provided here, as well as significant trends in rangeland area since 2010.

The National Resources Inventory (NRI), administered by the U.S. Department of Agriculture, Natural Resources Conservation Service (USDA NRCS), estimated 169 million ha of non-Federal rangelands in 1982 (USDA NRCS 2018). By 2017, the estimated area of non-Federal rangelands was 163 million ha, representing a loss of 6 million ha or 3.6 percent of the non-Federal rangeland base (168,571 ha average loss per year from 1982 to 2017). More than half of the net loss in rangeland area (3.6 million ha, 2.1 percent) occurred between 1982 and 1992. The decline in rangeland area was driven by net movement of 2.3 million ha to developed uses (urban and rural transportation infrastructure) and 1.2 million ha to cropland. Smaller net losses were observed in shifts to forest and other rural land including farmsteads.

The Rocky Mountain Region has the most non-Federal rangeland area in the United States (about 106 million ha in 2017), followed by the South, Pacific Coast, and North Regions (table 8-1). While all regions lost rangelands from 1982 to 2017, the Rocky Mountain Region lost the greatest total amount of rangeland and the North Region lost the highest percentage of rangeland over this period. Missouri is the only State in the North Region for which the NRI has recorded rangeland data, and it has lost 39 percent of its rangeland base since 1982. In all regions, the largest rangeland conversions were transitions to crop and urban land cover.

Federally managed rangelands generally do not undergo land use transitions and are therefore assumed to stay constant. The rare exception is when public lands are transferred to, or purchased by, non-Federal ownership. For example, the U.S. Bureau of Land Management (BLM) had a net disposal of 56,376 ha from all 50 States in 2020, approximately 0.00057 percent of the BLM land base (BLM 2020). Similarly, the 2020 U.S. Department of Agriculture (USDA), Forest Service land base was 67,275 ha larger than the average area from 2013 to 2019 (94,093,141 ha), an increase of 0.00072 percent (USDA Forest Service 2020). These examples support the validity of the stationarity assumption from a national perspective. Non-Federal rangelands lost about 168,571 ha per year from 2010 to 2017 for a total loss of about 1.7 million ha. Given that Federal rangeland area remains essentially constant over time and that Reeves and Mitchell (2011) estimated a total rangeland area in the conterminous United States of about 268 million ha, it follows that the total rangeland area in the conterminous United States in 2017 was about 266.3 million ha.

Table 8-2 shows the proportional ownership of rangelands across the conterminous United States. Private rangelands cover a larger area than all other rangeland ownerships combined. Of the non-private rangelands, the BLM manages

Table 8-1. Non-Federal rangeland area by RPA region.

	1982	2017	Change (1982 to 2017)	Proportion of non-Federal rangeland area (2017)
Region	thousand ha		thousand ha (%)	%
North	51	31	-20 (-38.9)	0.02
South	45,290	43,429	-1,861 (-4.1)	26.64
Rocky Mountain	108,762	105,654	-3,108 (-2.9)	64.81
Pacific Coast	14,841	13,906	-935 (-6.3)	8.53
National	168,948	163,020	-5,928 (-3.5)	

ha = hectares.
Source: USDA NRCS 2018.

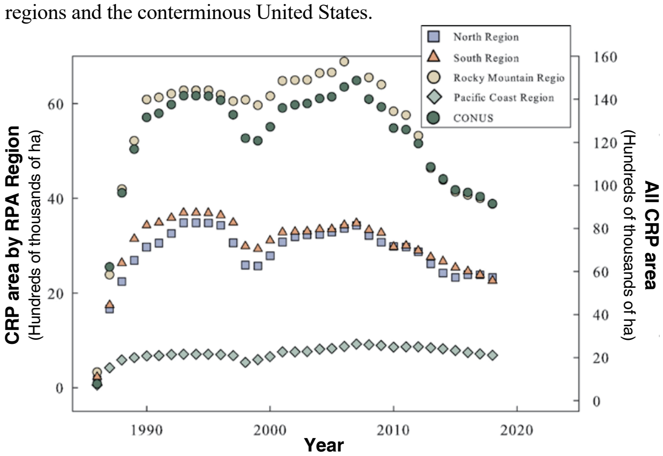
Table 8-2. Approximate proportion of rangeland under management in the conterminous United States.

Ownership	Proportion of all rangeland	Proportion of publicly owned rangeland
	percent	percent
U.S. Bureau of Land Management	21	47
U.S. Department of Defense	2	5
U.S. National Park Service	2	4
Privately owned	55	0
State government	6	13
Tribal	5	12
U.S. Fish and Wildlife Service	1	2
USDA Forest Service	8	17

the largest proportion (47 percent) while the U.S. Fish and Wildlife Service (FWS) manages the smallest proportion (about 2 percent). The proportion of U.S. rangelands managed by State governments is about 6 percent.

The CRP, administered by the U.S. Department of Agriculture, Farm Service Agency, has impacts on rangelands and rangeland sustainability. CRP lands are not considered rangeland in the NRI because the cover is not "permanent"; however, CRP lands planted to grasses, forbs, or shrubs may provide similar ecological functions and act to decrease fragmentation in landscapes dominated by rangeland vegetation. These lands can provide connectivity between disjunctive patches of rangelands that are often fragmented by agricultural or urban land uses (Reeves et al. 2018, Augustine et al. 2021) and provide benefits from reduced erosion and wildlife viewing and hunting (Sullivan et al. 2004). In addition, CRP lands generally improve ecological condition when compared with agricultural land uses. Enrollment in CRP has led to enhanced soil productivity, increased provision of wildlife habitat, and improved water quality, all of which are also traits of healthy rangelands. Moreover, CRP lands have the potential to sequester a significant quantity of atmospheric carbon dioxide (Yang et al. 2019). Participation in the CRP has also led to unintended negative consequences (Bakker and Higgins 2009). For example, millions of hectares enrolled in the CRP are seeded with nonnative species, such as crested wheatgrass (*Agropyron cristatum*), intermediate wheatgrass (*Thinopyrum intermedium*), and smooth brome (*Bromus inermus*). CRP area reached a national peak in 2007 of about 14.7 million ha followed by a steady decline to 9.1 million ha in 2018, representing a loss of 38 percent (figure 8-1). Regionally, the Rocky Mountain Region had the most CRP land (peaking at 7.5 million ha in 2007), followed by the South Region (3.7 million ha in 1993), North Region (3.5 million ha in 1993), and Pacific Coast Region (920,000 ha in 2007) (figure 8-1). The amount of CRP land has decreased steadily since 2007 in all regions, and in 2018 the Rocky Mountain Region exhibited 41 percent less CRP land than in 2007. The Pacific Coast Region has exhibited losses of about 24 percent since 2007, while the South and North Regions have lost 32 and 28 percent, respectively, since 2007.

Figure 8-1. Area of CRP under contract from 1986 to 2018 for the RPA regions and the conterminous United States.



CONUS = conterminous United States; CRP = Conservation Reserve Program; ha = hectares.

Source: https://www.fsa.usda.gov/programs-and-services/conservation-programs/reports-and-statistics/conservation-reserve-program-statistics/index (20 May 2021).

Rangeland Condition and Health

- ❖ Relatively healthy conditions were found on approximately 75 percent of non-Federal rangeland from 2011 to 2015 and between 79 to 86 percent of BLM rangelands from 2011 to 2018. Relatively healthy is defined as less-than-moderate departure from reference conditions for all three rangeland health attributes—soil and site stability, hydrologic function, and biotic integrity.
- ❖ Invasive species are having a relatively larger impact on rangeland health than other factors.
- ❖ This inaugural RPA evaluation of vegetation trends across all lands using remote sensing corroborates findings from both the NRI and the Assessment Inventory and Monitoring (AIM) processes.
- ❖ The northern Great Plains exhibited the largest increases in perennial herbaceous cover while the Interior West and California exhibited the largest declines. Annual grasses and forbs are increasing almost universally across rangelands, with the largest increases observed in Washington, Oregon, northern Nevada, and southern Idaho.
- ❖ Annual net primary productivity has been generally increasing in the North while decreasing in the South, especially the desert Southwest, while interannual variability has been increasing almost universally since 2000. Drought events since 2000 have created continually lower production in California, New Mexico, and Arizona.
- ❖ Bare ground is decreasing in many areas due to the increasing trend of annual herbaceous species. The exception is the desert Southwest, particularly New Mexico and west Texas, which has experienced increased bare ground attributable to reduced annual net primary productivity since 2000.

Rangeland health assessments provide information on the function of ecological processes relative to ecological potential. The process most commonly used to evaluate rangeland health in the United States considers 17 indicators relating to the attributes of biotic integrity, hydrologic function, and soil and site stability (Pellant et al. 2020, USDA NRCS 2018). The NRI uses the rangeland health assessment process to regularly monitor rangeland health on non-Federal lands, although inferences from this monitoring are only applicable for non-Federal lands and for relatively large areas (i.e., bigger than most counties). On Federal lands, the BLM regularly collects data on rangeland health attributes and vegetation composition and structure as part of the AIM Program (Toevs et al. 2011a, 2011b). The AIM sampling effort reports on the status, condition, and trend of rangeland resources in 13 Western States by annually surveying thousands of random locations across BLM lands (Yu et al. 2020). The USDA Forest Service does not collect all of the data necessary for rangeland health assessment (i.e., biotic integrity, hydrologic function, and soil and site stability), but does collect data on vegetation composition and structure from nonforest lands using Forest Inventory and Analysis (FIA) protocols through the All Conditions Inventory (ACI) project (Bush 2012). The capacity to quantify rangeland conditions and trends across large areas has significantly increased since the last RPA rangeland assessment due to the addition of the AIM program (the NRI has been collecting data since 1982) and increased remote sensing analytical capabilities (Reeves et al. 2014b). While remotely sensed indicators of rangeland trends can enhance our understanding of rangeland condition and health, they are not necessarily directly comparable to the ground sampling efforts documented in this report given sample size issues, spatial autocorrelation, and other considerations.

Non-Federal Lands

Rangeland Health

Our examination of non-Federal rangeland health was based on the 2018 NRI Rangeland Resource Assessment (USDA NRCS 2018), where the data collected for 17 rangeland health indicators at individual sample locations, assessed based on guidance by Pellant et al. (2005), were aggregated to a broader spatial scale (Major Land Resource Area). Each indicator was assigned a degree of departure based on the extent to which the indicator fell outside the range of natural variability for a site: none-to-slight, slight-to-moderate, moderate, moderate-to-extreme, extreme-to-total. The smaller the degree of departure, the "healthier" the site. The data collected during the 2011 to 2015 time period were compared against a 2004 to 2010 reference period; trend analysis is not possible until multiple data points can be compared against the reference period. When considering rangeland health attributes individually, a large majority of non-Federal rangeland in the Western United States showed relatively minor departures from reference conditions during the 2011 to 2015 period. Rangelands exhibited the best health for the soil and site stability attribute, with 87.3 percent exhibiting none-to-slight or slight-to-moderate departure from reference conditions and only 3.2 percent exhibiting moderate-to-extreme or extreme-to-total departure. Conversely, rangelands departed most significantly from reference conditions for the biotic integrity indicator, with 77.3 percent of rangelands exhibiting none-to-slight or slight-to-moderate departure and 5.8 percent exhibiting moderate-to-extreme or extreme-to-total departure (table 8-3). The biotic integrity indicator factors in the presence of nonnative species, explaining in part why this element of rangeland health departs the most from reference conditions (table 8-3).

Between 77 and 87 percent of non-Federal rangeland in the conterminous United States was in relatively healthy condition from 2011 to 2015, depending on the attribute being examined. The remaining 12 to 23 percent of non-Federal rangeland showed moderate or greater departures from reference conditions for at least one of the rangeland health attributes, while 10.5 percent showed moderate or greater departures for all three rangeland health attributes (figure 8-2). For all three rangeland health attributes, the extent of departure from reference condition varied widely across Western States. Relatively large departures for all three attributes were found in Texas, Oklahoma, eastern Colorado, western Kansas, and eastern Washington and Oregon, along with smaller areas in other places such as northern Utah and southern Idaho.

Prolonged periods of severe or extreme drought encompassed portions of Arizona, New Mexico, southeast Colorado, northwest Texas, western Oklahoma, and southwest Kansas from 2011 to 2015. These areas also experienced at least moderate departures from reference conditions for each rangeland health attribute during this same time period, suggesting that extended droughts may impact rangeland health (figure 8-2).

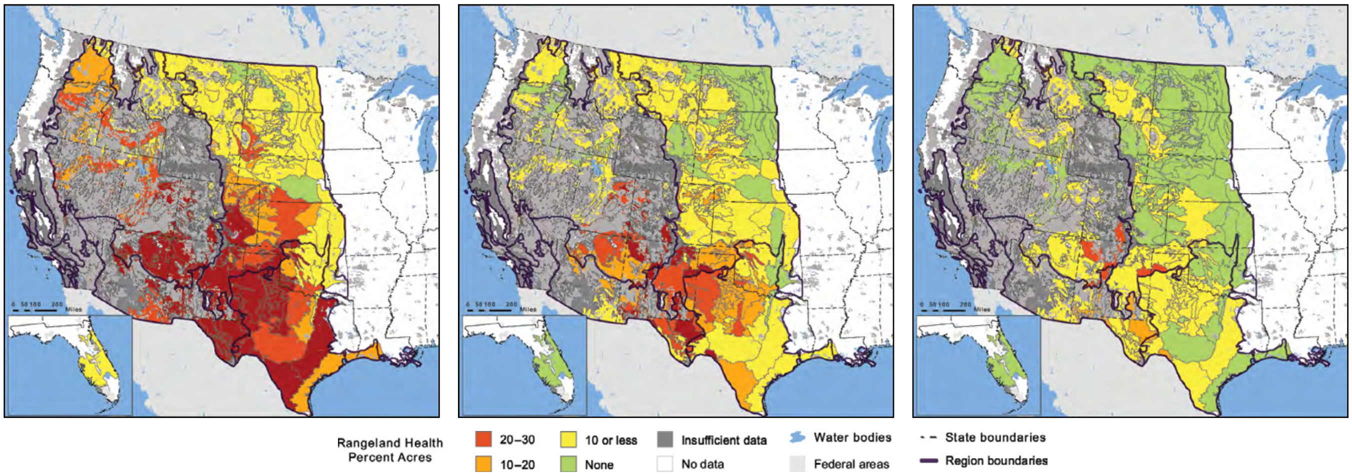
Table 8-3. Proportion of non-Federal rangelands (2011 to 2015) in different categories of departure from reference conditions for rangeland health.

Attribute	None-slight, slight-moderate	Moderate	Moderate-extreme, extreme-total
	percent of rangeland area[a] (margin of error)		
Soil/site stability	87.3 (1.0)	9.5 (0.9)	3.2 (0.5)
Hydrologic function	84.0 (1.2)	12.2 (1.1)	3.8 (0.5)
Biotic integrity	77.3 (1.4)	16.9 (1.2)	5.8 (0.6)

[a] *Rangeland with no data (5.5 percent) is excluded.*

Source: USDA NRCS 2018.

Figure 8-2. Area of non-Federal rangeland where rangeland health attributes exhibit moderate or larger departures from reference condition from 2011 to 2015: (left) locations where at least one attribute exhibits moderate departures (25.8 ±1.4 percent), (middle) locations where all three attributes exhibit moderate departures (10.5 ±0.9 percent), and (right) locations where all three attributes exhibit above moderate departures (2.0 ±0.3 percent). The colored portions of the maps represent Major Land Resource Areas where sufficient non-Federal rangeland was sampled by the National Resources Inventory to estimate the rangeland health parameters.



Source: USDA NRCS 2018.

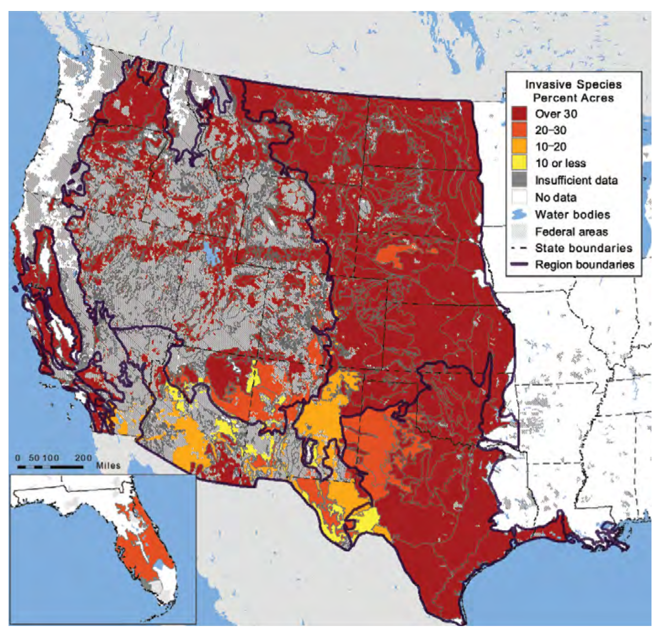
Invasive Species

Invasive plant species on rangelands are nonnative plant species that are harmful to rangelands. Nonnative species are introduced from other countries or were native to the United States but historically absent from (or only minor components of) rangeland plant communities. Not every nonnative species is considered invasive; most nonnative species do not pose a significant problem, and some are considered beneficial. For example, crested wheatgrass is commonly recommended and introduced onto rangelands in semiarid regions for forage production and soil stabilization even though its presence can affect some species composition-related measures of rangeland health in the biotic integrity category.

We examined specific groups of invasive grasses, forbs, and woody plant species selected because of their prevalence in rangeland plant communities. We provide a cursory overview of dominant themes and offer some specific examples of problematic invasive species influencing relatively large areas of U.S. rangelands. A comprehensive evaluation describing dozens of invasive species on non-Federal rangelands is provided in the 2018 NRI Rangeland Resource Assessment (USDA NRCS 2018).

Invasive species occupy every State in the rangeland domain (figure 8-3). With the exception of the Southwestern United States, invasive species are found on 30 percent or more of the non-Federal rangelands. Invasive annual brome grasses are particularly abundant in shrub communities like sagebrush and pinyon-juniper and often outcompete native

Figure 8-3. Percent of non-Federal rangeland area where invasive species were present between 2011 to 2015. The colored portions of the maps represent Major Land Resource Areas where sufficient non-Federal rangeland was sampled by the National Resources Inventory to estimate the rangeland health parameters.

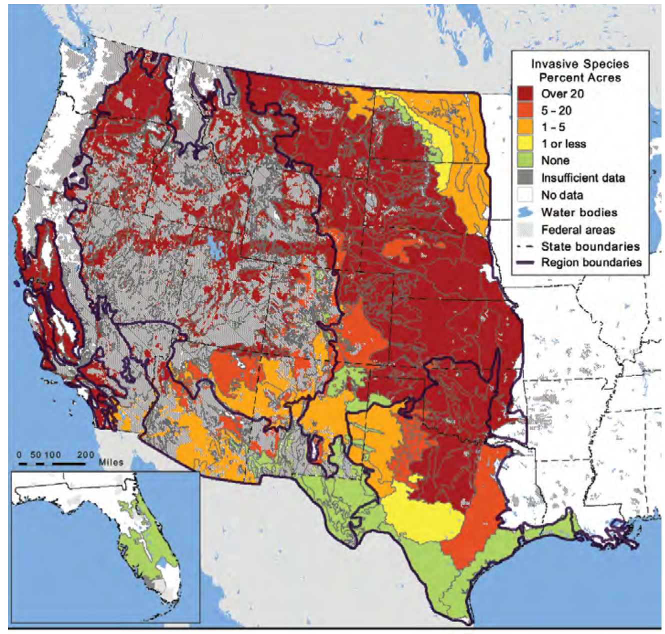


Source: USDA NRCS 2018.

grasses and forbs. Invasive annual bromes were present on 30 (±1.4) percent of non-Federal rangelands during the 2011 to 2015 time period, with over 70 percent of rangelands affected in the States of California, Washington, and Oregon that comprise the Pacific Coast Region (figure 8-4, table 8-4). Cheatgrass is the most prevalent invasive annual brome species, and has the potential to dramatically alter the ecosystems it invades by completely replacing native vegetation and increasing fire-return intervals (Brooks et al. 2004, Bush et al. 2004, Chambers et al. 2007, DiTomaso 2000, Pyke et al. 2016; see the Disturbance Chapter). Cheatgrass was present on 18.6 (±1.0) percent of non-Federal rangeland from 2011 to 2015, with 50 percent or more occupation of non-Federal rangelands in Oregon, Washington, Idaho, Nevada, South Dakota, and Utah (table 8-4). In addition to annual brome grasses, the 2018 NRI Rangeland Resource Assessment indicates that other annuals such as medusahead *(Taeniatherum caput-medusae)* and ventenata *(Ventenata dubia)* have a significant presence, especially in the Pacific Coast Region.

Like invasive annual grasses, some nonnative perennial grasses such as Kentucky bluegrass *(Poa pratensis)*, Canada bluegrass *(P. compressa)*, and smooth brome are also negatively impacting U.S. rangelands in some regions. Kentucky and Canada bluegrass are perennial sod-forming

Figure 8-4. Percent of non-Federal rangeland area where annual bromes (*Bromus* spp.) meet the criteria of covering a majority (at least 50 percent) of the soil surface from 2011 to 2015.



Source: USDA NRCS 2018.

Table 8-4. Proportion of State area where select invasive species occur, provided only for States where NRI rangeland samples are collected. The values in parentheses represent margins of error as the 95th percent confidence intervals. Estimates with a double asterisk denote that the species was not detected on non-Federal rangelands within the State. Some estimates with a large margin of error in relation to the estimate are based on very few observations. The lower bound of the confidence interval may also be inappropriately negative.

State	RPA region	Annual *Bromus* spp.	*Bromus tectorum*	*Poa pratensis* or *P. compressa*	*Centaurea* and *Acropitolon* spp.	*Euphorbia esula*	*Juniperus* spp.	*Prosopis* spp.
Florida	South	**	**	**	**	**	**	**
Louisiana	South	**	**	**	**	**	**	**
Oklahoma	South	37.3 (5.4)	24.2 (5.9)	0.5 (1.1)	**	**	20.9 (5.8)	6.9 (3.4)
Texas	South	6.2 (1.8)	1.3 (0.7)	**	**	**	14.5 (3.8)	54 (4.7)
Arizona	RM	3.6 (3)	1.5 (1.9)	**	**	**	11.4 (5.4)	18.4 (5.5)
Colorado	RM	19.4 (5.7)	14.5 (4.3)	7.1 (2.3)	0.3 (0.6)	0.2 (0.2)	5.3 (3.0)	**
Idaho	RM	72 (6.1)	58.1 (8.6)	18.1 (7.2)	1.8 (2.2)	**	2.3 (2.2)	**
Kansas	RM	57.7 (5.1)	32.2 (4.8)	39.8 (5.8)	**	**	3.9 (1.4)	**
Montana	RM	48.9 (7.1)	22.2 (4.3)	32.1 (5.6)	1.4 (1.1)	2.3 (1.6)	8.4 (4.0)	**
Nevada	RM	52.4 (12.3)	52.4 (12.3)	1.9 (3.5)	2.1 (3.2)	**	6.3 (4.0)	**
Nebraska	RM	41 (5.8)	27.7 (5.1)	37.8 (4.8)	**	0.7 (0.8)	5.4 (2.3)	**
New Mexico	RM	1.5 (0.9)	1.5 (0.9)	0.2 (0.4)	**	**	14.8 (3.9)	15.7 (3.8)
North Dakota	RM	9.1 (3.4)	0.7 (0.9)	86 (3.7)	**	9.8 (4.0)	4.5 (1.7)	**
South Dakota	RM	54 (5)	45.4 (4.9)	62.9 (3.4)	**	0.4 (0.5)	2.1 (1.2)	**
Utah	RM	53.1 (7.1)	51 (7.4)	9.6 (5.1)	0.6 (1.1)	**	14.2 (4.9)	**
Wyoming	RM	47.2 (6.3)	31.8 (5.6)	12.2 (4.1)	0.2 (0.5)	0.3 (0.5)	1 (0.7)	**
California	PC	73.2 (8.4)	9.3 (4.2)	**	16.6 (6.2)	**	2.6 (2.2)	**
Oregon	PC	83.7 (6.7)	78.5 (6.7)	6.9 (4.5)	2.1 (2.4)	**	15.7 (7.6)	**
Washington	PC	87.1 (5.1)	82.6 (6.7)	5.6 (3.8)	4.1 (3.4)	**	**	**
National		30 (1.4)	18.6 (1.0)	14.5 (0.8)	1.1 (0.4)	0.6 (0.2)	9.4 (1.2)	15.8 (1.3)

NRI = National Resources Inventory; PC = Pacific Coast; RM = Rocky Mountain.

Source: USDA NRCS 2018.

species commonly planted on pasturelands (Hall 1996) but are listed as invasive in the Great Plains (Bush 2002, Toledo et al. 2014, Wennerberg 2004). While providing reasonable sources of forage, both bluegrass species can displace native vegetation if not properly managed (St. John et al. 2012, Toledo et al. 2014). Kentucky and Canada bluegrass were present on 14.5 (±0.8) percent of all non-Federal rangeland from 2011 to 2015, with the largest presence in the eastern part of the Rocky Mountain Region (table 8-4). These species occupy 86 (±3.7) percent of non-Federal rangelands in North Dakota alone.

The 2018 NRI Rangeland Resource Assessment also provides information on invasive forbs; here we evaluated leafy spurge *(Euphorbia esula)*, knapweeds *(Acroption* spp.*)*, and starthistles *(Centaurea* spp.*)*. Leafy spurge is a difficult to eradicate, deep-rooted invasive plant that forms nearly monocultural stands. It is generally considered poisonous to cattle and horses because it contains the alkaloid euphorbon, a known co-carcinogen also toxic to humans (Washington State Noxious Weed Control Board 2021). However, sheep and goats appear relatively unaffected by the plant. Leafy spurge was found on 0.6 (±0.2) percent of non-Federal rangelands from 2011 to 2015 but is relatively common in non-Federal rangelands in North Dakota (table 8-4). Leafy spurge occurs in the same habitats as knapweeds and starthistles in some areas, which were present on 1.1 (±0.4) percent of non-Federal rangelands. In California, however, these species are found on 16.6 (±6.2) percent of non-Federal rangelands (table 8-4). Knapweeds and starthistles inhibit other plants through production of chemical substances reducing germination or growth (Alford et al. 2009). As a result, knapweeds and starthistles can rapidly replace native species, especially perennial graminoids, making lands less resilient to drought and other disturbances.

Some native woody plant species such as junipers *(Juniperus* spp.*)* and mesquite *(Prosopis* spp.*)* can also replace native grasses and forbs. Encroachment by shrubs, especially *Juniperus* spp., has rapidly escalated since pre-Euro-American settlement (Coates et al. 2017). These invasions have significantly changed fire effects and behavior where they have occurred, and decreased resiliency to drought. Juniper species were present on 9.4 (±1.2) percent of non-Federal rangelands, with the largest presence in Oklahoma, followed by Oregon, New Mexico, Texas, Utah, Arizona, and Montana (table 8-4). Like junipers, mesquite species typically have a deep root system that enables them to withstand droughts and outcompete grasses. Honey mesquite *(P. glandulosa)* and velvet mesquite *(P. velutina)* are the two most common species found in the Southwestern United States (Ansley et al. 1997). Mesquite species were present on 15.8 (±1.3) percent of non-Federal rangelands, observed most commonly in Texas, Arizona, New Mexico, and Oklahoma (table 8-4).

In terms of invasive species threats to rangelands, annual grasses, especially cheatgrass, are often posited as the largest threat to U.S. rangelands. They are the most commonly occurring group of invasive species in non-Federal rangelands (table 8-4), and their ability to alter fuel compositions facilitates fire spread and reduces fire-return intervals (Balch et al. 2013, Pilliod et al. 2017), leading to larger and more frequent wildfires (Chambers et al. 2014). Other species such as Kentucky bluegrass negatively impact rangeland health through reduction of biotic integrity, even though they also provide beneficial services like offering good forage for native and domestic ungulates.

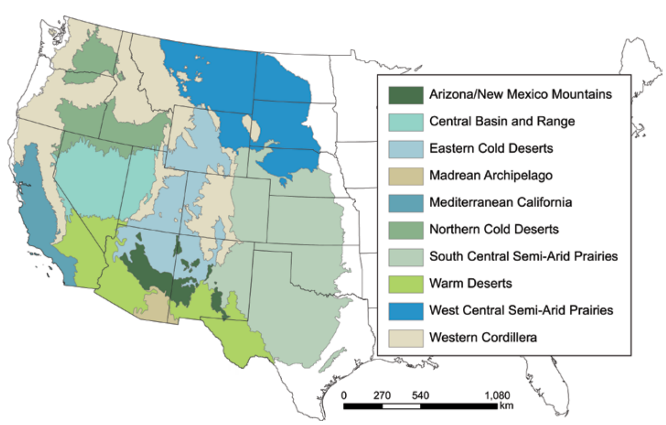
Federal Lands

U.S. Bureau of Land Management

The BLM manages approximately 98.7 million ha of Federal lands in the conterminous United States and Alaska for the U.S. Department of the Interior, of which 78.5 million ha are rangelands (BLM 2013). The BLM manages rangelands to ensure their health and productivity for the use and enjoyment of current and future generations (Public Law 95–514; PRIA 1978). Although the NRI Rangeland Resource Assessment reported results at the scale of Major Land Resource Areas, BLM rangelands are characterized here using nine Level II Ecoregions to maintain consistency with other BLM reporting efforts (Omernik 1987; figure 8-5). Because almost half of BLM-administered lands fall within the Cold Deserts Level II Ecoregion, this ecoregion was further divided into Level III Ecoregions: Northern Cold Deserts, Eastern Cold Deserts, and Central Basin and Range (Karl et al. 2016; figure 8-5).

In this section we describe the status and trends of BLM rangelands nationally and within ecoregions from 2010

Figure 8-5. Level II and III Omernik ecoregions used for the BLM rangeland health assessment.



BLM = U.S. Bureau of Land Management.

Source: Omernik 1987.

to 2020 using data from the BLM Landscape Monitoring Framework (LMF), part of the AIM project. The LMF annual survey of approximately 2,000 random locations across BLM lands (Yu et al. 2020) gathers information on attributes of rangeland health using the same process as the NRI (Pellant et al. 2005), in addition to gathering information on BLM terrestrial core metrics (Herrick et al. 2017) for reporting national-level status and trends. We also separately provide data on the trend of bare ground on BLM lands and the presence of nonnative invasive species to allow subsequent comparison with consistent national-level trends derived from remote sensing in the section All Lands Trends. Percent cover of bare ground was determined using the line-point intercept method (Herrick et al. 2017) while presence of nonnative invasive species is derived from the species inventory method (Herrick et al. 2017).

Results of the BLM rangeland health assessment are provided as either the proportion of the area within a condition class or as an average status across the area, and are weighted based on the BLM land area sampled. Each indicator estimate is presented using four categories of departure from reference conditions (similar to the NRI Rangeland Resource Assessment): (1) none-to-slight or slight-to moderate departure from reference for biotic integrity, (2) none-to-slight or slight-to moderate departure from reference for hydrologic function, (3) none-to-slight or slight-to-moderate departure from reference for soil and site stability, and (4) none-to-slight or slight-to-moderate departure from reference for biotic integrity, hydrologic function, and soil and site stability. Although the same rangeland health evaluation process is used by both the BLM and NRI, these two programs report their official results slightly differently. The BLM focuses on proportion of *healthy* rangelands, framing and reporting rangeland health in terms of none-to-slight or slight-to-moderate departure from reference conditions. In contrast, the 2018 NRI Rangeland Resource Assessment results span the scoring spectrum, although most of the figures focus on *unhealthy* rangelands by showing only moderate-to-extreme departures. Even though these similar data are portrayed and described from opposite ends of the rangeland health scoring perspective, they can be interpreted the same way. For example, when the BLM reports that 79 percent of all rangelands in its jurisdiction exhibit none-to-moderate levels of departure, this means that approximately 21 percent of BLM lands exhibit moderate or greater departure. This can be directly compared to the results in figure 8-2 (left), which show that non-Federal rangelands exhibit moderate-to-extreme departure on 25.8 (±1.4) percent of the land base (and conversely that 74 percent of non-Federal rangelands exhibit none-to-moderate departure). By taking the inverse of either the BLM or NRI results we can make direct health comparisons between BLM and non-Federal rangelands.

Rangeland Health

The LMF rangeland health assessments show that the majority of BLM rangelands are relatively healthy, with only none-to-slight or slight-to-moderate departure from reference conditions in terms of any one attribute (figures 8-6, 8-7, 8-8). Between 79 and 86 percent of BLM rangelands from 2011 to 2018 exhibited less-than-moderate departure from reference conditions for the three rangeland health attributes (figures 8-6, 8-7, 8-8). Conversely, 14 to 21 percent of BLM rangelands exhibited moderate-to-extreme departure in one of the three rangeland health categories. Of the three rangeland health attributes, biotic integrity exhibited the highest values (i.e., had the greatest amount of departure), consistent with non-Federal lands.

Compared to national conditions, the Western Cordillera and the West-Central Semiarid Prairies have a larger percentage of BLM rangeland in better condition (more area with none-to-slight or slight-to-moderate departure from reference for at least one attribute of rangeland health), while the Warm Deserts have a larger percentage of rangeland in worse condition (less area with none-to-slight or slight-to-moderate departure from reference). Rangeland health attributes appear to be stable or improving in all ecoregions. These BLM rangeland health results support the results found on non-Federal rangelands, however the wide confidence intervals (figures 8-6, 8-7, 8-8) suggest that some trends may not be significant and more research is needed to establish the level of significance.

Figure 8-6. Percent of BLM rangelands where biotic integrity exhibits none-to-slight or slight-to-moderate departure from reference conditions (80 percent confidence interval). The remaining rangeland area corresponds to relatively higher departure.

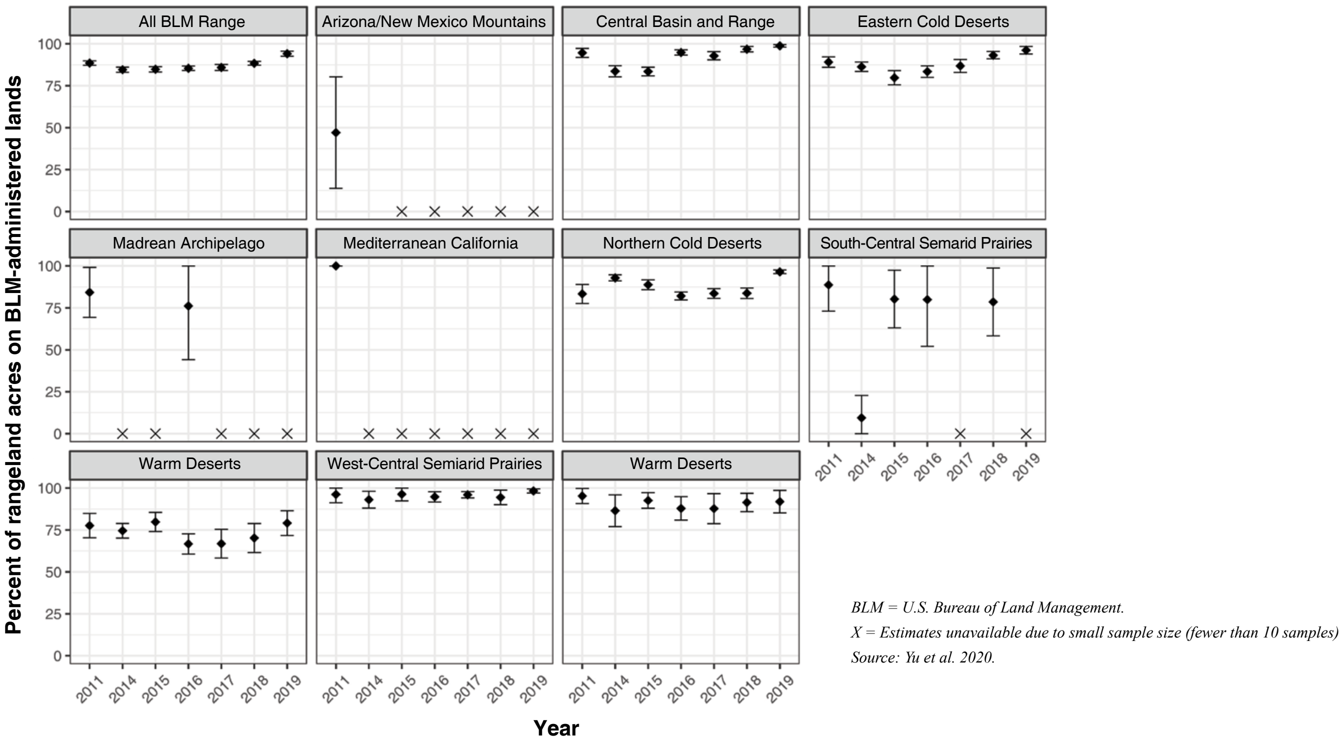


Figure 8-7. Percent of BLM rangelands where soil and site stability exhibits none-to-slight or slight-to-moderate departure from reference conditions (80 percent confidence interval). The remaining rangeland area corresponds to relatively higher departure.

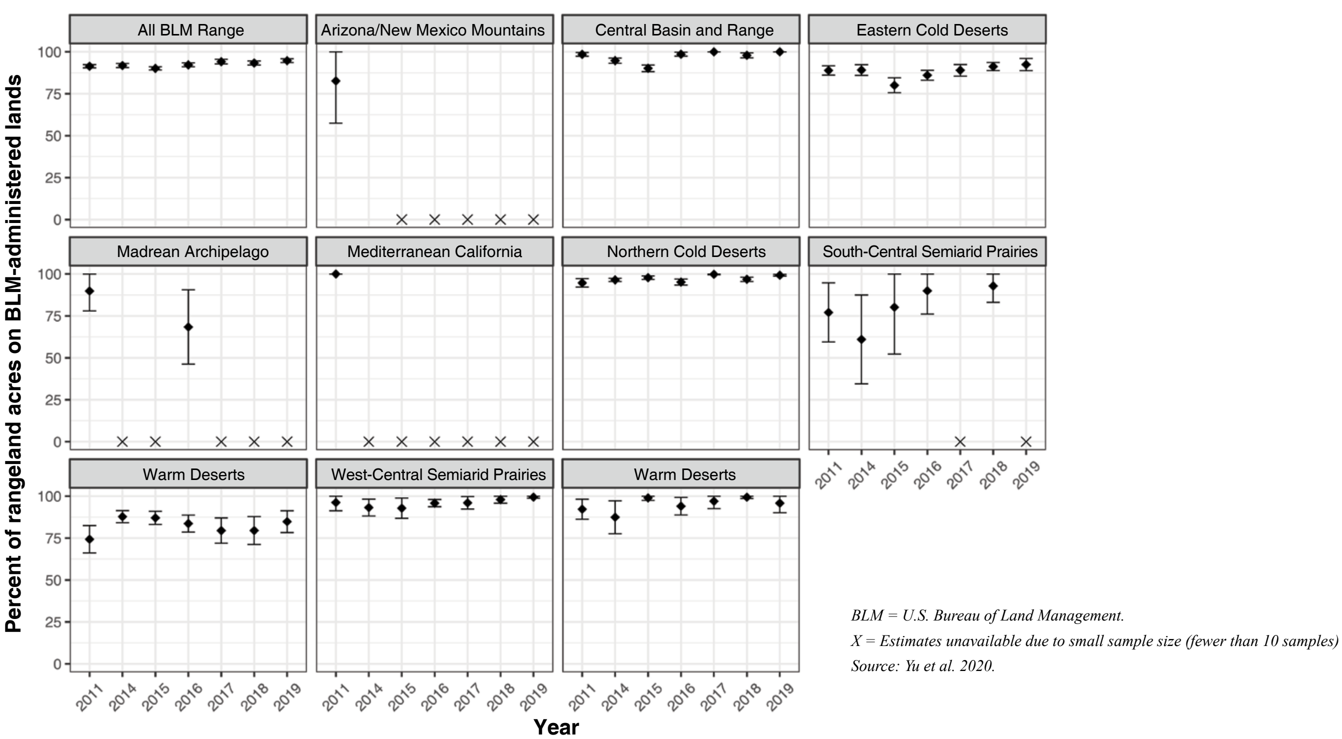
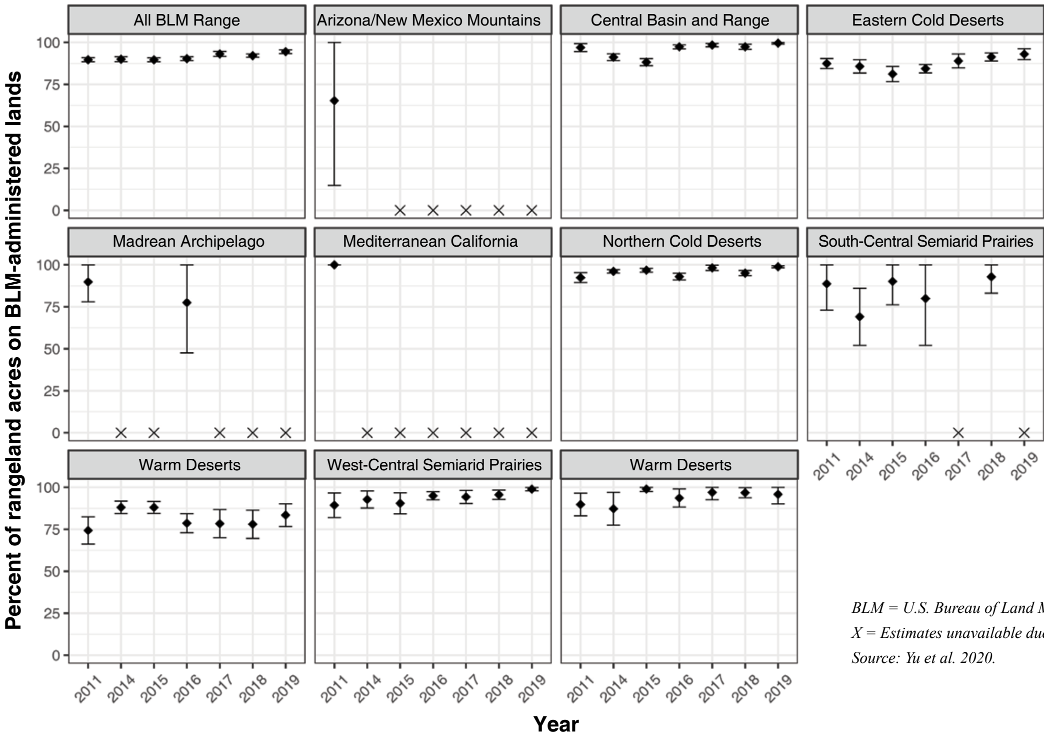


Figure 8-8. Percent of BLM rangelands where hydrologic function exhibits none-to-slight or slight-to-moderate departure from reference conditions (80 percent confidence interval). The remaining rangeland area corresponds to relatively higher departure.



BLM = U.S. Bureau of Land Management.
X = Estimates unavailable due to small sample size (fewer than 10 samples)
Source: Yu et al. 2020.

Invasive Species

Nonnative invasive species occurred on BLM rangelands in all ecoregions, present on about half and abundant (≥25 percent absolute foliar cover) on 15.8 million ha of BLM rangelands in 2018 (table 8-5). Nonnative invasive species appear to be constant or increasing for nearly all ecoregions except South-Central Semiarid Prairies. The Northern Cold Deserts, Central Basin and Range, and Mediterranean California (at least for 2015) are most affected by nonnative invasive species, which are increasing in presence across these ecoregions (figure 8-9). In the Mediterranean California ecoregion, although the sample size has been too small for inclusion in figure 8-9 in most years, nonnative invasive species presence was 100 percent in 2015. Increases in nonnative invasive species also occurred in the Warm Desert and West-Central Semiarid Prairie ecoregions (figure 8-9), while the amount of bare ground in these areas has generally decreased (figure 8-10).

Table 8-5. Estimated BLM rangeland area where nonnative invasive species were present and abundant (absolute foliar cover ≥25 percent) in 2018. The - indicates insufficient data to make the estimate.

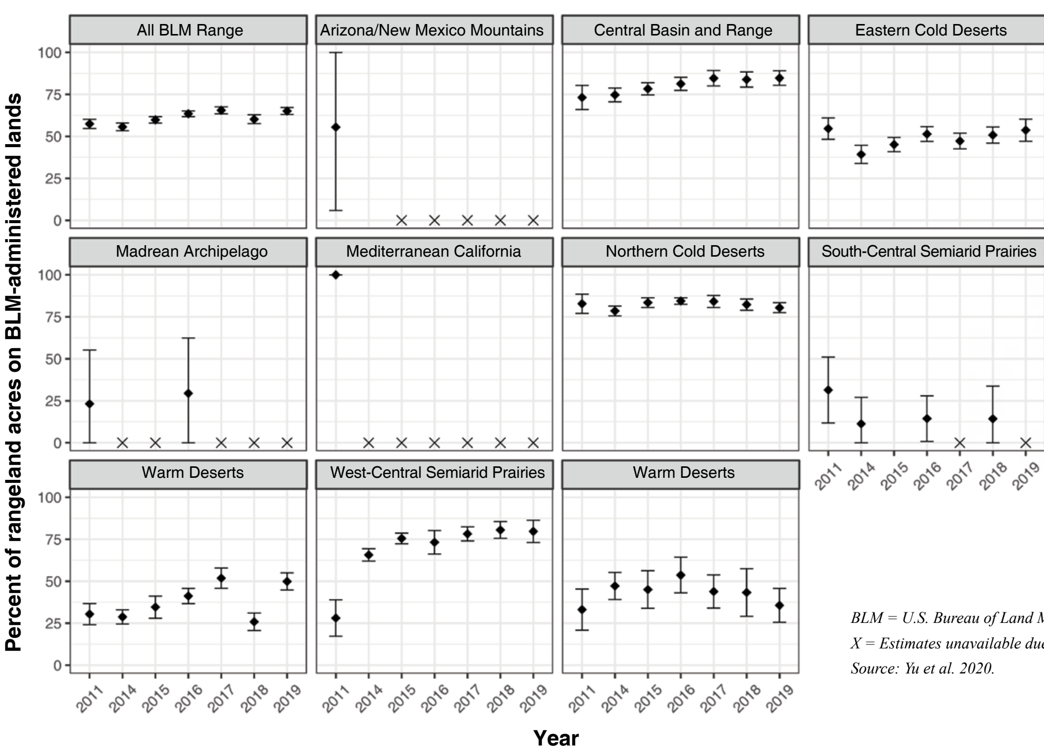
Ecoregion	Nonnative invasive species present		Absolute foliar cover composed of ≥25% nonnative invasive species	
	million ha	standard error	million ha	standard error
Arizona/New Mexico Mountains	-	-	-	-
Central Basin and Range[a]	13.8	0.69	6.03	0.9
Eastern Cold Deserts	7.43	0.48	2.32	0.55
Madrean Archipelago[a]	-	-	-	-
Mediterranean California[a]	0.38	0.38	0.38	0.38
Northern Cold Deserts[a]	8.89	0.3	5.02	0.44
South-Central Semiarid Prairies	0.11	0.12	-	-
Warm Deserts	3.12	0.48	0.82	0.26
West-Central Semiarid Prairies	2.46	0.26	0.71	0.21
Western Cordillera	1.67	0.5	0.58	0.34
All BLM Lands	**37.86**	**1.33**	**15.87**	**1.27**

[a] Level III ecoregion.

BLM = U.S. Bureau of Land Management; ha = hectares.

Source: Yu et al. 2020.

Figure 8-9. Percent of BLM rangelands with presence of nonnative invasive plant species (80 percent confidence interval). See Karl et al. (2016) for a list of plant species considered nonnative invasive species.

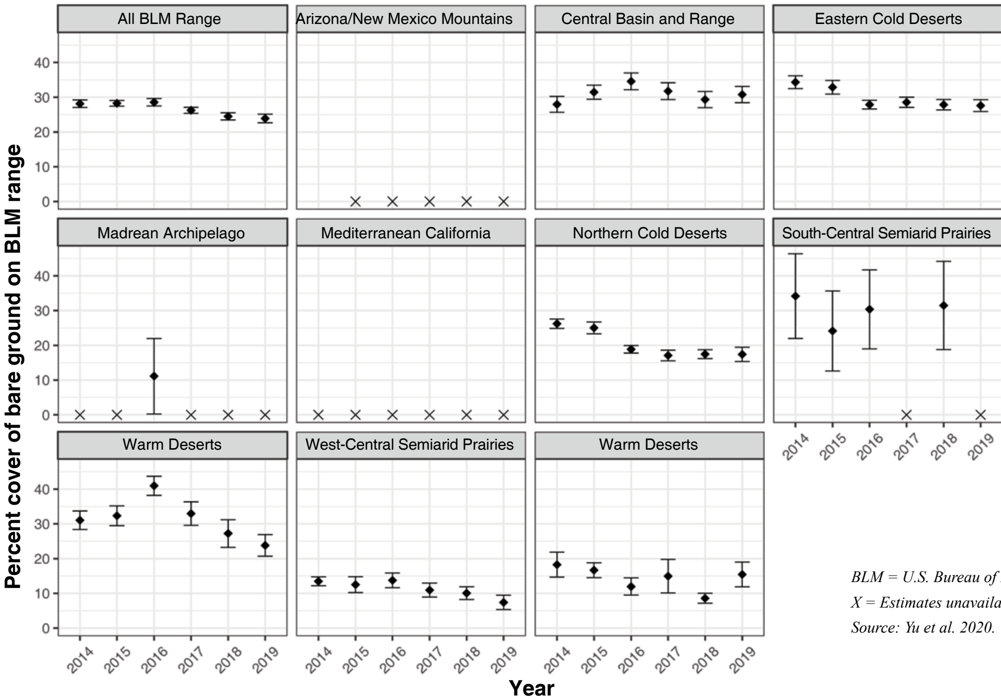


BLM = U.S. Bureau of Land Management.

X = Estimates unavailable due to small sample size (fewer than 10 samples)

Source: Yu et al. 2020.

Figure 8-10. Average bare ground cover on BLM rangelands (80 percent confidence interval).



BLM = U.S. Bureau of Land Management.

X = Estimates unavailable due to small sample size (fewer than 10 samples)

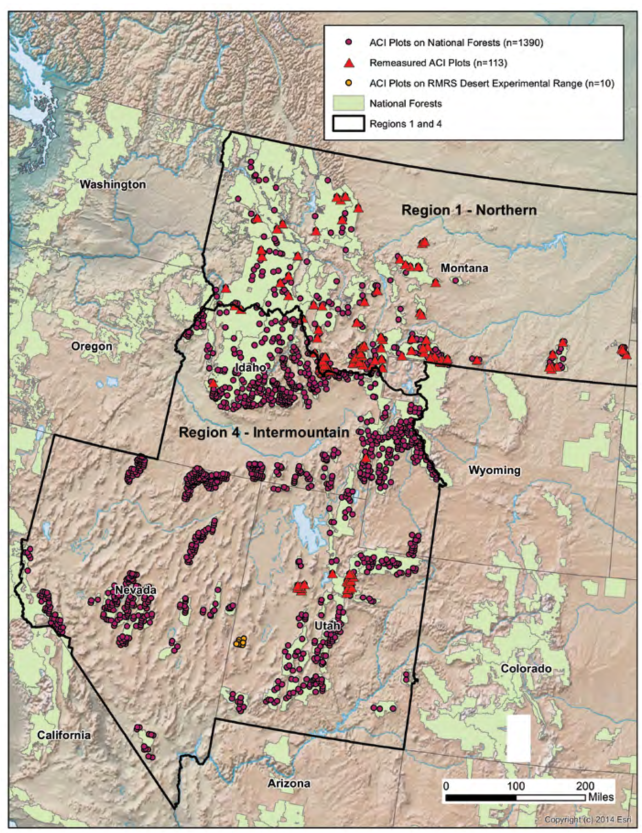
Source: Yu et al. 2020.

USDA Forest Service

The USDA Forest Service has conducted the FIA All Conditions Inventory (ACI) sporadically on National Forest System lands in the Western United States since 2004. Unlike the NRI and AIM projects, the ACI protocols do not evaluate rangeland health attributes so no formal comparison can be made with non-Federal (NRI) or BLM (AIM/LMF) lands. In addition, not all national forests participate in this program. Approximately 1,400 ACI plots have been established throughout USDA Forest Service Regions 1 (northern Idaho, western Montana) and 4 (southern Idaho and Utah) as of July 2017 (figure 8-11). Of these, 113 plots (8.1 percent) were remeasured within 10 years of their initial installation (91 plots in Region 1 and 22 plots in Region 4; table 8-6). ACI plots were found in all 21 national forests in USDA Forest Service Regions 1 and 4 (table 8-7). Only limited inferences can be made given the relatively small sample size and plot density and the low number of plots that were revisited at the time of this analysis (2017). We can confirm the presence of key invasive species such as cheatgrass, knapweed, toadflax *(Linaria dalmatica)*, and leafy spurge in plots across these regions; all of these species have the propensity to significantly change ecological conditions.

For all plots with initial measurements, 217 plots contained at least one of the four key invasive plants, with 21 plots occurring in Region 1 and 196 in Region 4. Cheatgrass was most prevalent, occurring in 215 of these plots (table 8-7). Plots with cheatgrass had a weighted average cheatgrass foliar cover of 5.9 percent across all ACI plots.

Figure 8-11. Spatial distribution of All Conditions Inventory (ACI) plots, administered by the USDA Forest Service Forest Inventory and Analysis Program throughout the Western United States.



Source: Bush 2012.

Table 8-6. Distribution of ACI plots and associated 2005 to 2017 remeasurement information, by USDA Forest Service region and State.

USDA Forest Service Region	Location	ACI plots	Remeasured
		n	
1	Northern Idaho	42	7
1	Montana	225	84
4	Nevada	372	0
4	Utah	212	20
4	Southern Idaho	412	2
4	Wyoming	137	0
Total		**1,400**	**113**

ACI = All Conditions Inventory.
Source: Bush 2012.

These findings show cheatgrass occurring on 15 percent of the sampled area within USDA Forest Service rangelands, less than the 18-percent occurrence on non-Federal rangelands (tables 8-4, 8-7). The Payette and Sawtooth National Forests in Idaho had the highest mean cheatgrass cover, each with approximately 12-percent cover and an occurrence rate in ACI plots of 38 and 19 percent, respectively. In comparison, cheatgrass was found on 58 (±8.6) percent of non-Federal rangelands in Idaho (table 8-4). While the ACI and NRI both yield valuable information, differences in sample size and sample design mean that the data are not directly comparable and limit our ability to make statistical comparison and inferences. In addition, lands managed by the USDA Forest Service are typically higher in elevation than the non-Federal counterparts and cheatgrass currently exhibits preferences for lower elevation (warmer and drier) landscapes. As a result, the findings could reflect the biophysical preferences of cheatgrass for relatively warmer lower elevation sites, more so than land use history. Although this introduction to the ACI program does not quantify rangeland health on USDA Forest Service lands, it raises awareness of data that have previously been underutilized for rangeland assessments.

Table 8-7. Total number and density of All Conditions Inventory (ACI) plots in USDA Forest Service Regions 1 and 4. Number of plots and mean foliar cover of cheatgrass occurring on initial measurement ACI plots are also provided. Plots with no cheatgrass are indicated by "-". Plot data current as of 2017.

USDA Forest Service Region	Forest name	ACI plots	Plots/ million acres	Plots with cheatgrass	Foliar cover of cheatgrass (%)
1	Bitterroot	11	6.6	1	10.8
1	Idaho Panhandle	7	2.4	-	-
1	Nez Perce-Clearwater	30	7.4	7	8.8
4	Boise	44	17.4	22	5.6
4	Caribou-Targhee	112	36.4	7	3.9
4	Payette	26	10.8	10	11.8
4	Salmon-Challis	133	30.3	25	6.4
4	Sawtooth	108	49.3	21	12.2
1	Beaverhead-Deerlodge	85	23.5	-	-
1	Custer-Gallatin	89	26.1	7	3.7
1	Flathead	11	4.2	-	-
1	Helena-Lewis and Clark	22	6.9	3	3.5
1	Kootenai	5	1.9	-	-
1	Lolo	7	2.7	1	1.3
4	Humboldt-Toiyabe	372	55.5	82	3.7
4	Ashley	46	32.8	7	6
4	Dixie	36	21	7	5.8
4	Fishlake	45	25.2	8	8.8
4	Manti-La Sal	31	21.9	-	-
4	Uinta-Wasatch-Cache	55	18.9	4	1.5
4	Bridger-Teton	115	33.2	-	
4	RMRS Desert Experimental Range	10	179.6	3	
Total (average)		**1,400**	**(23)**	**215**	**(5.9)**

ACI = All Conditions Inventory; RMRS = Rocky Mountain Research Station.
Source: Bush (2012).

All Lands Trends

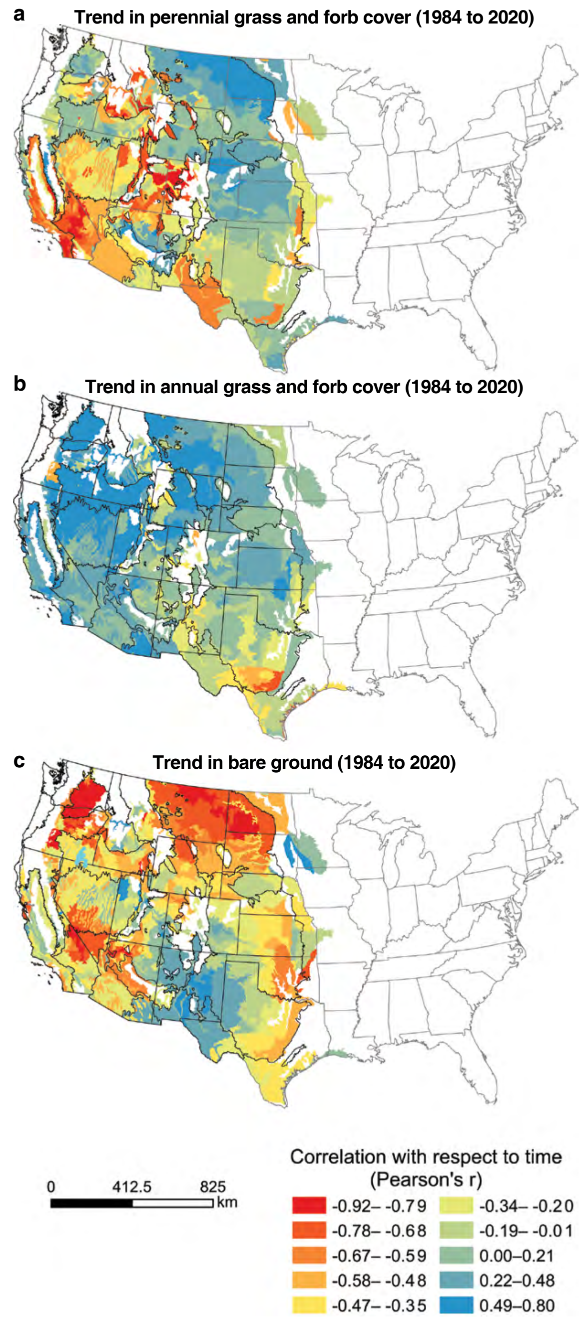
While national-level sampling programs offer valuable information about the status of U.S. rangelands, they do not provide the spatial or temporal resolution needed to evaluate rangeland trends consistently for all ownerships. The widespread availability of remotely sensed data and the dramatic increase in computational power over the last few decades has improved the capability for rangeland trend analysis. In this section we highlight these new capabilities by describing trends of annual forb and grass cover (AFGC), perennial forb and grass cover (PFGC), bare ground (BG), net primary productivity (NPP), and interannual variability of NPP. Evaluation of AFGC, PFGC, and BG come from the Rangeland Analysis Platform (RAP) (Jones et al. 2018) due to availability on the Google Earth Engine platform, although the U.S. Geological Survey Back in Time data (Homer et al. 2020, Rigge et al. 2021) could also have been used. The NPP data come from the Rangeland Productivity Monitoring Service (RPMS) (Reeves et al. 2020).

Rangeland Cover

Evaluating trends in AFGC, PFGC, and BG can indicate emerging problems, such as reduced rangeland health or reduced resiliency to drought or climate change. By examining changes in the foliar cover of different life forms and cover of bare ground, we can make general statements about the condition of the landscape. For example, decreases in cover of perennial species suggests reduced rangeland health, carrying capacity, and resiliency to drought. To perform this analysis, we calculated the linear trend (correlation with respect to time; Pearson's r) of AFGC, PFGC, and BG from 1984 to 2020 across most rangelands of the conterminous United States. While the original data were available at a 30-m resolution, we aggregated the information to Bailey's ecoregions at the ecological subsection level (Bailey and Hogg 1986), and to Omernik regions (table 8-8) and the Major Land Resource Areas used previously for comparative purposes with the AIM/NRI analyses. Because preliminary analysis suggested that the post-2000 period ushered in significant changes in rangelands of the conterminous United States, we divided the time series into two periods (1984 to 1999 and 2000 to 2020) to confirm when most of the changes in rangeland attributes took place.

At the ecological subsections spatial scale (Bailey and Hogg 1986), PFGC is strongly increasing on the northern Great Plains, principally eastern Montana, most of North Dakota, and northern South Dakota (figure 8-12), due in part to significant increases in growing season precipitation (Reeves et al. 2020). The most widespread declines in PFGC occur in California, most of Utah, western

Figure 8-12. Correlation of (a) perennial forb and grass cover, (b) annual forb and grass cover, and (c) bare ground with respect to time on rangelands, derived using Pearson's r from 1984 to 2020 for ecological subsections (Bailey and Hogg 1986). Negative Pearson's r values correspond to declining trends. Rangeland Analysis Platform data are not available for the Eastern United States.



Source: Rangeland Analysis Platform (Jones et al. 2018). (20 May 2021).

Colorado, and western Montana. In contrast to declines in PFGC, AFGC has increased in magnitude and extent throughout much of the West. The significant increases in AFGC are likely due to invasive annual grasses such as cheatgrass, red brome *(Bromus rubens)*, and ventenata noted throughout this assessment. Eastern Washington and Oregon, as well as southern Idaho, central Utah, and northern Nevada have experienced the greatest increases in AFGC, with additional increases found in eastern Montana and Wyoming (figure 8-12). These findings are consistent with recent evidence suggesting that annual grasses are expanding across the West, including at higher elevations than previously expected (Nicolli et al. 2020, Pawlak et al. 2014).

Evaluation of the two separate time periods (1984 to 1999 and 2000 to 2020) reveals that most changes in the remotely sensed rangeland indicators have taken place since 2000. The national average for both PFGC and BG were reduced by approximately 8 percent when comparing 1984 to 1999 with 2000 to 2020. Seventy-three percent of rangelands experienced losses of PFGC from 2000 to 2020, while 72 percent of rangelands experienced decreases of BG. In contrast, the national average for AFGC increased by 15 percent when comparing the period 1984 to 1999 versus 2000 to 2020. Eighty-five percent of rangelands experienced increases of AFGC from 2000 to 2020 relative to 1984 to 1999. These data coincide with the distribution of invasive annual bromes found on non-Federal land in the NRI Rangeland Resource Assessment (figure 8-4).

The widespread increases in annual forbs and grasses are directly responsible for the accompanying decreases in bare ground over much of the Western U.S. rangelands (figure 8-12). Decreases in bare ground are often considered positive, indicating that annual NPP is likely increasing or at least maintaining yields. Many of these decreases in bare ground, however, are related to increases in invasive annual forbs and grasses, which are causing significant ecological changes manifested through increased fire frequencies and behavior (Pilliod et al. 2017), and changes in forage quantity, quality, and phenology. The majority of U.S. rangelands have been exhibiting decreasing bare ground trends since 1984. While most rangelands have exhibited some decrease in bare ground, there are some notable exceptions, including the areas of west Texas and most of New Mexico (figure 8-12).

This remotely sensed evaluation of rangeland components has also been summarized across the Omernik ecoregions, to allow comparison with the AIM rangeland health evaluation (table 8-8). For example, the increase in invasive species in the Central Basin and Range on BLM lands (figure 8-9) corresponds with the finding that AFGC is increasing on all rangelands in the Central Basin and Range (r = 0.44),

Table 8-8. Correlation of perennial forb and grass cover (PFGC), annual forb and grass cover (AFGC), and bare ground (BG) with respect to time on rangelands, derived using Pearson's r from 1984 to 2020 for Omernik's ecoregions. Negative Pearson's r values correspond to declining trends, while positive numbers indicate an increasing trend. Larger numbers indicate a higher positive correlation of cover over time (cover is going up over time).

Omernik Level II Ecoregion	Rangeland sampled	PFGC	AFGC	BG
	million ha	correlation (r)		
All Rangelands	124.9	-0.3	0.3	-0.3
Arizona/New Mexico Mountains	2	-0.1	0.1	0
Central Basin and Range	11.8	-0.4	0.4	-0.4
Eastern Cold Deserts	15.7	-0.3	0.2	-0.2
Madrean Archipelago	1.7	-0.2	0.3	-0.1
Mediterranean California	3.5	-0.5	0.5	-0.2
Northern Cold Deserts	10.8	-0.2	0.6	-0.4
South-Central Semiarid Prairies	28.5	0	0.1	-0.2
Warm Deserts	17.9	-0.5	0.2	-0.3
West-Central Semiarid Prairies	23.9	0.1	0.3	-0.5
Western Cordillera	9.1	-0.3	0.3	-0.3

Source: Rangeland Analysis Platform (Jones et al. 2018). (20 May 2021).

with concomitant decreases in bare ground as a result (table 8-8). Notable differences between the remotely sensed data and those from AIM include the fact that remotely sensed data cover all rangeland ownerships while AIM covers only BLM lands and that BG is the only attribute approached consistently by both efforts.

Rangeland Annual Production

Net primary productivity is a critical indicator of rangeland health, and it serves as forage for native and domestic ungulates, small mammals, and insects. The RPMS provides spatially explicit estimates of rangeland NPP across the conterminous United States from 1984 to 2021 and beyond, at a 30-m spatial resolution, but 2020 is the most recent data included in this report because of the RPA production schedule. Using these data, we quantified the average NPP values, trend in NPP values, and interannual variability (standard deviation of the time series compared to the mean). Because trends and variability from 1984 to 1999 differ from results for the 2000 to 2020 time period (Reeves et al. 2020), we analyzed rangeland NPP trends and variability for three timeframes: 1984 to 2020, 1984 to 1999, and 2000 to 2020. As with the analysis of the trends in cover data, we calculated the linear trend of NPP (correlation with respect to time; Pearson's r).

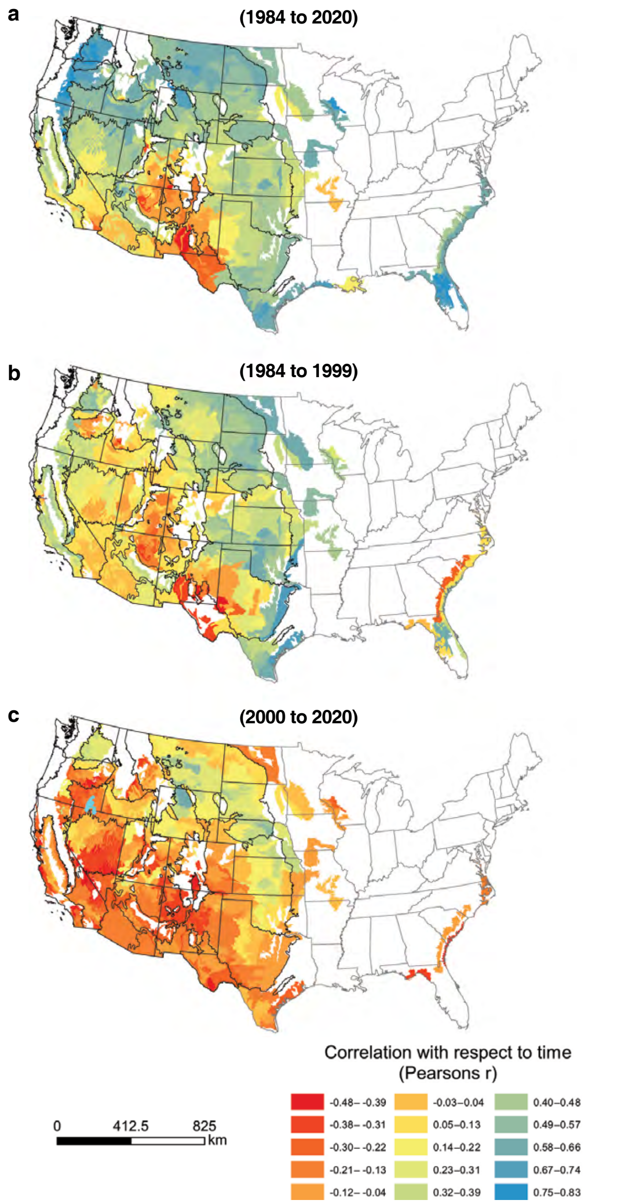
Increases in annual NPP have occurred in all RPA regions since 1984 (table 8-9). The highest NPP values (>4,400 kg ha^{-1}) were observed in the North Region. Conversely, the Rocky Mountain Region exhibited the lowest NPP values (1,140 kg ha^{-1}). Interannual variability was highest in the South and Pacific Coast Regions, with coefficients of variability (CV) of 0.17 and 0.16, respectively, meaning that NPP (and forage) varied about 17 percent annually on average from 1984 to 2020. Variability in NPP was higher from 2000 to 2020 compared to 1984 to 1999—with both higher highs and lower lows in NPP—while NPP trends, which were positive from 1984 to 1999, stagnated or declined from 2000 to 2020.

These broad national and regional averages, however, mask trends taking place on rangelands at the subregional level (figure 8-13). In all time periods (1984 to 2020, 1984 to 1999, and 2000 to 2020) the desert Southwest exhibited declining trends in NPP. In contrast, increases in NPP occurred east of the Cascade Mountains in the Pacific Northwest and the northern Great Plains of North Dakota, South Dakota, and Montana (Reeves et al. 2020, figure 8-13). In addition to these asymmetric trends in annual NPP, interannual variability after 2000 was greater than from 1984 to 1999 for all regions (table 8-9). The cause of increased variability is not known but could be linked to more intense rainfall events and greater occurrences of extreme temperatures (Frame et al. 2020). The increased variability in annual NPP has significant implications for rangeland forage supplies.

We estimated forage quantity, the relative proportion of herb cover to total vegetation cover, and a universal estimate of forage beneath forest canopies using RPMS data. Forage quantities on rangelands were estimated for average, above-average, and below-average forage conditions, calculated as the average plus or minus one standard deviation from the mean from 1984 to 2020. Key assumptions made in the analysis are outlined in table 8-10.

Private lands are the largest contributor to rangeland forage pools (table 8-10), due to both the large extent of private rangelands (55 percent) relative to public rangelands (table 8-2) and the higher NPP rates relative to other jurisdictions.

Figure 8-13. Correlation of annual net primary productivity with respect to time on rangelands derived using Pearson's r from (a) 1984 to 2020, (b) 1984 to 1999, and (c) 2000 to 2020. Negative Pearson's r values correspond to declining trends.



Source: Rangeland Production Monitoring Service (Reeves et al. 2020). (20 May 2021).

Table 8-9. Rangeland NPP characteristics including mean, coefficient of variability (a measure of interannual variability), and correlation (r) with respect to time for three periods: 1984 to 2020, 1984 to 1999, and 2000 to 2020.

	1984 to 2020	1984 to 1999	2000 to 2020	1984 to 2020	1984 to 1999	2000 to 2020	1984 to 2020	1984 to 1999	2000 to 2020
RPA region	**Mean kg ha^{-1}**			**Coefficient of variability**			**Correlation (Pearson's r)**		
	percent								
North	4,402	4,125	4,620	0.08	0.05	0.07	0.75	0.58	0.07
South	1,590	1,410	1,720	0.17	0.13	0.15	0.56	0.33	0.07
Rocky Mountain	1,140	1,043	1,207	0.14	0.13	0.13	0.60	0.42	0.27
Pacific Coast	1,300	1,168	1,399	0.16	0.14	0.15	0.53	0.37	-0.05

ha = hectares; kg = kilograms; NPP = net primary productivity.

Source: Rangeland Production Monitoring Service (Reeves et al. 2020). (20 May 2021).

Table 8-10. Total forage by ownership and land cover class and the associated number of animal units these lands can support on an annual basis under different conditions in the conterminous United States from 1984 to 2020.

Ownership or Management	Average total NPP (favorable conditions)	Average total NPP	Average total NPP (unfavorable conditions)	Average herbaceous NPP (favorable conditions)	Average herbaceous NPP	Average herbaceous NPP (unfavorable conditions)
	teragrams					
U.S. Bureau of Land Management	42.2	32.9	23.6	26.1	20.4	14.6
U.S. National Park Service	2.6	2	1.4	1.3	1	0.7
Tribal	18.5	14.2	9.9	14.8	11.2	7.7
Private land	236.7	182	127.2	184.5	141.6	98.6
U.S. Army	3.5	2.6	1.7	2.1	1.6	1
U.S. Fish and Wildlife Service	2.9	2.2	1.6	1.7	1.3	0.9
USDA Forest Service	18.1	14.4	10.7	10	7.9	5.8
Other	118	91	64	87.5	67.2	47
Rangeland total	442.5	341.3	240	328.1	252.2	176.3
Pastures[a]	151.3	151.3	151.3	151.3	151.3	151.3
Forage beneath forested canopies[b]	64.3	64.3	64.3	64.3	64.3	64.3
Total forage (rangeland, pasture, forests)	**721**	**556**	**391**	**606**	**467**	**329**
	estimated animal units per year[c]					
AUY from all forage pools[d]	**49,383,562**	**38,082,192**	**26,780,822**	**41,506,849**	**31,986,301**	**225,342,467**

Assumptions:

[a] The national annual average yield from pastures of 3,235 kg ha^{-1} (2,886 pounds per acre) was derived from RPMS (Reeves et al. 2020). Irrigated pastures are not included on this assessment.

[b] In areas not considered rangeland and where tree canopy cover exceeded 1 percent we assumed a conservative forage estimate of 241 kg ha^{-1} (215 pounds per acre) (Gaines et al. 1954, Reeves and Mitchell 2012).

[c] An animal unit is defined as one mature cow of about 450 kg, either dry or with calf up to 6 months of age, and has a general nutritional requirement of about 12 kg of dry matter per day (Smith et al. 2017). We assumed that 30 percent of the forage in a given year could be sustainably harvested to support animals.

[d] Excluding agronomically derived feedstuffs such as corn or soy meal.

AUY = animal units per year; kg = kilogram; NPP = net primary productivity; RPMS = Rangeland Productivity Monitoring Service.

Source: Rangeland Analysis Platform (Jones et al. 2018) (20 May 2021) and Rangeland Production Monitoring Service (Reeves et al. 2020). (20 May 2021).

The higher NPP rates on private lands reflect the spatially explicit settlement patterns of the Western United States; the most productive lands were usually privatized during settlement while less productive areas—areas predisposed to reduced NPP due to abiotic factors such as drier climatology, thin soils, and juxtaposition on the landscape (e.g., rain shadow)—were left in the public domain. Production on USDA Forest Service land averages 1,544 kg ha^{-1}, approaching the level of non-Federal lands (1,614 kg ha^{-1}) and more than twice the level of BLM productivity (622 kg ha^{-1}). Rangelands managed by the USDA Forest Service tend to occur on higher elevations, which typically receive greater precipitation than lower elevation landscapes. Despite lower NPP, the BLM is the second largest producer of forage in conterminous United States rangelands due to the large extent of lands under its jurisdiction (table 8-10).

The average annual rangeland forage pool across all rangelands in the conterminous United States is roughly 341.3 Tg, including 252.2 Tg of herbaceous forage (table 8-10; Reeves et al. 2020). The average annual pasture forage pool is 151.3 Tg (table 8-10) and the forage pool beneath forested canopies is approximated at 64.3 Tg. These forage calculations do not include areas dominated by transitional rangelands identified in Reeves and Mitchell (2011). Transitional rangelands are lands where the dominant vegetation is shrubs and grasses, but because the site will transition to forest it does not meet the criteria for being classified as rangeland. In some regions, transitional rangelands represent large pools of forage suitable for herbivory, but their contribution to the forage base is relatively smaller and ephemeral from a national perspective (Allen 1988).

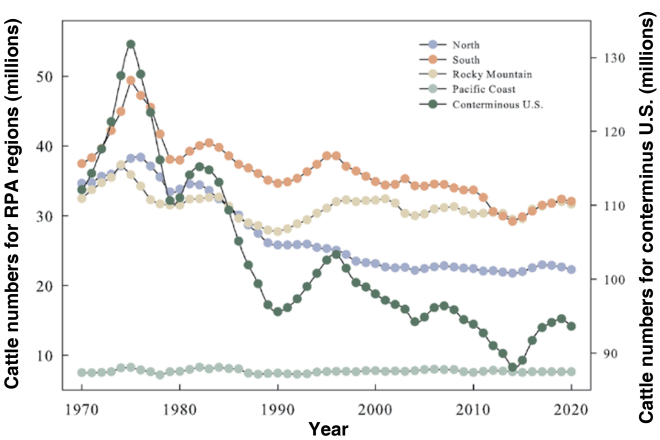
The animal units that can be supported annually (animal unit year) by this total forage pool ranges from 45 to 84 million depending on the growth conditions (below-average, average, or above-average production year). Not all livestock receive sustenance solely on rangelands, however; many livestock also consume hay or other agronomically derived feedstuffs such as corn, oats, and barley. This is especially true for public land permittees who often have only temporary access to public land forage and are eventually required to move livestock in accordance with the terms of their permits, or in areas where snowfall limits access to forage. This analysis also does not account for forage that may be unavailable due to terrain or distance from water which may prohibit some classes of ungulates from accessing some forage.

Livestock Trends

❖ The average number of cattle in the conterminous United States decreased almost 30 percent between the 1975 peak and 2020. Despite these declines, the beef yield has remained relatively steady, attributable to larger cattle.

The number of cattle in the United States peaked at about 132 million in 1975, followed by a continual decline (figure 8-14). By 2020 the average number of cattle in the conterminous United States decreased almost 30 percent to approximately 93 million. Despite this decline, total beef production remained stable due to increased efficiencies leading to larger cattle, including advances in growth enhancers, feed milling, and feed additives. The average yearling bodyweight of Angus breed bulls and heifers increased from the early 1970s to the mid-2000s by 3.6 and 2.6 kg per year, respectively (Ohio Country Journal 2017, NASS 2021).

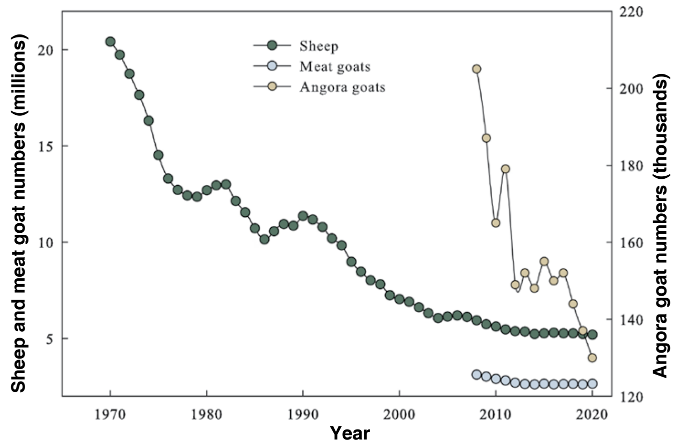
Figure 8-14. Number of beef cattle in the conterminous United States, nationally and by RPA region.



Source: NASS 2021. (20 May 2021).

Cattle production in the Pacific Coast and Rocky Mountain Regions remained relatively steady over this time period, while the North Region experienced the largest declines (figure 8-14). The South Region, which was significantly impacted by droughts during 2011 and 2012, experienced some rebounds in cattle numbers following those years, but not enough to reverse long-term decline. The number of sheep in the conterminous United States has declined even more rapidly: sheep numbers have decreased about 74 percent since 1970 (to an average of 5.3 million since 2015). While commercially raised goats have not been monitored for as long as cattle and sheep, both meat goats and Angora goats have seen declines of 15 and 37 percent, respectively since 2008 (figure 8-15).

Figure 8-15. Number of sheep, meat goats, and Angora goats in the conterminous United States.



Source: NASS 2021. (20 May 2021).

Outlook for Rangelands

This section focuses on the impacts of climate change on rangeland phenology, NPP, and land use. Changes in these vegetation metrics and use patterns were estimated under two bounding climate futures: Representative Concentration Pathway (RCP) 4.5, which represents a lower warming future, and RCP 8.5, which represents a high-warming future. We paired these two climate futures with five different climate models that capture the range of projected future temperature and precipitation across the conterminous United States to provide 10 distinct climate projections (two RCPs, five climate models). The five climate models selected by RPA represent least warm, hot, dry, wet, and middle-of-the-road climate futures for the conterminous United States (table 8-11); however, characteristics can vary at finer spatial scales. The Scenarios Chapter describes how these climate models were selected; Joyce and Coulson (2020) provide more extensive information. To facilitate interpretation, although we run our analyses using each RPA climate projection, we only present minimum and maximum results below (each the result of using a different climate projection), as well as an ensemble result that reduces complexity by providing the average amount of change projected for various attributes across climate projections and across U.S. rangelands (performed for RCP 4.5 and RCP 8.5 separately). We also examine how to interpret projected changes in climate using statistical analogs. The goal of these statistical analogs is to identify what city (or location) today best represents the expected future climate of a given city by 2080.

Table 8-11. Five climate models selected to reflect the range of U.S. climate futures in the year 2070. Each model was run under RCP 4.5 and RCP 8.5, and therefore provides distinct climate projections for each RCP.

	Least warm	Hot	Dry	Wet	Middle
Climate model	MRI-CGCM3	HadGEM2-ES	IPSL-CM5A-MR	CNRM-CM5	NorESM1-M
Institution	Meteorological Research Institute, Japan	Met Office Hadley Centre, United Kingdom	Institut Pierre Simon Laplace, France	National Centre of Meteorological Research, France	Norwegian Climate Center, Norway

RCP = Representative Concentration Pathway.
Source: Joyce and Coulson 2020.

Projections of Rangeland Phenology

- ❖ Growing seasons are projected to be 3 to 4 days shorter by early century and 6 to 10 days shorter by mid-century, primarily due to nutrient limitations. Local growing seasons could be reduced by as much as 20 days under the RCP 8.5 ensemble scenario.
- ❖ Earlier projected shifts to the start of the rangeland growing season are most pronounced in eastern Washington and Oregon and throughout the Great Basin, relative to other areas.
- ❖ Earlier projected shifts to the end of the growing season are more pronounced than changes to the start of the growing season, especially on the southern plains of Texas and Oklahoma where the end of the season is projected to occur up to 31 days earlier by 2070 under RCP 8.5.

Phenology—the timing of plant lifecycle events—influences the abundance and distribution of organisms, ecosystem services, food webs, and global cycles of water and carbon (https://www.usanpn.org/). Climate change can create a mismatch between the time specific vegetation (food) is available and the time when consumers are seeking that vegetation. For example, if pollinators such as bees and butterflies arrive to an area after vegetation flowering, there would be little opportunity for pollination and seed development, thereby threatening food webs and the ability of the species to reproduce. In this section we explore projected changes in phenology represented by alterations in phenological timing, which we define as the time from the onset of greenness to the cessation of greenness (https://www.usgs.gov/special-topics/remote-sensing-phenology). This should not be confused with the growing season length associated with plant hardiness zones, which is defined by the frost-free period and has been increasing across U.S. rangelands (https://www.epa.gov/climate-indicators/climate-change-indicators-length-growing-season). While increasing frost-free periods could theoretically result in longer growing seasons, we found that critical nutrients such as water and nitrogen were not sufficiently abundant to support extended growing seasons, and that limitations in the availability of these nutrients actually lead to shorter growing seasons across U.S. rangelands.

The impact of climate change on rangeland phenology is relatively understudied at the national level; however, spatially explicit metrics of key phenological attributes, including start of season (SOS), end of season (EOS), and length of vegetation growth (referred to here as the growing season), are available for the period between 2000 to 2020 from the U.S. Geological Survey (https://www.usgs.gov/core-science-systems/eros/phenology) (Gu et al. 2010). To better understand potential future changes in rangeland phenology we used these data to model future changes in SOS and EOS (Zimmer et al. 2022). The phenology models developed in Zimmer et al. (2022) relate a series of abiotic and biotic predictors to SOS and EOS including vegetation type, elevation, and basic climatic forcing, including solar radiation, maximum temperature, vapor pressure deficit, and accumulated growing degree days (Zimmer et al. 2022). Relatively little modeling was conducted in desert areas, particularly the Sonoran and Chihuahuan deserts, because phenology is notoriously difficult to characterize in these areas (Zimmer et al. 2022). In addition, vegetation phenology in the North Region was not modeled due to a lack of available data from Gu et al. (2010). Results portrayed here represent the change in Julian days compared against the 2000 to 2014 baseline period (selected due to data availability at the time of analysis).

Results were summarized to ecological subsections and provided for the individual RPA climate projections that produce the minimum and maximum amount of change by early- and mid-century (2020 to 2040 and 2041 to 2070, respectively), as well as for the ensemble phenological response. The climate projections that produce the minimum and maximum amount of change in SOS or EOS provide information about the full range of potential future change in rangeland growing seasons, while ensemble results provide the average projected change in vegetation phenology (based on all five climate model projections). Climate projections that produce minimum and maximum change were selected based on results for the entire extent of rangelands across the conterminous United States and are therefore not always representative of the minimums and maximums for individual regions.

Start of Season

Growing seasons are projected to both start and end earlier in the future, and these shifts are projected to intensify over time, with SOS starting even earlier in mid-century than early century (table 8-12). Compared with the baseline period, the growing season was projected to start 4 to 5 days earlier on average across all three regions for early century (2020 to 2040) under RCP 4.5, while the growing season for mid-century (2041 to 2070) was projected to start 6 to 8 days earlier (table 8-12). Projected SOS generally occurs earlier under RCP 8.5 than under RCP 4.5, a likely result of the intensified radiative warming, with the exception of SOS minimum change projected by the least warm climate projection.

The Pacific Coast Region is projected to see the largest average earlier shift in SOS, followed by the Rocky Mountain and South Regions, however the potential exists for the Rocky Mountain Region to experience a similar early shift in SOS, shown by the maximum SOS result. Local patterns exhibit greater variability in modeled phenological changes than the regional patterns described above. In addition to growing seasons starting and ending earlier under RCP 8.5 than RCP 4.5, there is also more spatial variability in the amount of change exhibited across U.S. rangelands under RCP 8.5 (figure 8-16). For both early- and mid-century under RCP 4.5 and 8.5, the Great Basin, eastern Washington and Oregon, and the southern reaches of the Colorado Plateau (especially near northeastern Arizona) showed the largest shift to an earlier SOS (up to 22 days; figure 8-16).

End of Season

As with SOS, the EOS is projected to occur earlier in the future, more so under RCP 8.5 than RCP 4.5 due to the intensified radiative warming. EOS is projected to shift more than SOS—for all regions, in both time periods, and under both RCPs—resulting in a shorter annual growing season. The growing season is projected to see the largest average earlier shift in EOS in the South Region, followed by the Pacific Coast and Rocky Mountain Regions (table 8-12). Compared with the baseline period, early century EOS ensemble projections under RCP 4.5 ranged from 6 days early in the Rocky Mountain Region to 9 days early in the South Region, increasing at mid-century to 10 and 16 days early, respectively (table 8-12). As with SOS, local patterns of EOS exhibit greater variability than in the regional patterns described above (figures 8-16 and 8-17). The EOS projections show a different spatial pattern than SOS, with the southern Great Plains (principally Texas and Oklahoma) projected to experience the largest change, ending the growing season up to 31 days earlier by mid-century under RCP 8.5 (figure 8-17).

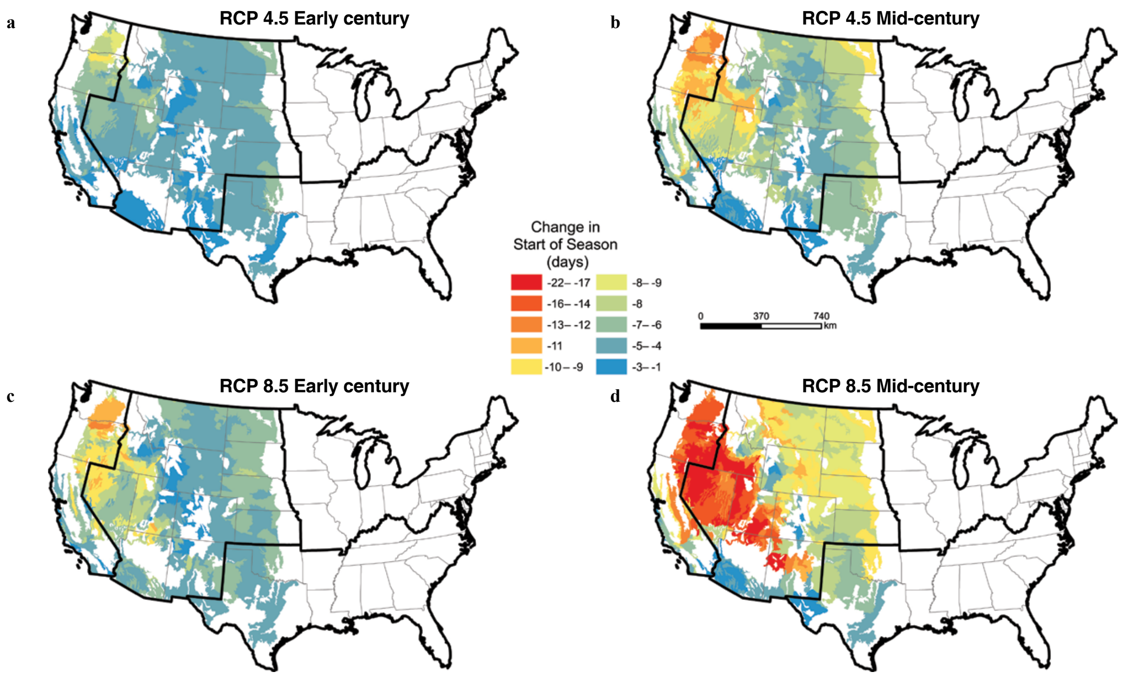
Table 8-12. Projected changes in start of season (SOS) and end of season (EOS) phenology (Julian days) for early century (2020 to 2040) and mid-century (2041 to 2070), compared with the baseline period of 2000 to 2014. The ensemble result provides the average amount of change that is projected nationally and for each region across all five climate projections. The least warm climate projection produces the minimum amount of change in SOS under RCP 4.5 and 8.5. The wet and hot climate projections produce the maximum amount of change in SOS under RCP 4.5 and RCP 8.5, respectively. The least warm and hot climate projections produce the minimum and maximum amount of change in EOS, respectively, under both RCPs 4.5 and 8.5. Climate projections that produce minimum and maximum change were selected based on results for the entire extent of rangelands in the conterminous United States and are therefore not always representative of the minimums and maximums for individual regions.

	RCP 4.5		RCP 8.5	
Phenology Parameter	2020 to 2040	2041 to 2070	2020 to 2040	2041 to 2070
	change in Julian Days			
National				
SOS (Ensemble)	-4.7	-7.1	-5.6	-8.1
SOS (Max)	-4.0	-6.8	-8.2	-12.2
SOS (Min)	-5.6	-7.2	-2.8	-4.1
EOS (Ensemble)	-7.9	-13.1	-9.2	-17.8
EOS (Max)	-8.3	-14.2	-11.6	-23.8
EOS (Min)	-5.6	-10.0	-7.7	-17.5
South Region				
SOS (Ensemble)	-4.2	-5.8	-5.5	-6.3
SOS (Max)	-1.5	-2.5	-7.5	-9.2
SOS (Min)	-3.9	-6.6	-3.6	-3.6
EOS (Ensemble)	-9.4	-16.5	-11.3	-22.9
EOS (Max)	-12.8	-21.3	-14.6	-31.1
EOS (Min)	-4.6	-9	-7.9	-20.8
Rocky Mountain Region				
SOS (Ensemble)	-4.8	-7.2	-4.8	-8.3
SOS (Max)	-5.2	-8.9	-7.8	-13.2
SOS (Min)	-6.4	-7.5	-1.9	-3.5
EOS (Ensemble)	-6.5	-10	-6.9	-13.8
EOS (Max)	-7.9	-13.8	-9	-18.8
EOS (Min)	-4.2	-4.9	-5.9	-13.6
Pacific Coast Region				
SOS (Ensemble)	-5.1	-8.2	-6	-9.7
SOS (Max)	-5.2	-8.9	-9.3	-14.3
SOS (Min)	-6.4	-7.5	-2.8	-5.1
EOS (Ensemble)	-7.9	-12.9	-9.3	-16.8
EOS (Max)	-4.1	-7.4	-11.3	-21.5
EOS (Min)	-8.1	-16	-9.3	-18.2

EOS = end of season; max = maximum; min = minimum; RCP = Representative Concentration Pathway; SOS = start of season.

Source: Zimmer et al. 2022.

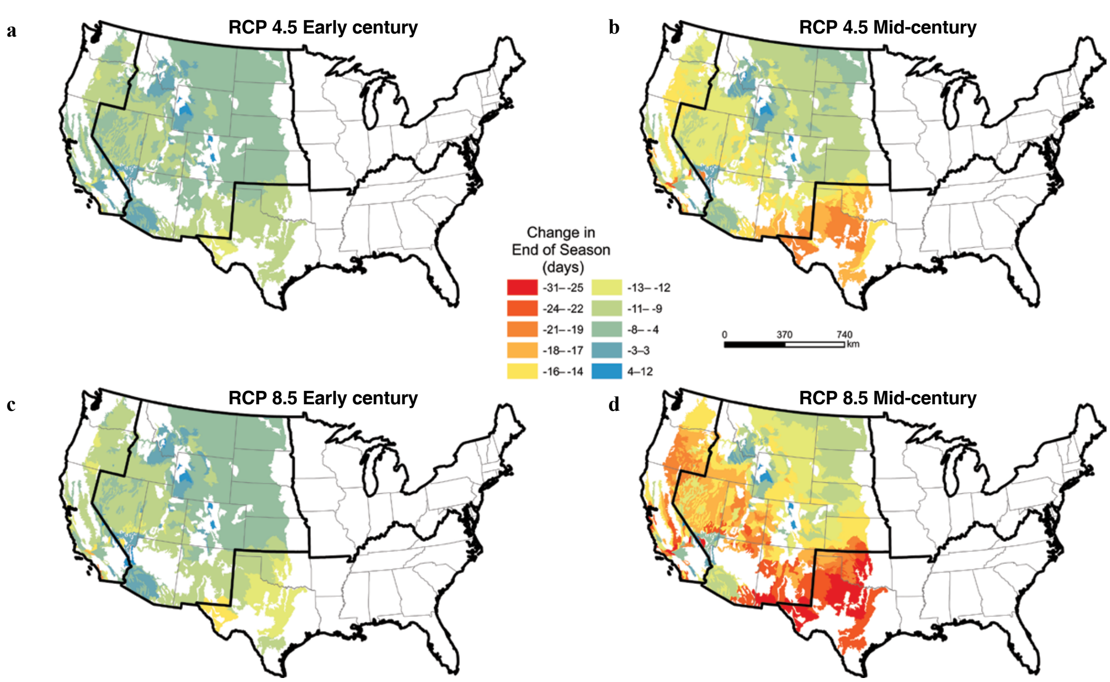
Figure 8-16. Projected ensemble change in the start of the growing season compared to a 2000 to 2014 baseline for (a) RCP 4.5 early century, (b) RCP 4.5 mid-century, (c) RCP 8.5 early century, and (d) RCP 8.5 mid-century. The ensemble result provides the average amount of projected change across all five RPA climate projections. Pixel-level phenology projections were aggregated to ecological subsections (Bailey and Hogg 1986).



RCP = Representative Concentration Pathway.

Source: Zimmer et al. 2022.

Figure 8-17. Projected ensemble change in the end of the growing season compared to a 2000 to 2014 baseline for (a) RCP 4.5 early century, (b) RCP 4.5 mid-century, (c) RCP 8.5 early century, and (d) RCP 8.5 mid-century. The ensemble result provides the average amount of projected change across all five RPA climate projections. Pixel-level phenology projections were aggregated to ecological subsections (Bailey and Hogg 1986).



RCP = Representative Concentration Pathway.

Source: Zimmer et al. 2022.

Growing Season Considerations

Regardless of the RCP or climate projection evaluated, shorter growing seasons and an earlier onset of greenup were universally projected. While EOS timing has often been overlooked in phenology research, our findings confirm it may be as or more significant than SOS timing in the future. Nationally, earlier EOS and SOS suggest the potential for growing seasons to be between 3 to 4 days shorter by early century and 6 to 10 days shorter by mid-century.

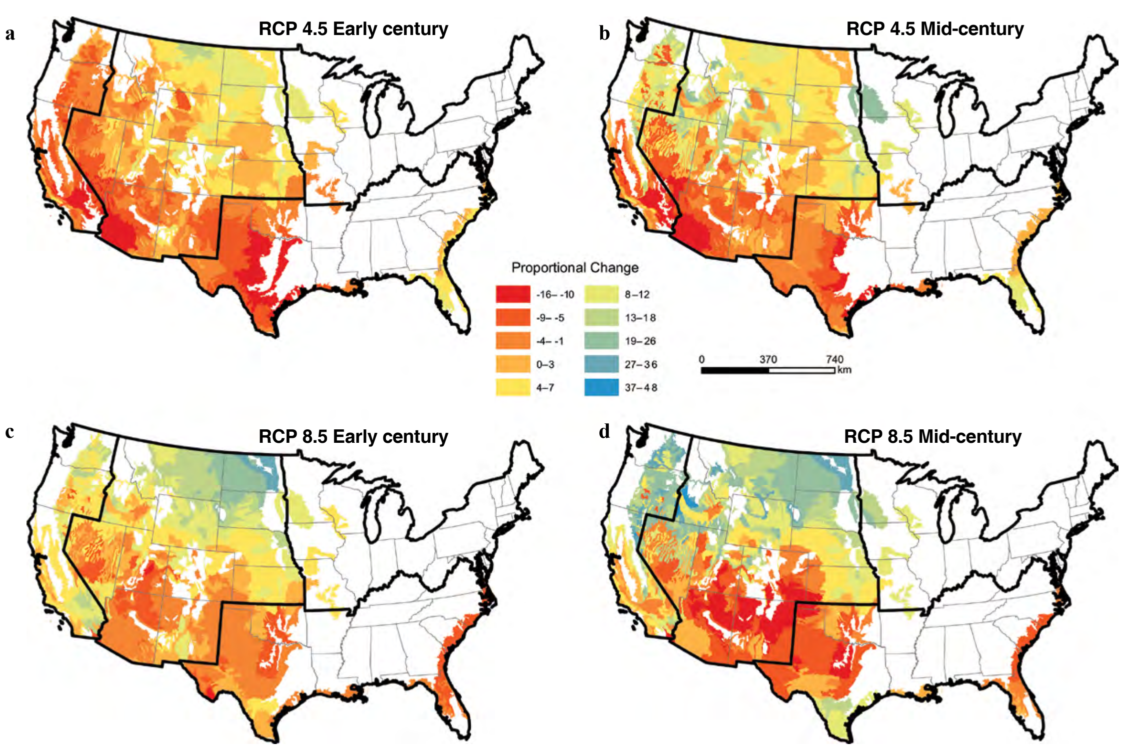
Projections of Rangeland Productivity

- Productivity changes will have modest effects on the total national forage supply in the future, but impacts will be significant regionally and locally.
- Projections suggest that many of the trends that have been observed since 1984—including decreased NPP in the South, increased NPP in the North, and greater interannual variability—will continue and possibly intensify in the future.
- The Southwestern United States is projected to experience the largest and most widespread NPP reductions, especially in desert areas, followed by the southern plains and Four Corners area.
- The northern Great Plains, especially North Dakota, South Dakota, and Montana, are projected to experience the largest gains in productivity.

We developed annual projections of aboveground NPP on rangelands under RCP 4.5 and 8.5 using the RPA climate projections and the MC2 dynamic global vegetation model (Bachelet et al. 2015, Kim et al. 2018) using a 2015 to 2019 baseline due to data availability. Results were summarized to ecological subsections (Bailey and Hogg 1986) and RPA regions and provided for the individual climate projections that produce the minimum and maximum NPP values as well as the ensemble NPP response (the average NPP across all five RPA climate projections). Climate projections that produce minimum and maximum NPP projections were selected based on results for the entire extent of rangelands across the conterminous United States and may not always be representative of the minimums and maximums for individual regions.

NPP is projected to increase with increasing latitude in all regions relative to the baseline when examining the ensemble results, particularly for mid-century under RCP 8.5 (figure 8-18). NPP is projected to increase over time in both the North and Rocky Mountain Regions for the ensemble results, with the largest gains occurring in the North and with gains for both

Figure 8-18. Projected ensemble proportional change in NPP compared to a 2015 to 2019 baseline for (a) RCP 4.5 early century, (b) RCP 4.5 mid-century, (c) RCP 8.5 early century, and (d) RCP 8.5 mid-century. The ensemble result provides the average amount of projected proportional change across all five RPA climate projections.



RCP = Representative Concentration Pathway.

Source: Kim et al. 2018.

regions being larger under RCP 8.5 than RCP 4.5 (table 8-13; figure 8-18). The hot and dry climate projections, however, produce NPP declines for the Rocky Mountain Region, while the dry climate projection produces NPP decline for the North Region by mid-century (table 8-13; figure 8-19). The South Region is projected to experience declines in NPP by the hot, dry, and ensemble results, but is projected to experience increases in NPP by the least warm climate projection (table 8-13; figures 8-19, 8-20). Results for the Pacific Coast Region are the most variable between RCPs, with the largest NPP declines of any region projected under RCP 4.5 over all timescales, and increases in NPP projected by all climate projections and under RCP 8.5 at levels meeting or exceeding those projected for the Rocky Mountain Region (table 8-13; figures 8-18, 8-19, 8-20).

Table 8-13. Projected proportional changes in NPP for early century (2020 to 2040) and mid-century (2041 to 2070), compared with the baseline period of 2015 to 2019. The ensemble result provides the average amount of change that is projected nationally and for each region across all five RPA climate projections. The hot and dry climate projections produce the minimum NPP values under RCP 4.5 and 8.5, respectively. The least warm climate projection produces the maximum NPP values under RCP 4.5 and 8.5. Climate projections that produce minimum and maximum NPP values were selected based on results for the entire extent of rangelands in the conterminous United States and are therefore not always representative of the minimums and maximums for individual regions.

	RCP 4.5		RCP 8.5	
NPP Parameter	**2020 to 2040**	**2041 to 2070**	**2020 to 2040**	**2041 to 2070**
		percent		
National				
NPP (Ensemble)	-1.5	3.0	3.0	6.5
NPP (Max)	2.3	10.5	8.0	22.0
NPP (Min)	-7.8	-2.5	3.0	-6.3
North Region				
NPP (Ensemble)	4	10	5	11
NPP (Max)	7	27	17	36
NPP (Min)	3	1	4	-7
South Region				
NPP (Ensemble)	-4	-2	-2	-2
NPP (Max)	1	8	7	13
NPP (Min)	-8	-3	-9	-23
Rocky Mountain Region				
NPP (Ensemble)	0	4	4	7
NPP (Max)	3	9	6	20
NPP (Min)	-9	-2	9	-2
Pacific Coast Region				
NPP (Ensemble)	-6	0	5	10
NPP (Max)	-2	-2	2	19
NPP (Min)	-17	-6	8	7

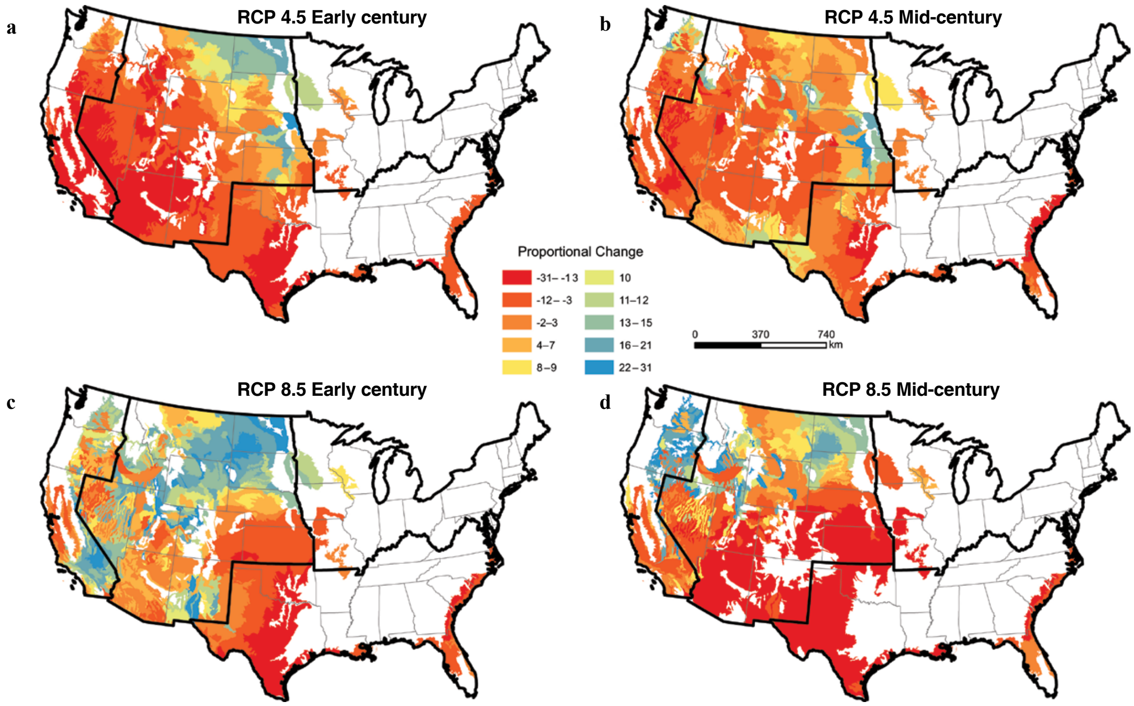
Max = maximum; Min = minimum; NPP = net primary productivity; RCP = Representative Concentration Pathway.

Source: Kim et al. (2018).

These large regional averages, however, mask noteworthy subregional patterns that are evident when comparing the projected smallest and largest future overall levels of NPP (figures 8-19, 8-20). The northern Great Plains tend to outperform all other areas, especially in North Dakota and eastern Montana, ranging from moderate losses of NPP (figure 8-19) to substantial gains (figure 8-20). However, these increasing NPP trends could be partly caused by expanding shrub and other woody species cover (Klemm et al. 2020). Productivity is projected to decrease by as much as 31 percent under the worst-case scenario in much of the desert Southwest and southern plains, especially Kansas, Oklahoma, and eastern Colorado, with similar losses in Utah and southern California (figure 8-19). Although the extent of severe declines is reduced under the best-case scenario, these areas are still under high risk (figure 8-20). The least warm climate projection produced the highest overall NPP projections; however, the desert Southwest is still projected to experience declines from 5 to 25 percent by mid-century, depending on the locality.

Increasing temperatures throughout the entire projection period are likely responsible for driving patterns in most regions (Reeves et al. 2014a); however, some offsetting is possible as increasing CO_2 concentrations may also increase soil moisture via reduced evapotranspiration, especially in the presence of warm season species (C4 photosynthetic pathway) (Morgan et al. 2011). While increased temperatures are expected across most regions, variable projected precipitation patterns and trends create most of the subregional differences in NPP and forage quality (Augustine et al. 2018).

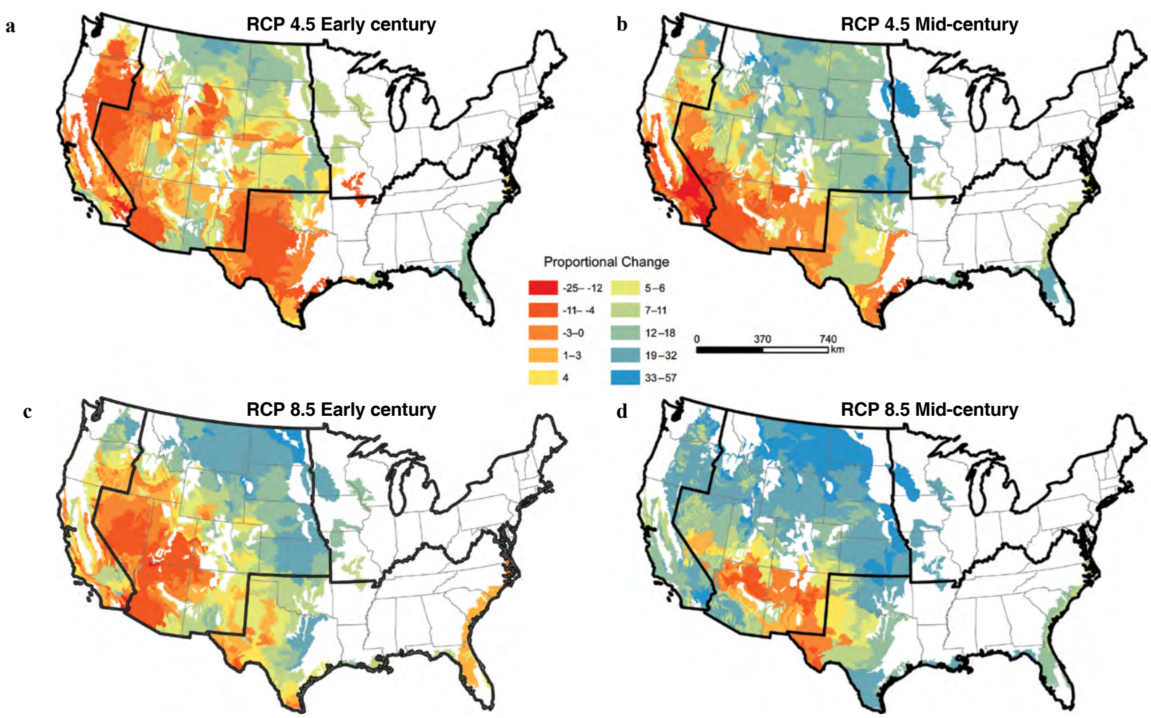
Figure 8-19. Projected proportional change in NPP from the 2015 to 2019 baseline representing the lowest NPP projections (NPP min) for (a) RCP 4.5 early century, (b) RCP 4.5 mid-century, (c) RCP 8.5 early century, and (d) RCP 8.5 mid-century. The hot climate projection produced the lowest overall NPP projections under RCP 4.5, while the dry climate projection produced the lowest NPP projections under RCP 8.5.



NPP = net primary productivity; RCP = Representative Concentration Pathway.

Source: Kim et al. 2018.

Figure 8-20. Projected proportional change in NPP from the 2015 to 2019 baseline representing the highest NPP projections (NPP max) for (a) RCP 4.5 early century, (b) RCP 4.5 mid-century, (c) RCP 8.5 early century, and (d) RCP 8.5 mid-century. The least warm climate projection produced the highest overall NPP projections under both RCPs.



NPP = net primary productivity; RCP = Representative Concentration Pathway.

Source: Kim et al. 2018.

Land Use Projections

- ❖ Rangeland losses are expected to be minor nationally, decreasing 2.7 percent to a base of 257 million ha by mid-century, but regional and local impacts will be significant.
- ❖ The Pacific Coast Region is projected to lose the most rangeland area, about 6 percent under both RCPs, but some counties within that region may lose up to 25 percent of their rangelands to urbanization.
- ❖ Some gains in rangeland area are projected where agricultural land use decreases, particularly in Nevada.

Land use projections and the associated methodology are discussed in the Land Resources Chapter, as well as in Mihiar and Lewis (2019) and Brooks et al. (2020). Our calculations of changes to the rangeland land base differ from calculations in the Land Resources Chapter. Here, we calculate the average change in projected rangeland area across the early century period (2020 to 2040) and mid-century period (2041 to 2070) to compare against the observed NRI 2012 baseline rangeland land base. This method incorporates fluctuations to the rangeland land base that occur over the early- and mid-century time periods and makes comparisons against observed values. The Land Resources Chapter, however, compares projected rangeland area in the years 2040 and 2070 (not averaged) against a projected 2020 baseline, thus eliminating interannual variability in the rangeland land base and confining results to the 2020 to 2070 RPA projection period.

We provide results and interpretation focused on estimated changes in rangelands by RPA region and counties under RCPs 4.5 and 8.5 for the early- and mid-century periods, although it is important to note that the land use projections are influenced by economic factors (in the form of Shared Socioeconomic Pathway, SSP) in addition to RCP and climate. While there are not many differences in the national results between RCPs 4.5 and 8.5, there are notable differences among RPA regions and between the early century and mid-century periods. We again provide results for the individual climate projections that produce the minimum and maximum amount of percentage change in rangeland area, as well as for the ensemble response (the average projected change in rangeland area across all five climate projections). The minimum and maximum selections were again based on analysis for the entire extent of rangelands across the conterminous United States and may therefore not always represent the minimums and maximums for individual regions. The North Region was not included in this analysis because rangelands are not projected in the North Region by Brooks et al. (2020). Missouri is the only State in the North Region where rangelands are monitored by the NRI Assessment (USDA NRCS 2018) due to the scarcity of rangelands in the Northeastern United States; the lack of available monitoring data restricts the ability to make projections.

All regions are projected to lose rangelands in the future, and these losses are projected to increase from early- to mid-century (table 8-14). Results from both RCPs are similar, as are results across the different climate projections. The South Region exhibits the slowest rate of rangeland loss under all climate projections, scenarios, and time periods (rangeland

Table 8-14. Projected percent change in rangeland land use for early century (2020 to 2040) and mid-century (2041 to 2070), compared with the 2012 baseline under RCPs 4.5 and 8.5. Data represent the change in land use as a percentage of the baseline. The ensemble result provides the average amount of change that is projected nationally and for each region across all five RPA climate projections. The wet and hot climate projections produce the minimum change under RCPs 4.5 and 8.5, respectively. The dry climate projection produces the maximum change under RCPs 4.5 and 8.5. Climate projections that produce minimum and maximum change were selected based on results for the entire extent of rangelands across the conterminous United States and are therefore not always representative of the minimums and maximums for individual regions.

	2020 to 2040 (%)			2041 to 2070 (%)		
	RCP 4.5					
RPA region	**Minimum**	**Ensemble**	**Maximum**	**Minimum**	**Ensemble**	**Maximum**
National	-1.1	-1.1	-1.1	-3.3	-3.4	-3.5
South	-0.4	-0.4	-0.4	-1.3	-1.3	-1.3
Rocky Mountain	-0.5	-0.5	-0.5	-1.4	-1.5	-1.5
Pacific Coast	-2.3	-2.4	-2.4	-7.2	-7.4	-7.7
	RCP 8.5					
National	-0.9	-1.1	-1.2	-2.3	-3.2	-3.7
South	-0.4	-0.4	-0.5	-0.9	-1.3	-1.4
Rocky Mountain	-0.4	-0.5	-0.5	-1.2	-1.4	-1.6
Pacific Coast	-1.8	-2.3	-2.5	-4.9	-7	-8.1

RCP = Representative Concentration Pathway.

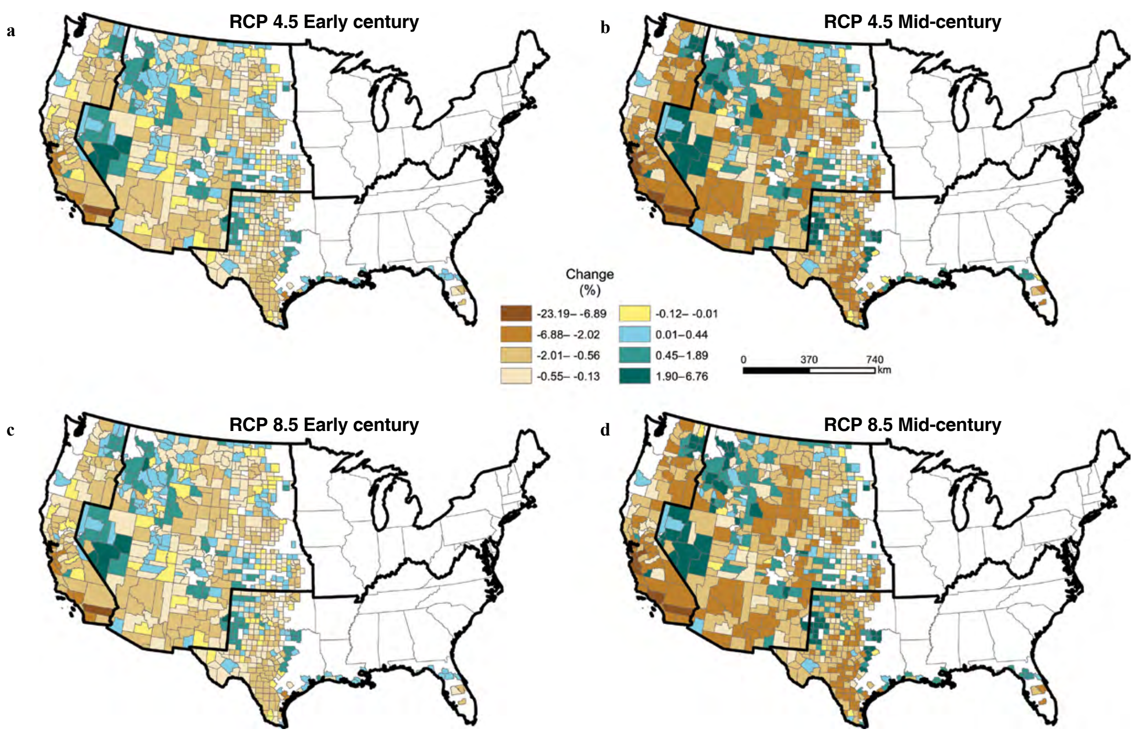
Sources: Mihiar and Lewis 2019; Brooks et al. 2020.

losses are never projected to exceed 1.5 percent), while the Pacific Coast Region exhibits the fastest rate of rangeland loss, as high as 8.1 percent by mid-century under RCP 8.5 (table 8-14).

These national and regional trends obscure subregional patterns of change in rangeland area (figure 8-21). Under RCP 8.5, ensemble results project that 63 counties will lose at least 1 percent of their rangeland base in the early century period, with 7 counties in California projected to exhibit losses greater than 3 percent. By mid-century, 326 counties were projected to lose at least 1 percent of their rangeland base (or between 296 and 343 counties in the minimum and maximum results, respectively), with 61 counties projected to exhibit losses exceeding 3 percent (63 counties in the maximum change results). Three counties in California were projected to exhibit losses exceeding 10 percent of their rangeland base by mid-century under RCP 8.5, primarily to urban expansion, including Riverside (-21 percent), Santa Clara (-17 percent), and Stanislaus (-13 percent). Wyoming, southeastern Oregon, and northern Arizona are also projected to lose substantial amounts of rangeland relative to other areas. Reeves et al. (2018) demonstrated how large urban growth rates have been observed and are projected to continue in the near future in hotspots around the West such as Bozeman, MT; Boise, ID; and Phoenix, AZ.

In contrast, Nevada appears to increase in rangeland area in several counties, especially White Pine and Nye. Rangelands in White Pine County are projected to increase by up to 6 percent under RCP 8.5. Causes for the increased rangeland area are unclear but these data suggest that the climate in those areas will likely become unsuitable for agriculture, and abandoned croplands will transition to rangelands. Abandoned cropland typically becomes weedy, however, and the usefulness of these lands is therefore likely low from a rangeland health perspective or from a habitat perspective for wildlife species that depend on properly functioning rangelands.

Figure 8-21. Projected change in rangeland area compared with the 2012 baseline as the ensemble of results across the five RPA climate projections for (a) RCP 4.5 early century, (b) RCP 4.5 mid-century, (c) RCP 8.5 early century, and (d) RCP 8.5 mid-century.



RCP = Representative Concentration Pathway.
Source: Mihiar and Lewis 2019; Brooks et al. 2020.

Management Implications

This RPA rangeland assessment identified current and future trends on rangelands that may present ongoing challenges to managers, producers, and policymakers. Managers will likely be facing both decreasing rangeland area and health in the future, as the changing climate results in increasing invasive species, asymmetric and increasingly variable NPP in some regions, and shorter growing seasons that both start and end earlier in the year. The increasing frequency of drought and wildfires on rangelands (see the Disturbance Chapter) could exacerbate these impacts. Given the trends and projected futures documented in this Assessment, managers and policymakers will likely face increasingly difficult choices based on tradeoffs. Maintaining flexibility in the management of public land grazing leases and reconsidering and updating annual operating instructions (USDA Forest Service 1997) more frequently as changing conditions are identified in new data streams (e.g., availability of remotely sensed rangeland) can help managers adjust to changing conditions. Managers may need to consider social factors more consistently than in the past and may benefit from widening their circle of stakeholders to address issues that increasingly demand cross-discipline and cross-boundary solutions (Reed et al. 2009).

Land managers have new tools and resources available, such as the Climate Change Adaptation Library (http://adaptationpartners.org/library.php), a searchable database that contains ideas for increasing ecological resiliency for all lands including rangelands. Similarly, the 2021 Rangeland Technology Summit (https://vimeo.com/showcase/8429328/h) brought together and discussed more than 30 technologies that range managers can use to enhance monitoring-informed adaptive management and professional development. Using new tools and improved communication styles can help managers quantify and cope with the increased variability occurring on U.S. rangelands.

Conclusions

In this RPA rangeland assessment, we assembled the available nationally consistent data to examine the conditions and trends of rangelands in the conterminous United States, along with the impacts of climate change. Technological advancements in computer processing power and remotely sensed data, combined with new sampling programs from the BLM (AIM) and the USDA Forest Service (ACI), enabled enhanced analyses over past RPA Assessments. The inaugural assessment of vegetation trends across all lands using remotely sensed data from 1984 to 2020 corroborated findings from both the NRI and AIM processes. We also developed projections of phenology, NPP, and land use across plausible future climates that can be used by the USDA Forest Service and the broader range management community to address policy and management needs.

Through these analyses, we identified three significant findings for U.S. rangelands. First, the U.S. rangeland base has been decreasing at a rate of about 161,874 ha (399,000 acres) per year since 1982, with the most significant losses resulting from transitions to urban and agricultural land uses. Future losses are expected to remain relatively constant at about 98,101 ha (242,412 acres) per year, totaling additional losses of around 4.7 million ha (11,613,935 acres) by 2070. While this is a small percentage of the total rangeland base, these rangeland losses have spatially explicit ramifications, including increasing difficulty associated with maintaining critical habitat and corridors for wildlife and genetic diversity.

Second, rangelands are experiencing a range of disturbances, some of which are changing ecosystem dynamics in unprecedented ways, including invasive species, wildfires, and drought. Rangelands are exhibiting increases in invasive annual herbaceous species (e.g., cheatgrass and red brome) and woody species of concern (e.g., mesquite and juniper); these trends are visible in data from all evaluated plot-level rangeland monitoring programs (NRI on non-Federal lands, AIM on BLM lands, and FIA ACI on USDA Forest Service lands) as well as through remote sensing. Increases in invasive annual herbaceous species influence fire regimes and create continuing feedback cycles. The amount of area burned in rangelands has nearly doubled since 2000 (see the Disturbance Chapter), caused in large part by the increasing prevalence and density of invasive annual herbaceous species. These changes, combined with increasing drought intensity and frequency (see the Disturbance Chapter), are creating increased interannual variability of forage with impacts to rangeland health. Importantly, the combination of increasing drought and presence of invasive annual grasses reduces resiliency to drought (Chambers et al. 2014). Prolonged droughts in the Southwestern United States and California are creating novel conditions that have not been experienced since well before Euro-American settlement (Szejner et al. 2021). These conditions are expected to occur with greater frequency in the future, creating ecological, social, and economic challenges. These disturbances are already negatively affecting social fabrics and economic patterns around rangelands in the conterminous United States (Maczco et al. 2022), and projected future disturbances may exacerbate existing stressors such as reduced incomes from rangelands, fewer recreational opportunities (e.g., greater restrictions on public land when wildfire risk is extreme), and higher costs for red meat. These plausible outcomes suggest the need for novel ways of communicating about and responding to disturbance, with an emphasis on adaptation to prepare for potentially more severe conditions in the future.

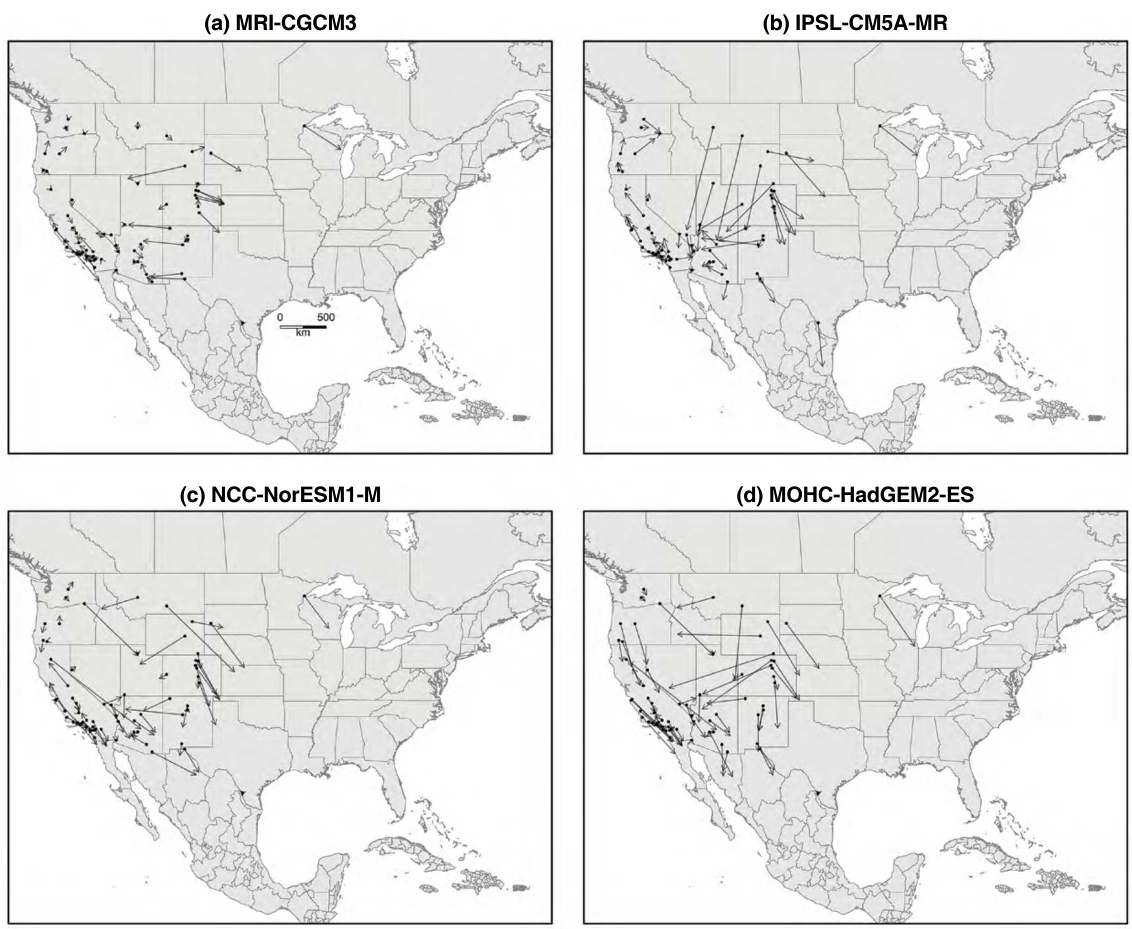
Third, the past and current trends documented here are projected to continue at least through the mid-century period. The start and end of the vegetation growing season are both projected to continue to shift earlier through time, with the end shifting more than the start resulting in shorter periods of plant growth overall. At the same time, NPP declines are projected to continue in southern rangelands, along with continued increases in interannual variability. Although NPP increases are projected in many northern rangelands, this is likely attributable to increasing annual grass presence. In addition, rangeland area is projected to continue to decline as the result of conversion to urban land use, with the largest declines projected for the Pacific Coast Region. The projected continuation of the trends identified in this assessment suggest ecological challenges to the sustainability of goods and services provided by U.S. rangelands.

Analog Projections

Translating climate model projections into intuitive assessments for the public is a major challenge for the scientific community. Climate-analog mapping involves matching the expected future climate at a location (such as a city or national forest) with the current climate of a different location. This method provides a relatable, place-based assessment of potential impacts of climate change. Here we demonstrate a climate analog analysis to provide a sense of the magnitude of projected climate change for cities in regions dominated by rangelands (Fitzpatrick and Dunn 2019). Future climate for the 2080s (30-year running mean of the period 2070 to 2099) were obtained from the Consultative Group for International Agricultural Research program on Climate Change, Agriculture and Food Security (http://www.ccafs-climate.org/). Four Earth system models, which are similar to the climate models selected for the RPA Assessment, were used to estimate climate futures under RCPs 4.5 and 8.5: MOHC-HadGEM2-ES (similar to RPA hot model), MRI-CGCM3 (similar to RPA least warm model), IPSL-CM5A-MR (similar to RPA dry model), and NCC-NorESM1-M (similar to RPA middle model).

We focused on a group of 65 cities surrounded by rangelands, primarily in the Western United States, and performed climate-analog mapping (Fitzpatrick and Dunn 2019, Mahony et al. 2017, Williams et al. 2007) (figures 8-22, 8-23). Averaged across the 65 cities and 4

Figure 8-22. Vectors show the distance and direction from each city (filled circles) to the location of the best contemporary climatic analog for that city's projected 2080 climate under RCP 4.5 for these climate projections: (a) MRI-CGCM3 (similar to RPA least-warm model), (b) IPSL-CM5A-MR (similar to RPA dry model), (c) NCC-NorESM1-M (similar to the RPA middle model), and (d) MOHC-HadGEM2-ES (similar to the RPA hot model).



Source: Fitzpatrick and Dunn 2019.

climate models, annual mean temperature was projected to increase by nearly 5 °C, with the largest seasonal increases in temperature expected in the summer and autumn under RCP 8.5. Average annual precipitation was projected to decline by 6 percent, with seasonal precipitation projected to decrease by at least 10 percent in all seasons except winter, where a 15-percent increase was projected. Averaging across cities obscures important regional variation. For example, cities in the Southwest were projected to experience declines in annual precipitation, whereas cities in the Pacific Northwest, northern Great Plains, and portions of California were projected to experience increases in precipitation. However, some of these same regions were also expected to experience the largest temperature increases, which could offset increases in precipitation through reductions in soil moisture.

To aid comprehension of the results, we provide case studies for Helena, MT, and Denver, CO. Table 8-15 shows current climate attributes of Helena and Denver, along with the current climate attributes for the cities that serve as the best analog during the late century period (30-year running mean of the period 2070 to 2099). The analogs suggest that Helena's climate will become most like St. Ignatius, MT; Lapwai, ID; Kooskia, ID; or Salt Lake City, UT. Comparing the climates of these analog cities against the climate normals for Helena allows for some generalizations. First, average high temperature in July increases from 28 to 33 °C. Second, the average January minimum temperature increases from -11 to -5 °C. These increases in temperature have a negative effect on snowfall, projected to decline by 300 mm (about 12 inches), which will likely negatively impact skiing and other winter recreation activities. Precipitation is expected to stay near normal or increase, but the effectiveness of the rainfall to improve hydrologic conditions (fill reservoirs, keep streams running with cold-enough water to protect endangered bull trout, etc.) decreases due to significantly higher temperatures. The decrease in effective precipitation will likely alter both native and domestic vegetation assemblages; for example, the climate in Lapwai is presently suitable for vineyards, while currently growing tomatoes in Helena is difficult.

Analog conditions for Denver suggest that its climate will come to resemble current conditions in Tyrone, OK; Clarendon, TX; Plains, TX; or Seminole, TX. These analog cities occur at 954 m above sea level, on average, while Denver is 1,609 m above sea level; these analog cities represent a 40-percent decrease in elevation, and climate expectations vary significantly with a 650-m change in elevation. The average of the analog cities

Table 8-15. Results of the climate analog analysis for RCP 8.5. The current climate attributes of Helena, MT, and Denver, CO, are shown, along with the current climate attributes for the cities that serve as the best analog during the late century period (30-year running mean of the period 2070 to 2099).

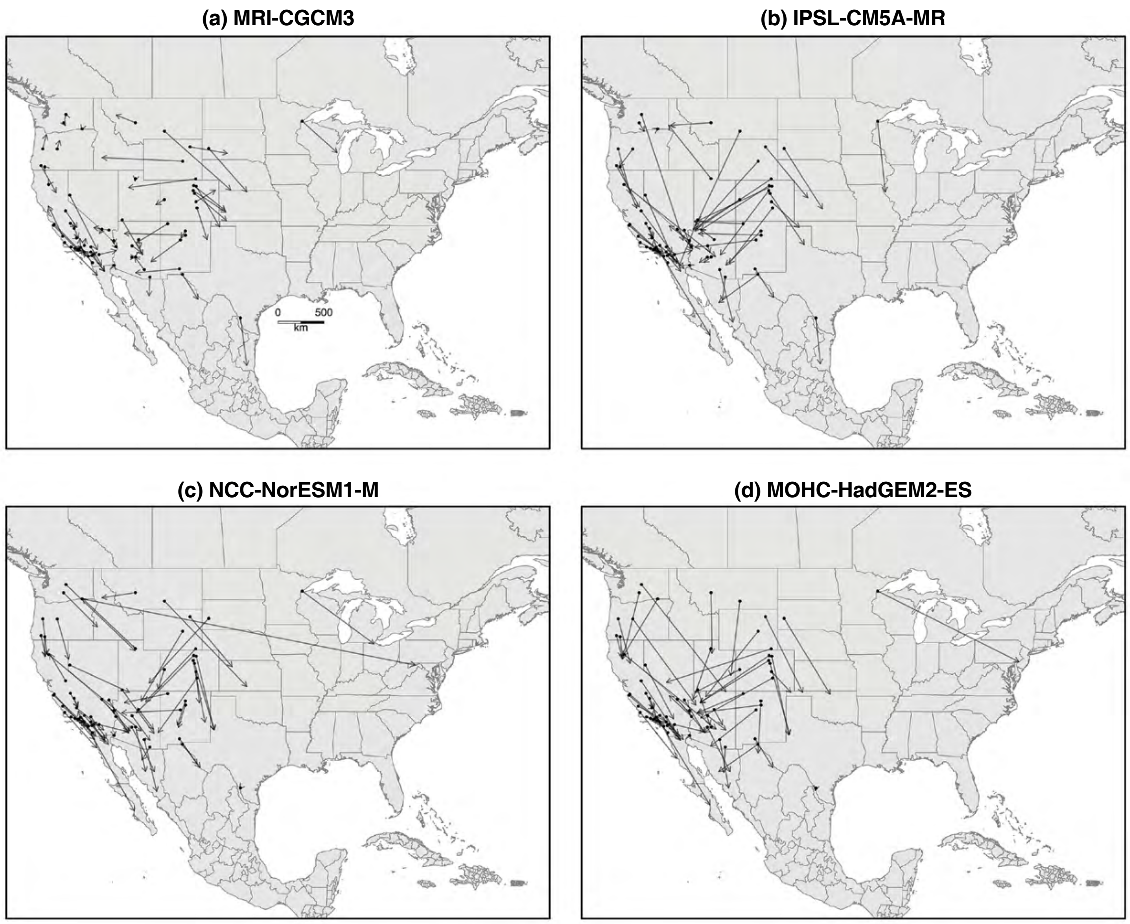
City	Climate normal	MRI-CGCM3	IPSL-CM5A-MR	NCC-NorESM1-M	MOHC-HadGEM2-ES	Average change relative to present day
Denver, CO	1,948 - 2,005	Tyrone, OK	Clarendon, TX	Plains, TX	Seminole, TX	
Elevation (m)	1,609	890	823	1,097	1,006	-655
Average July high temperature (°C)	31	34	35	33	34	3
Average January low temperature (°C)	-8	-7	-4	-3	-2	4
Rainfall (mm)	406	483	610	457	457	95
Snowfall (mm)	1,524	432	127	76	178	-1,321
Helena, MT	1,938 - 2,016	Saint Ignatius, MT	Lapwai, ID	Kooskia, ID	Salt Lake City, UT	
Elevation (m)	1,181	884	290	393	1,280	-469
Average July high temperature (°C)	28	29	34	33	34	5
Average January low temperature (°C)	-11	-8	-4	-4	-6	6
Rainfall (mm)	305	406	432	635	406	165
Snowfall (mm)	1,270	1,118	559	660	1,524	-305

m = meters; mm = millimeters; RCP = Representative Concentration Pathway.

Source: Fitzpatrick and Dunn 2019.

suggests that temperatures in Denver will increase in both July and January by 3 and 4 °C, respectively. The most dramatic change expected in Denver is a sharp decrease in snowpack. Presently, Denver receives about 1,524 mm of snowfall annually, and analog conditions suggest a loss of nearly 1,300 mm. This decrease in snowfall has the potential to substantially disrupt local economies dependent on winter activities. Some of the impact could be buffered at higher elevation areas where skiing is a major economic driver—such as in Telluride, CO, which has relatively high-elevation ski runs (top at 4,010 m)—however, less snow overall will likely increase competition for these resources, creating more crowded situations.

Figure 8-23. Vectors show the distance and direction from each city (filled circles) to the location of the best contemporary climatic analog for that city's projected 2080 climate under RCP 8.5 for these climate projections: (a) MRI-CGCM3 (similar to RPA least-warm model), (b) IPSL-CM5A-MR (similar to RPA dry model), (c) NCC-NorESM1-M (similar to the RPA middle model), and (d) MOHC-HadGEM2-ES (similar to the RPA hot model).



Source: Fitzpatrick and Dunn 2019.

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Chapter 9

Water Resources

Warziniack, Travis; Arabi, Mazdak; Froemke, Pamela; Ghosh, Rohini; Heidari, Hadi; Rasmussen, Shaundra; Swartzentruber, Ryan. 2023. Water Resources. In: U.S. Department of Agriculture, Forest Service. 2023. Future of America's Forest and Rangelands: Forest Service 2020 Resources Planning Act Assessment. Gen. Tech. Rep. WO-102. Washington, DC: 9-1–9-20. Chapter 9. https://doi.org/10.2737/WO-GTR-102-Chap9.

In this chapter, we examine trends in freshwater use and supply throughout the conterminous United States and their implications for future shortages due to socioeconomic and climate change. We focus on renewable freshwater, which includes surface and subsurface flows, and provide projections of freshwater supply and likelihood of water shortage under future scenarios. Regarding the sources of water supply, we found that 39 percent of all water within the conterminous United States originates on forested lands. Percentages are higher in the Eastern United States, where forests make up a larger share of the land base. Relative shares of water from forests are lower in the Western United States, but the percentage that comes from national forests is much higher, highlighting the need to manage public and private forests for sustainable water resources.

Among the most encouraging trends in water resources is the tremendous gains in water use efficiency. Water use in the United States decreased 9 percent between 2010 and 2015, making 2015 the lowest level of water use since before 1970 (Dieter et al. 2018). This decrease came despite population increases, in part due to efficiency gains in household appliances, thermoelectric power generation, and irrigated agriculture, along with structural changes within the U.S. economy that have favored less water-intensive service industries over traditional manufacturing (Dieter et al. 2018, Wang and Hejazi 2011). Both per capita water use and total water use have declined throughout the country. From households to agriculture to industry, meaningful changes have occurred in human behavior and conservation practices. Nonetheless, large regions of the United States

Key Findings

- Both per capita water use and total water use are declining in many parts of the country.
- Despite reductions in water use, many regions increasingly experience water shortages due to extended dry periods.
- Projected changes in national consumptive water use range from a 9-percent decrease to a 235-percent increase, with the largest impacts resulting from the needs of agriculture in response to climate change.
- Changes in projected aggregate water yield by mid-century range from a 25.7-percent increase under a wet future to a 10.9-percent decrease under a dry future.
- Short-duration droughts are likely to turn into long-duration droughts, and the intensity of drought is likely to increase substantially. Under higher future atmospheric warming, droughts lasting more than a year are projected to occur four times more often and increase in intensity by 76 percent.
- Adaptation options like increased reservoir storage have limited ability to curtail shortage in the long term. Responses to climate change will probably require substantial transfers from agriculture to urban users, which could have serious negative impacts on rural communities.

face increasing water scarcity. Droughts are increasing in frequency and duration, and there is a high amount of uncertainty in future drought characteristics. Whether these trends continue depends on future population growth, sector-specific rates of technology adaptation, and continued changes in regional climatic patterns. Climate models differ in their projected future precipitation patterns, more so than for projections of temperature. Regions that face decreasing water supply and either have large amounts of water use for agriculture or have high population growth are projected to face increasing shortages through the middle of the century. These compounding effects of climate and socioeconomic forces will likely challenge policymakers and force tough decisions about water use among sectors.

Trends in Freshwater Withdrawals: Past and Projected

- Most regions of the United States are expected to see declines or only modest increases in water withdrawals for household use.
- Warmer temperatures due to climate change are projected to increase water use in the energy sector by 20 to 60 percent (1 to 6 billion gallons of water per day)—more than would be needed without climate change.
- Total withdrawals for irrigated agriculture in the conterminous United States are projected to increase from 116 billion gallons in 2015 to 134 billion gallons in 2070 under a hot future.
- Total consumptive use is projected to decrease by as much as 9 percent nationally under a lower warming and moderate population growth future but increase by 235 percent under a high warming and high population growth future, indicating a high level of variation in potential futures and creating challenges for managers hoping to adapt to climate change.

This section of the Resources Planning Act (RPA) Assessment examines trends in past water withdrawals and makes projections for future withdrawals for the conterminous United States, drawing heavily on county-level data from the 5-year U.S. Geological Survey (USGS) water use circulars for which 2015 is the most recent data year (Dieter et al. 2018). Detail is given here for domestic, industrial, irrigated agriculture, and thermoelectric power generation sectors. Together these four sectors make up 72 percent of total water withdrawals in the country (Dieter et al. 2018). Projections of withdrawals extend trends in the USGS data following Brown et al. (2013), which are updated with methods and detailed results in Warziniack et al. (2022). Future projections are developed for the four core RPA scenarios and five climate models (see the sidebar RPA Scenarios). Though not specifically covered in this Assessment, much of this water comes directly from forested lands. Roughly 60 million people depend on forests for more than 50 percent of their water supply (Liu et al. 2021).

Projections of water use rely on three main components: a principal driver, a per-unit rate of withdrawal, and climate feedbacks (table 9-1). Principal drivers (such as population or acres of irrigated agriculture) are first multiplied by the per-unit rate of withdrawal (such as per capita withdrawals for domestic use) to get total freshwater withdrawals absent climate change effects. Rates of withdrawals in some sectors are then adjusted to include climate impacts on water use efficiency, the need for more water in a warmer climate, and changes in water use due to changes in precipitation. Climate feedbacks only affect the per-unit rates of withdrawals and do not address the viability of land to support a given use (e.g., viability of agriculture) or temperature limits on specific uses (e.g., temperature limitations on withdrawing water for thermoelectricity generation).

Table 9-1. Principal drivers, rates of withdrawals, and climate feedbacks used in water use projections.

Sector	Principal driver	Withdrawal rate	Climate impacts
Domestic	Population	Gallons per capita	Changes in summertime precipitation and evapotranspiration impact household outdoor water use
Thermoelectric	Population, total electricity use	Gallons per thermoelectric kWh produced using freshwater	Changes in temperature lead to changes in household and industrial energy demand
Irrigated agriculture	Acres irrigated	Gallons per acre	Changes in growing season precipitation lead to corresponding changes in irrigation demand
Industrial and mining	Personal income	Gallons per dollar income	No climate impacts in model
Livestock and aquaculture	Population	Gallons per person	No climate impacts in model

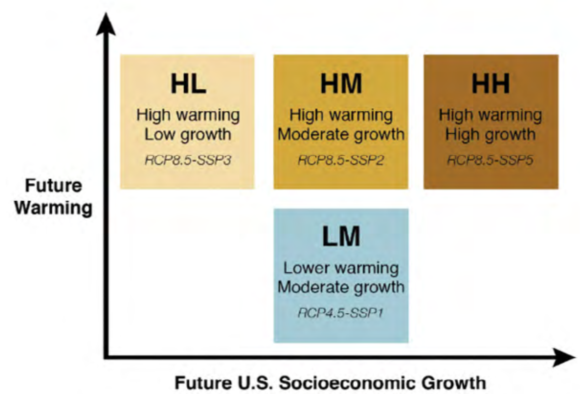
RPA Scenarios

The RPA Assessment uses a set of scenarios of coordinated future climate, population, and socioeconomic change to project resource availability and condition over the next 50 years. These scenarios provide a framework for objectively evaluating a plausible range of future resource outcomes.

The 2020 RPA Assessment draws from the global scenarios developed by the Intergovernmental Panel on Climate Change to examine the 2020 to 2070 time period (IPCC 2014). The RPA scenarios pair two alternative climate futures (Representative Concentration Pathways or RCPs) with four alternative socioeconomic futures (Shared Socioeconomic Pathways or SSPs) in the following combinations: RCP 4.5 and SSP1 (lower warming-moderate U.S. growth, LM), RCP 8.5 and SSP3 (high warming-low U.S. growth, HL), RCP 8.5 and SSP2 (high warming-moderate U.S. growth, HM), and RCP 8.5 and SSP5 (high warming-high U.S. growth, HH) (figure 9-1). The four 2020 RPA Assessment scenarios encompass the projected range of climate change from the RCPs and projected quantitative and qualitative range of socioeconomic change from the SSPs, resulting in four distinct futures that vary across a multitude of characteristics (figure 9-2), and providing a unifying framework that organizes the RPA Assessment natural resource sector analyses around a consistent set of possible world views. The Scenarios Chapter describes how these scenarios were selected and paired; more details are provided in Langner et al. (2020).

The 2020 RPA Assessment pairs these four RPA scenarios with five different climate models that capture the wide range of projected future temperature and precipitation across the conterminous United States. An ensemble climate projection that averages across the multiple model projections is not used because of the importance of preserving individual model variability for resource modeling efforts. The five climate models selected by RPA represent least warm, hot, dry, wet, and middle-of-the-road climate futures for the conterminous United States

Figure 9-1. Characterization of the 2020 RPA Assessment scenarios in terms of future changes in atmospheric warming and U.S. socioeconomic growth. These characteristics are associated with the four underlying Representative Concentration Pathway (RCP) – Shared Socioeconomic Pathway (SSP) combinations.



Source: Langner et al. 2020.

(table 9-2); however, characteristics can vary at finer spatial scales. Although the same models were selected to develop climate projections for both lower and high-warming futures, there are distinct climate projections for each model associated with RCP 4.5 and RCP 8.5. The Scenarios Chapter describes how these climate models were selected; Joyce and Coulson (2020) give a more extensive explanation.

Throughout the RPA Assessment, individual scenario-climate futures are referred to by pairing RPA scenarios with selected climate projections. For example, an analysis run under "HL-wet" assumes a future with high atmospheric warming and low U.S. population and economic growth (HL RPA scenario), as well as a wetter climate for the conterminous United States (wet climate projection).

Table 9-2. Five climate models selected to reflect the range of the full set of 20 available climate models in the year 2070. Each model was run under RCP 4.5 and RCP 8.5, providing a range of different U.S. climate projections.

	Least warm	Hot	Dry	Wet	Middle
Climate model	MRI-CGCM3	HadGEM2-ES	IPSL-CM5A-MR	CNRM-CM5	NorESM1-M
Institution	Meteorological Research Institute, Japan	Met Office Hadley Centre, United Kingdom	Institut Pierre Simon Laplace, France	National Centre of Meteorological Research, France	Norwegian Climate Center, Norway

Source: Joyce and Coulson 2020.

Figure 9-2. Characteristics differentiating the 2020 RPA Assessment scenarios. These characteristics are associated with the four underlying Representative Concentration Pathway (RCP) – Shared Socioeconomic Pathway (SSP) combinations.

RPA Scenario (RCP-SSP)	Global Temperature Rise	U.S. Population Growth	U.S. Economic Growth Rate	Bioenergy Demand	Energy Sector Focus	Global Energy Usage	International Trade Openness
LM Lower warming Moderate growth *RCP4.5-SSP1*	Lower	Medium	Medium-High	High	Renewables	Low	Medium
HL High warming Low growth *RCP8.5-SSP3*	High	Low	Low	Low	Fossil fuels	Medium	Low
HM High warming Moderate growth *RCP8.5-SSP2*	High	Medium	Medium	Medium	Mixed	Medium	Medium
HH High warming High growth *RCP8.5-SSP5*	High	High	High	High	Fossil fuels	High	High

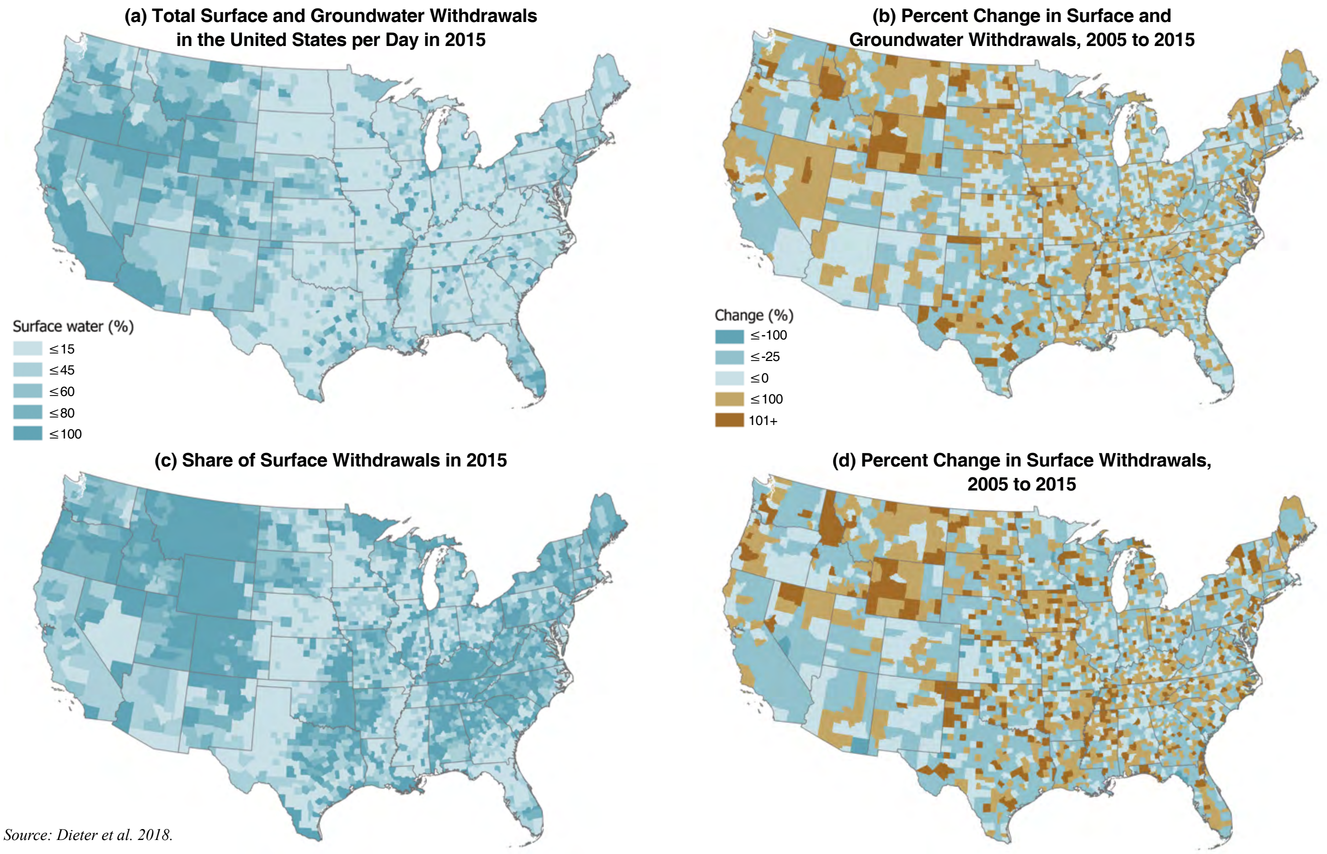
Past Water Withdrawals

Differences in water withdrawals throughout the United States (figures 9-3, 9-4) exist due to historical differences in water abundance, patterns of settlement, agricultural expansion, and industrial development. Agriculture is the largest user of water in most places, accounting for 42 percent of freshwater withdrawals nationally, and is likely to be the driving factor in future water shortages (Dieter et al. 2018, Warziniack and Brown 2019). Many crops require 20 to 30 inches of water per year; areas with precipitation below that amount have to rely on irrigation to successfully farm (Postel 1998). Water for irrigation dominates all other uses in these areas, leading to visual differences in figure 9-3. Comparatively, water withdrawn to produce electricity represents 34 percent of national freshwater withdrawals, and household water use makes up 9 percent of freshwater withdrawals.

Between 2005 and 2015, surface freshwater withdrawals decreased in 64 percent of counties in the conterminous United States to about 322 billion gallons per day (figure 9-3d). During that time, domestic withdrawals for household use fell by 10 percent nationally despite an 8-percent increase in population. Per capita household withdrawals fell from 98 gallons per day in 2005 to 82 gallons per day in 2015. Irrigation withdrawals fell by 7 percent, and thermoelectric withdrawals fell by 34 percent (Dieter et al. 2018).

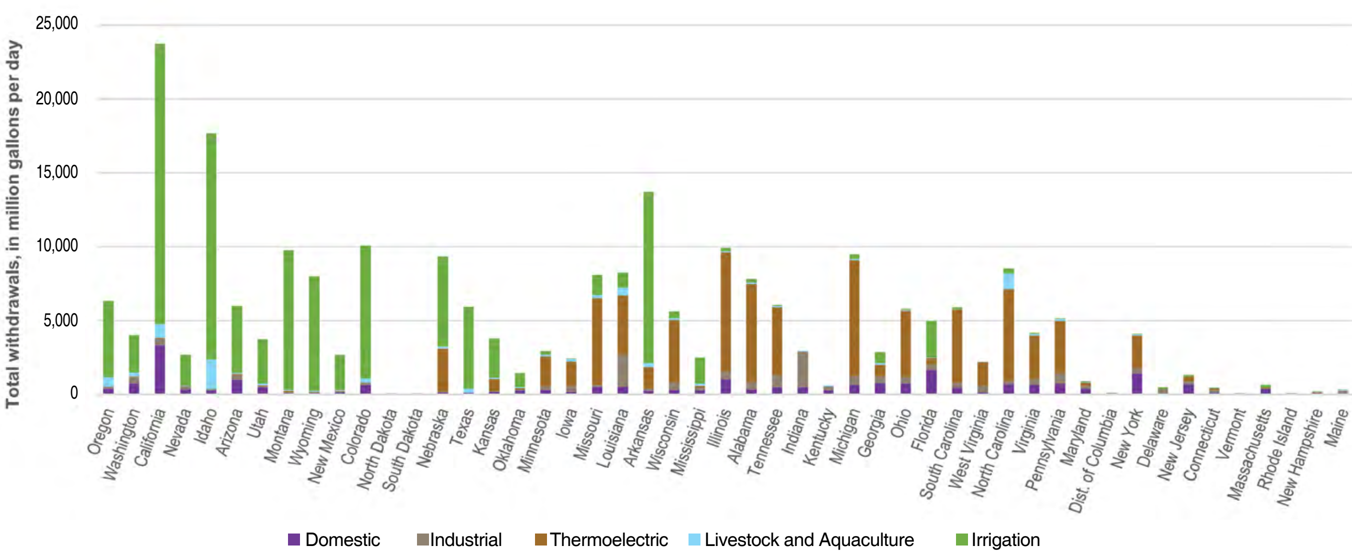
Some of those reductions in water use were necessary due to extreme droughts throughout the last 2 decades. In July 2021, Lake Mead, the largest reservoir in the United States, recorded its lowest water levels since it was filled (BOR 2021). Some reductions, however, have come by way of remarkable improvements in water use technology, including improvements in irrigations methods, increased use of low-flow toilets (the largest in-home use of water), increased use of high-efficiency showerheads and faucets, incentives to reduce outdoor water use, and government policies (Gleick et al. 2009, Lee et al. 2013, Millock and Nauges 2010). The U.S. economy continues to become less water-intensive, as seen by measures like gross domestic product per gallons of water use that have been falling for decades (Dieter et al. 2018, Wang and Hejazi 2011).

Figure 9-3. Freshwater withdrawals (surface and groundwater and share of surface) in 2015 and as percent change from 2005 to 2015.



Source: Dieter et al. 2018.

Figure 9-4. Water withdrawals (surface and groundwater) for each sector by State in 2015. States are ordered from west to east, left to right.



Source: Warziniack et al. 2022, based on data from Dieter et al. 2018.

Projections of Water Withdrawals

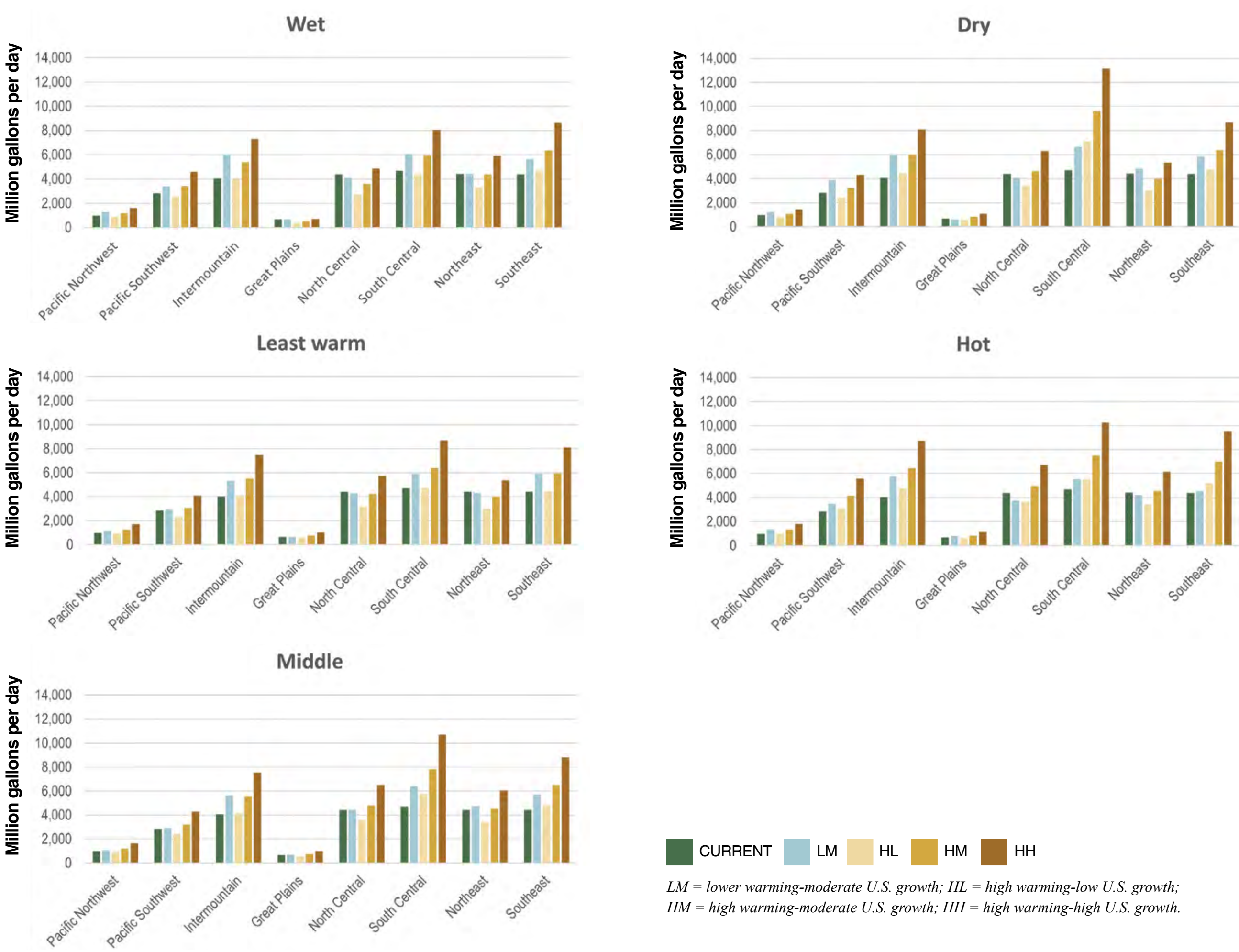
Projections for freshwater withdrawals are described briefly here for the domestic, industrial, and irrigated agriculture sectors. Projections for thermoelectric power generation are for consumptive use instead of withdrawals, making use of new data from USGS. Warziniack et al. (2022) provide more detailed methods as well as projections for all USGS water use sectors out to 2070. The analysis is done at the county scale for the conterminous United States and aggregated to RPA subregions (see figure 2-1 in the Introduction Chapter). Total water withdrawals were 322 billion gallons per day in 2015, of which 198 billion gallons per day were from fresh surface water sources. By 2070, we estimate withdrawals in the conterminous United States will range from a 10-percent reduction under HL-wet (the high atmospheric warming and low socioeconomic change RPA scenario using the wet climate projection) to an over 200-percent increase under HH-hot. Across all RPA scenario-climate futures, there is a mean increase of 47 percent in total withdrawals.

Domestic Water Withdrawals

Domestic water withdrawals are calculated as the product of county population projections and per capita withdrawals, adjusted for impacts on outdoor water use due to climate change. Wear and Prestemon (2019) estimate that U.S. population will increase by 24 to 44 percent under moderate-growth SSPs and by 56 percent under the high-growth SSP5. The fastest growing regions are expected to be in the West and Southwest, which are already facing water stress (U.S. Global Change Research Program 2018) and projected to see populations double under the high-growth SSP5.

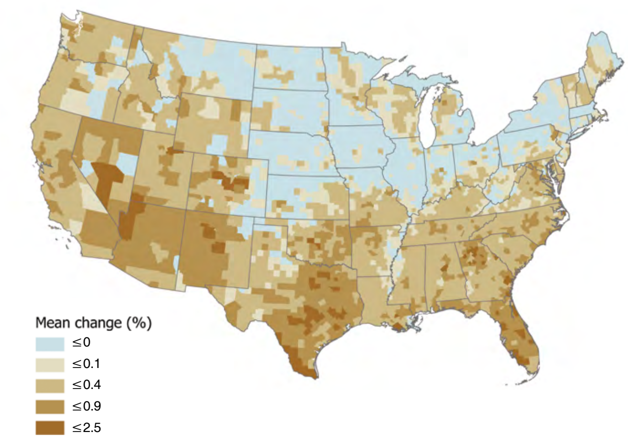
Despite these increases, most regions of the United States are expected to see declines or only modest increases in domestic water withdrawals associated with low- and moderate-growth scenarios (figures 9-5, 9-6). In 2015, total withdrawals for domestic use were 26.6 billion gallons per day, of which 23.3 billion gallons per day came from

Figure 9-5. Current (2015) and projected future (2070) domestic withdrawals by RPA subregion and RPA scenario for the five RPA climate projections.



LM = lower warming-moderate U.S. growth; HL = high warming-low U.S. growth; HM = high warming-moderate U.S. growth; HH = high warming-high U.S. growth.

Figure 9-6. Mean percent change from current (2015) to projected future (2070) in domestic water withdrawals across all RPA scenario-climate futures.

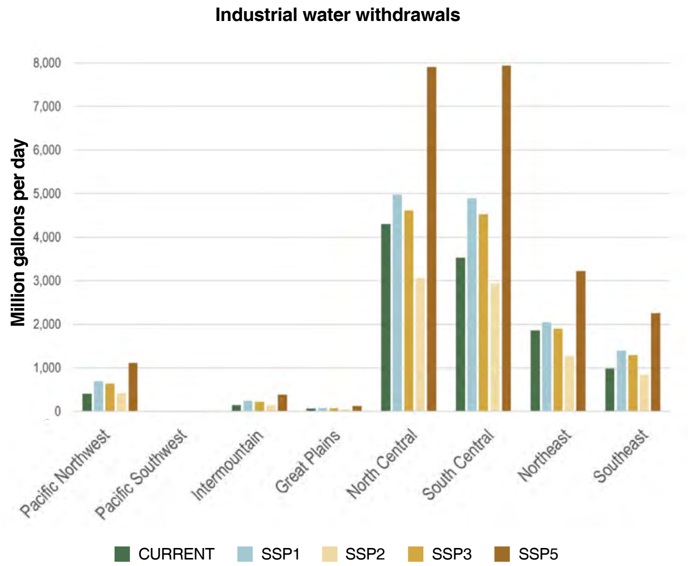


public suppliers and 3.3 billion gallons per day were self-supplied, largely through wells. Self-supplied surface water withdrawals were only 49 million gallons per day in 2015. In 2070, withdrawals for domestic use in the conterminous United States are projected to range from 22 billion gallons per day to 50 billion gallons per day. In the southern and western parts of the country, rapid population growth is expected to outpace improvements in water use efficiency, leading to increases in withdrawals for domestic use in those regions across all socioeconomic futures. Under high-growth HH-middle, all but 10 counties across the United States are projected to see increases in domestic withdrawals, compared to the low-growth HL, for which 78 percent of counties are projected to see decreases in domestic withdrawals. Because population is the primary driver for domestic demands, SSPs tend to impact projections more than atmospheric warming and climate model selection. The exception is the dry climate projection, particularly for the South Central Subregion, which shows a much larger area of drying centered on Texas and spreading throughout the subregion. Under these conditions, increases in outdoor water use drive large increases in total domestic withdrawals.

Industrial Water Withdrawals

The industrial sector is primarily made up of large users of self-supplied water. Thus, differences in figure 9-7 reflect regional differences in water availability as much as they do regional differences in economic activity. Water withdrawals in the industrial sector range from near zero in the Pacific Southwest to high amounts of withdrawals in the central regions, reflecting regional differences in manufacturing activity and how firms use water (Dieter et al. 2018). For the most part, gains in water efficiency and shifts in the economy toward less water-intensive industries lead to declines in industrial water withdrawals across the country.

Figure 9-7. Current (2015) and future (2070) industrial withdrawals by RPA subregion. Projections for industrial withdrawals do not have climate feedbacks so only vary by SSP.



SSP = Shared Socioeconomic Pathway.

Because projections for industrial withdrawals do not have climate feedbacks, results are modeled only using socioeconomic pathways and not using the integrated RPA scenarios or climate models. All regions are projected to see declines in industrial withdrawals for low-growth SSP3 and modest increases under moderate-growth SSPs 1 and 2. All regions are projected to see increases in industrial withdrawals under high-growth SSP5, with noticeable increases in the North Central and South Central Subregions due to the initial size of industry.

Thermoelectric Water Use

Thermoelectric power generation, which represents the largest segment of U.S. electricity production, requires water at several different points in the lifecycle of the generation process, including component manufacturing, fuel acquisition, processing and transport, and power plant operation and decommissioning, but water is primarily used for cooling purposes (Meldrum et al. 2013). Total water withdrawals for power generation peaked in 2010, and water use rates (units of water withdrawn per unit of electricity produced, in gallons/kilowatt hour) have fallen from 22.41 in 1985 to as low as 10.76 in 2015 due to larger adoption of recirculating cooling technologies allowing for greater efficiency in water use.

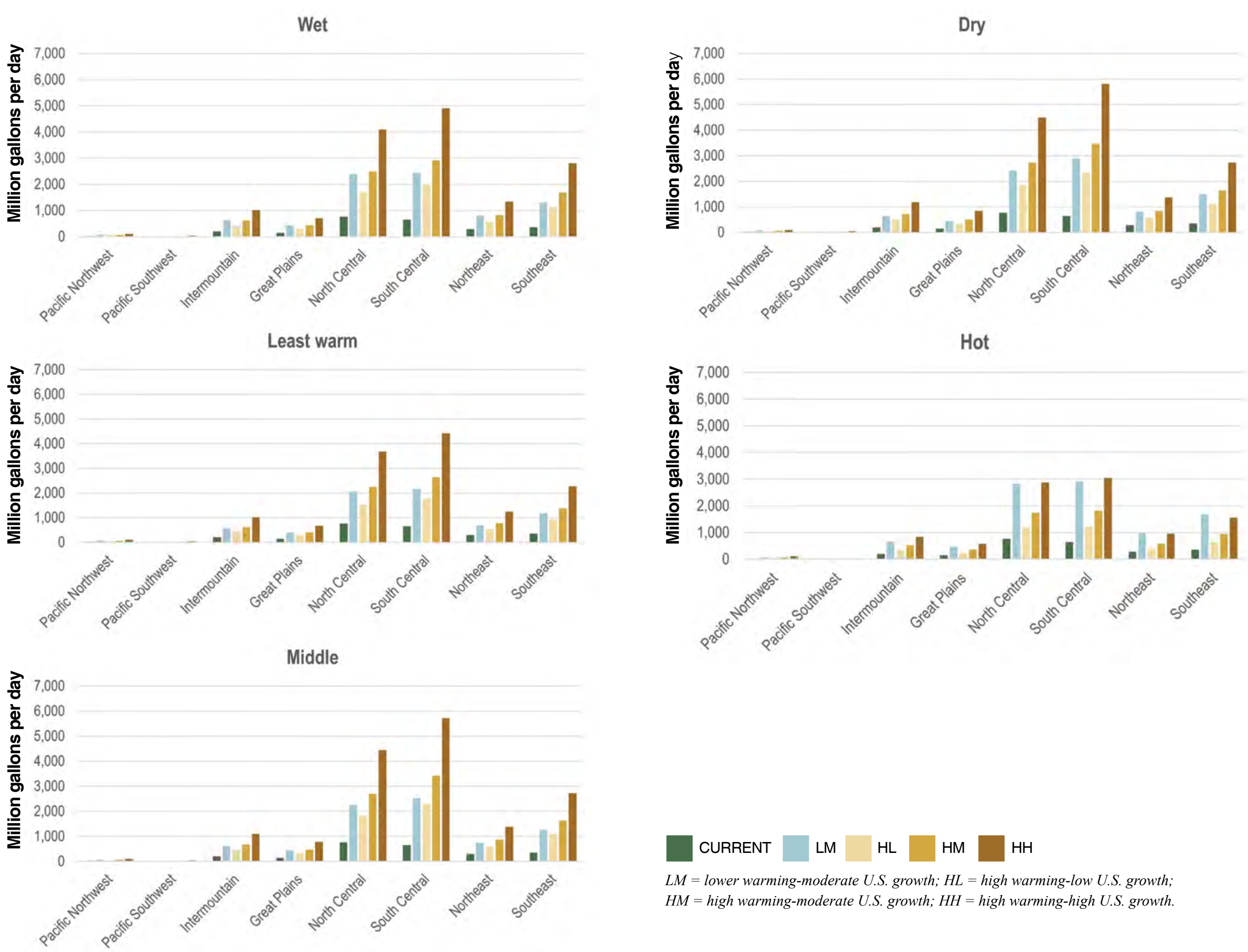
Estimation of electricity demand for freshwater thermoelectric plants is complicated by the fact that electricity consumed in one basin may be produced in another. A second complication arises because electricity is produced at not only freshwater thermoelectric plants but also at saltwater thermoelectric, hydroelectric, solar, wind, and other types of plants. For projecting future use of freshwater at thermoelectric plants, we estimate growth in thermoelectric production for large energy regions of the United States, subtract the portion of the production to be produced at non-freshwater thermoelectric plants, and apportion the remaining production to each county within respective regions.

Our approach utilizes recently released USGS updated estimates of thermoelectric water use in 2015 (Diehl and Harris 2014, 2019). The new USGS method categorizes thermoelectric plants in the United States that withdraw water based on their methods of generating electricity and disposing of waste heat. The USGS data include consumptive use at the plant level, which we make use of here. Instead of reporting withdrawals and then converting them to consumptive use based on regional averages, this section reports consumptive use directly.

The U.S. Energy Information Administration projects energy consumption to increase 0.3 percent for every 1.9-percent increase in U.S. output (U.S. Energy Information Administration 2020), leading to increases in energy use of 150 percent by 2070 for moderate-socioeconomic growth scenarios (SSP1 and SSP2) and over 400 percent for high-socioeconomic growth scenarios (SSP5). These increases in electricity production lead to increases in water consumption from just under 2.5 billion gallons of water per day in 2015 to between 5 and 17 billion gallons per day in 2070 (figure 9-8).

By 2070, increasing temperatures due to climate change are projected to require 20 to 60 percent more water for electricity production than would be needed without climate change. That increase is equivalent to an extra 1 to 6 billion gallons of water per day needed due to climate change. These projections assume a continuation of past trends in water use efficiency but do not account for large sudden shifts due to changes in policy, new technologies, or fuel types. They also do not account for increasing water

Figure 9-8. Current (2015) and future (2070) thermoelectric consumptive use by RPA subregion and RPA scenario for the five RPA climate projections.



LM = lower warming-moderate U.S. growth; HL = high warming-low U.S. growth; HM = high warming-moderate U.S. growth; HH = high warming-high U.S. growth.

temperatures that might impede cooling at thermoelectric power plants (Van Vliet et al. 2012).

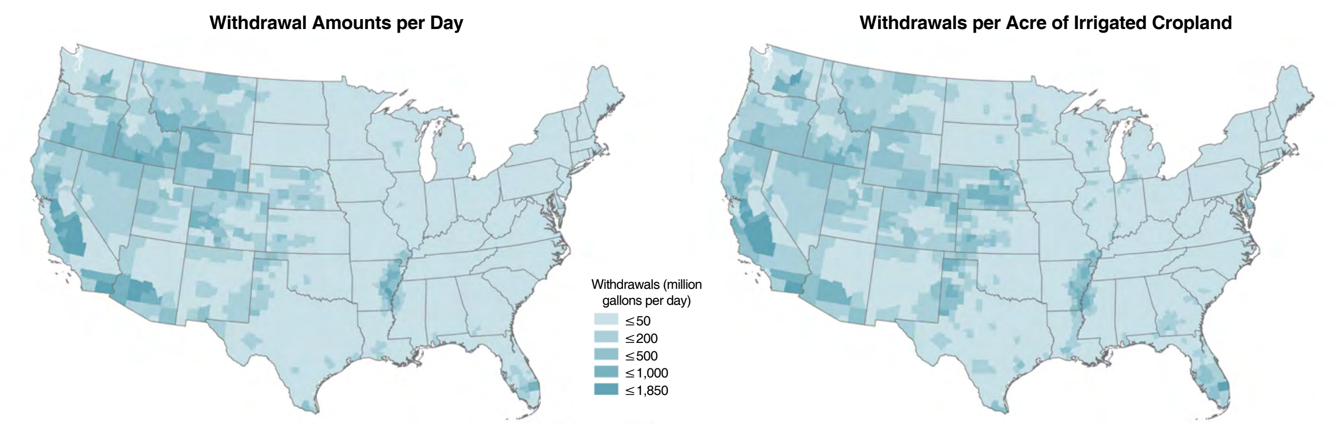
Irrigated Agriculture Withdrawals

Agriculture is the largest user of water nationally, accounting for 42 percent of total freshwater withdrawals. In dry regions like California, agriculture can make up more than 80 percent of total withdrawals. Significant amounts of water are also used for agriculture throughout the southern Mississippi River basin (figure 9-9). In 2015, the 17 Western States accounted for 91 percent of total surface water irrigation withdrawals (Dieter et al. 2018).

Previous water shortages and competition from urban uses have led to decreases in surface water use in the West through reductions in the amount of land irrigated, amount of water applied on any piece of land, and shifts from surface to groundwater supplies. Between 1985 and 2015, irrigation depth on an average acre in the West fell by an annualized rate of 0.85 percent. In the East, however, agricultural water use has increased as farmers use irrigation to offset impacts of more varied precipitation and seek more reliable yields. This analysis assumes rates of change in irrigated acres continue along past trends, as does the amount of water applied to an average acre in each region. Climate impacts are introduced through changes in crop water use due to changes in evapotranspiration; they do not include changes in crop type or growing seasons that might result due to warmer temperatures (Woznicki et al. 2015).

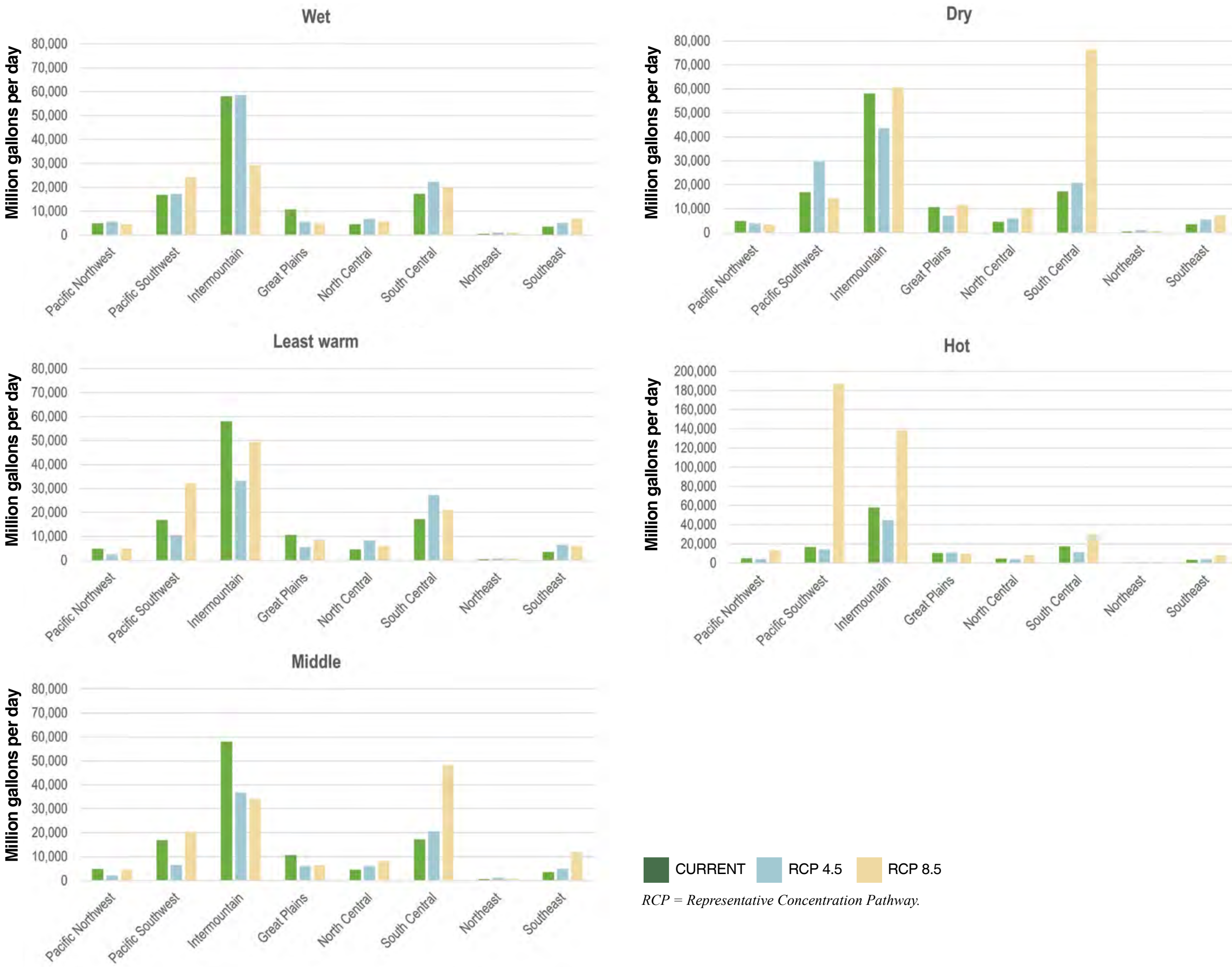
Under the hot climate projection, which represents a worst-case scenario for many of the agricultural regions, total water demanded for irrigation in the United States is projected to increase from 116 billion gallons per day in 2015 to 134 billion gallons per day in 2070 (figure 9-10). The hot climate projection is significantly drier than current conditions in the Pacific Southwest and Intermountain West Subregions, both of which rely on large amounts of irrigation for agriculture. Estimates for agricultural withdrawals do not consider changes in population or income but do include the changes in RCPs 4.5 (lower future warming) and 8.5 (higher future warming), as well as changes in amount of irrigated acreage. SSPs with high population growth are likely to decrease the amount of agricultural acreage faster than historically seen and that are projected here. In such cases, high population growth might decrease agricultural water use if it causes conversion of croplands to development.

Figure 9-9. Agricultural freshwater withdrawals.



Source: 2015 USGS estimates (Dieter et al. 2018).

Figure 9-10. Current (2015) and future (2070) agricultural withdrawals by RPA subregion by climatic pathway (RCP) for the five RPA climate projections. Note the change in scale for the hot climate projection.



RCP = Representative Concentration Pathway.

Projections of Consumptive Use

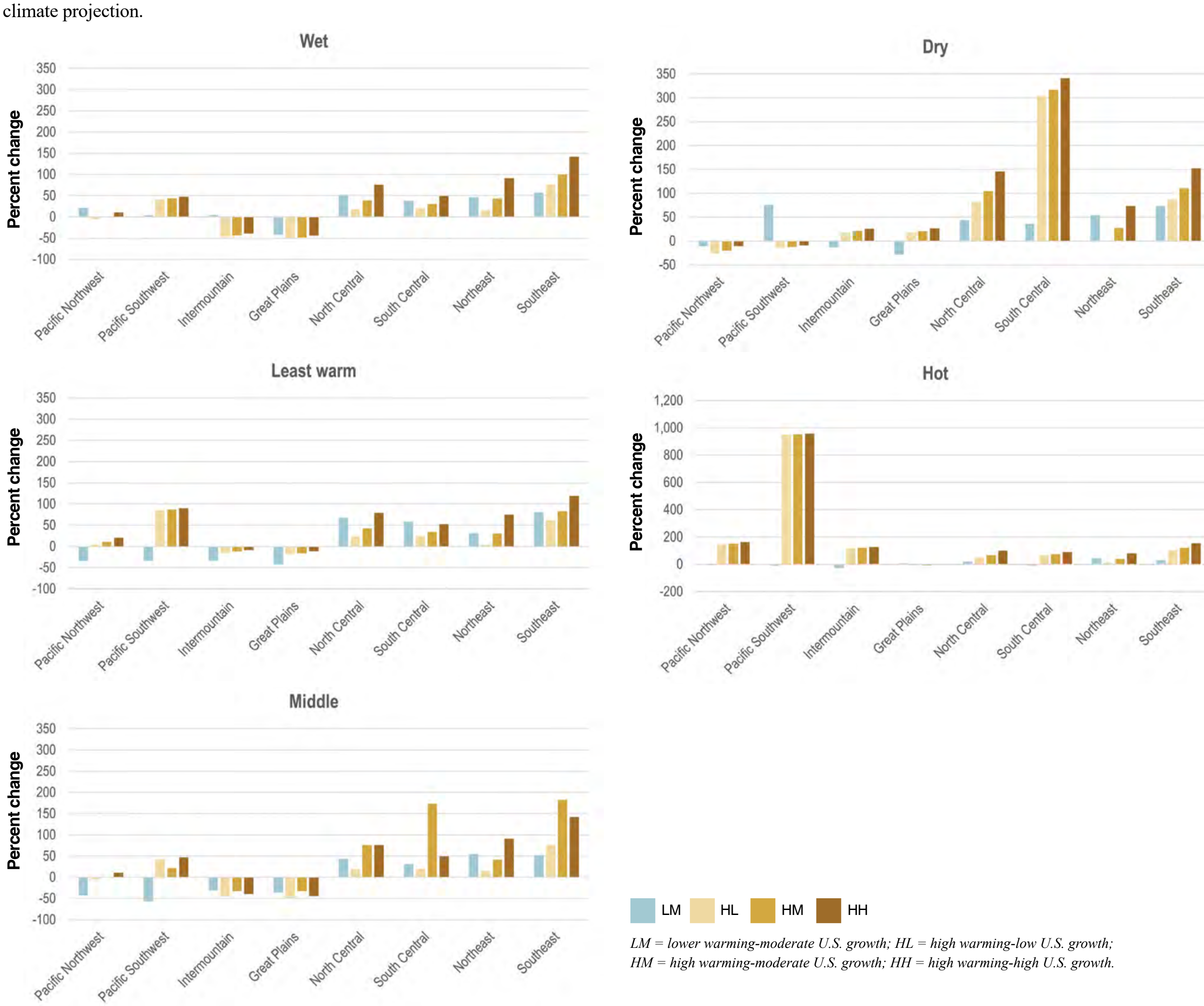
Much of the water withdrawn for human use is returned to the river basin from which it came in the form of runoff and sewage discharge. The portion not returned, and thus not available for downstream uses, is called consumptive use. The USGS estimated consumptive use for irrigated agriculture and thermoelectric power generation in 2015 but only reports withdrawals for other sectors. Nationally, about 62 percent of water withdrawn for agriculture is consumptively used, compared to 3 percent of water withdrawn for power generation (Deiter et al. 2018). Consumptive use for sectors not included in USGS estimates rely on older USGS estimates, dating back to 1990 and 1995 in many cases, and augmented with values from the literature when possible. For those sectors, consumptive use ratios are taken from Brown et al. (2013).

Total consumptive use is projected to fall by about 9 percent under LM-middle and LM-hot, continuing past downward trends in national water use (figure 9-11). Under HH-hot, consumptive use is projected to increase by 235 percent. The Great Plains Subregion sees decreasing consumptive water use for all but the dry climate projection, and the Intermountain Subregion shows decreasing consumptive water use for all but the hot and dry climate projections. The Pacific Northwest sees declines in consumptive use under 9 out of the 20 scenario-climate futures, and for all scenarios using the dry climate projection, which is actually wet for the region (see the Scenarios Chapter sidebar Using Scenarios and Projections in Resource Management Planning). The Pacific Southwest, which sees variation in future precipitation patterns between climate projections and between northern and southern parts of the subregion, sees declines for 6 out of the 20 models. Large increases are projected for the North Central, South Central, and Southeast Subregions, and to a lesser extent in the Northeast. These regions are consistently projected to see increases in consumptive use across all sectors of the economy.

Because agriculture is the dominant use of water in most regions, results often vary by climate projection more than by RPA scenario. Many regions see consumptive use more than double under the climate projections that yield the driest conditions for the respective regions. The most alarming projections across all models and scenarios are for the South Central Subregion, which sees consumptive use rise by over 300 percent under the dry climate projection. These consumptive use projections reflect outcomes if current trends in water use continue. In many cases, such outcomes are not feasible due to limited water supply and highlight areas in which large reductions may be needed.

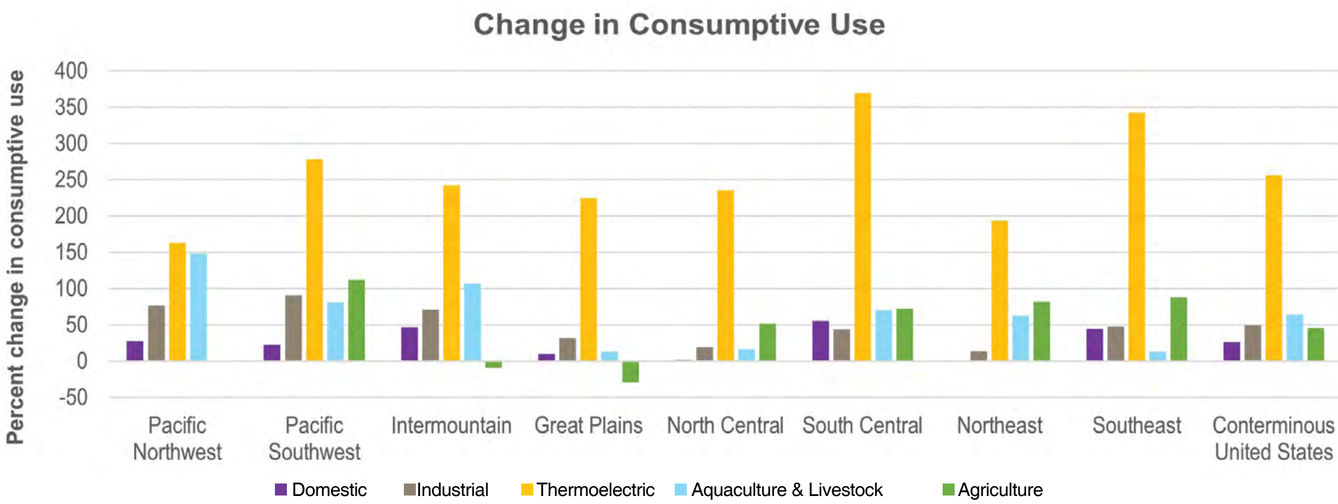
Figure 9-12 shows projected changes in consumptive use by sector. In most regions, projected changes in consumptive use in the domestic sector are relatively modest. Gains in water use efficiency have mostly kept up with increases in population. Consumptive use in the agricultural sector is highly variable, with decreases on average in the Great Plains and Intermountain Subregions. The largest percentage increases are projected in thermoelectric power generation. Adaptation in cooling technologies have led to improvements in the sector, but for this analysis, population and economic growth outpace historic rates of change. These results could be interpreted a few ways. Trends in the analysis reflect trends in per capita energy use and water used for an average kilowatt of energy produced; these estimates may miss sudden shifts in technology. However, the largest increases in water use for the thermoelectric generation sector are projected for the central regions of the United States. These regions drive much of the national results and have not seen as widespread adoption of more efficient cooling technologies.

Figure 9-11. Change in total consumptive use by RPA subregion and RPA scenario for the five RPA climate projections. Note the change in scale for the hot climate projection.



LM = lower warming-moderate U.S. growth; HL = high warming-low U.S. growth; HM = high warming-moderate U.S. growth; HH = high warming-high U.S. growth.

Figure 9-12. Mean changes in consumptive use by sector and RPA subregion from 2015 to 2070, across all scenario-climate futures.



Trends in Water Yield: Past and Projected

- ❖ Changes in water yield across the conterminous United States range from a 25.7-percent increase under a wet future to a 10.9-percent decrease under a dry future.
- ❖ The most consistent results across climate futures are increases in precipitation and yield for much of the Western United States, decreases in the Southwest, and decreases in the South.
- ❖ Many Eastern States receive more than 50 percent of their water from forested lands. Western States receive smaller shares of water from forests, but what water does come from forests overwhelmingly comes from national forests.

Hydrological responses to climate variability and change were assessed for the current (1986 to 2015) and mid-century (2041 to 2070) periods. The Variable Infiltration Capacity (VIC) model (Liang et al. 1994) was used to simulate hydrological responses. The model is a macroscale semi-distributed hydrological model that simulates land-atmosphere fluxes and water and energy balances at the land surface (Cherkauer and Lettenmaier 2003). Water yield represents discharge at the watershed outlet and includes both surface runoff and groundwater contributions. River storage and routing are not included in the model. In this section, yield is differentiated from supply, which is used in the next section on storage. Water yield is a function of precipitation and evapotranspiration within a watershed. Water supply includes water yield as well as increases and decreases due to water diversions between watersheds.

The current RPA study improves on spatial and temporal scales compared to past RPA water assessments. It utilizes an enhanced version of the VIC model that resolves hydrological processes at the 4- x 4-km grid resolution and daily time steps to project water yield and evapotranspiration based on bias-corrected and downscaled regional climate inputs. The analysis also incorporates improved parameterization of various model components for river basins across the conterminous United States (Naz et al. 2016, Oubeidillah et al. 2014). Hydrological responses are subsequently aggregated at the 8-digit hydrologic unit code (HUC 8) watershed scale for water shortage assessments (Heidari et al. 2021). Water yield from forested lands, including national forests, is shown by State in the sidebar Water Yield from Forests.

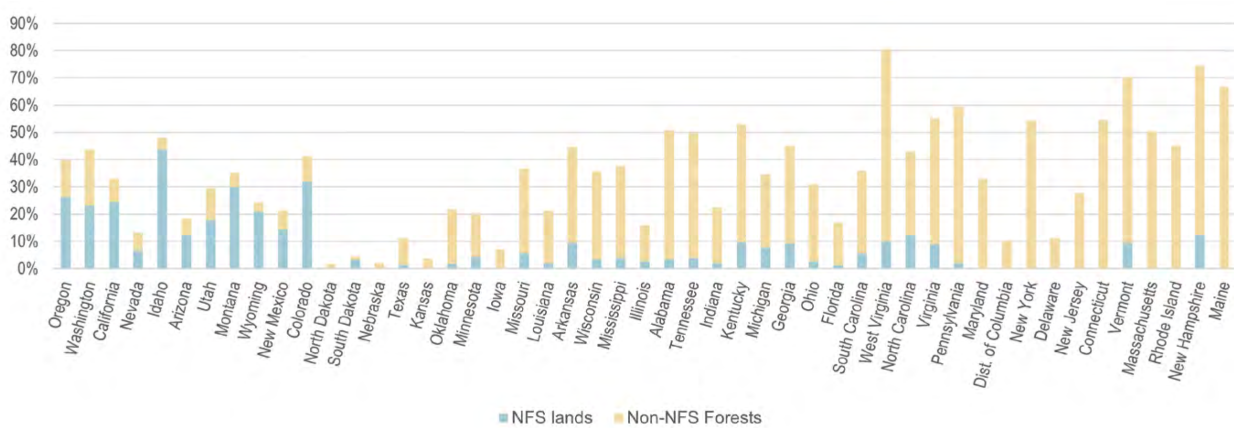
Current (1986 to 2015) daily precipitation and temperature are derived from Daymet (Thornton et al. 1997) and PRISM (Daly et al. 2008) datasets. The North American Regional Reanalysis (NARR) dataset (Mesinger et al. 2006) is used to obtain historical wind-speed data. Future climate conditions are characterized across pathways of climatic change associated with atmospheric warming (RCPs 4.5 and 8.5), using the five climate models described in the sidebar RPA Scenarios (table 9-1), selected to span least warm, hot, dry, wet, and middle climate conditions across the conterminous United States. These climate projections are used to

Water Yield from Forests

Forests play an important role in the provision of water, both because they provide high percentages of many States' total water yield and because the water from forests is generally more reliable and of higher quality than for other land uses (Ellison et al. 2017, Liu et al. 2021). Figure 9-13 shows percent of water yield from forested lands based on current conditions used in this assessment. Across the conterminous United States, 39 percent of water originates from forests, and 15 percent originates from national forests and grasslands. Many Eastern States receive more than 50 percent of their water from forested lands. West Virginia gets about 80 percent of its water from forests, followed by New Hampshire and Vermont with 74 and 70 percent, respectively. Western States receive smaller shares of water from forests, but what water does come from forests overwhelmingly comes from national forests. Idaho gets 44 percent of its water from national forests, a larger percentage than any other State. Colorado and Montana get 32 and 30 percent of their water from national forests, respectively.

Whether forests can continue to provide reliable water in a future with climate change is an important research question. National forests and grasslands are likely to experience larger changes in hydroclimatic conditions compared to the other lands within the conterminous United States (Heidari et al. 2021). Under the high atmospheric warming pathway and the dry, middle, and wet climate projections, national forests in mountainous regions are likely to have larger changes in water yield and other hydroclimatic conditions than other regions. Among U.S. Department of Agriculture, Forest Service management regions, the Southwestern Region is likely to experience the largest shifts in water yield and hydroclimatic characteristics. The Southern Region is likely to become more arid with significant decreases in water yield under the dry climate projection. The Pacific Southwest and Intermountain Regions are likely to become less arid and see increases in water yield. Water yield from national forests in the Pacific Northwest is likely to decline under all climate projections despite the projected increase in precipitation.

Figure 9-13. Percent of water yield in each State from forests and national forests, ordered from west to east.



assess shifts in hydrological responses and hydroclimatic conditions. Land use is represented by historical conditions and is held constant over the assessment period.

Precipitation, Water Yield, and Potential Evapotranspiration

In general, precipitation is higher in the Eastern United States, leading to higher water yield, while potential evapotranspiration is higher in the Southwestern United States (figure 9-14). By mid-century, changes in aggregate water yield across the conterminous United States range from a 25.7-percent increase under the wet climate projection to a 10.9-percent decrease under the dry climate projection. Figures 9-15, 9-16, and 9-17 show changes in the spatial patterns of precipitation, water yield, and potential evapotranspiration (PET) under the five selected climate projections and two pathways of climatic change for mid-century (2041 to 2070). The projections show high variability. In the South, Southeast, and Great Plains, the dry climate projection shows decreases in water yield, whereas the wet and hot projections show increases in water yield

Figure 9-14. Precipitation, water yield, and potential evapotranspiration for the baseline period (1986 to 2015).

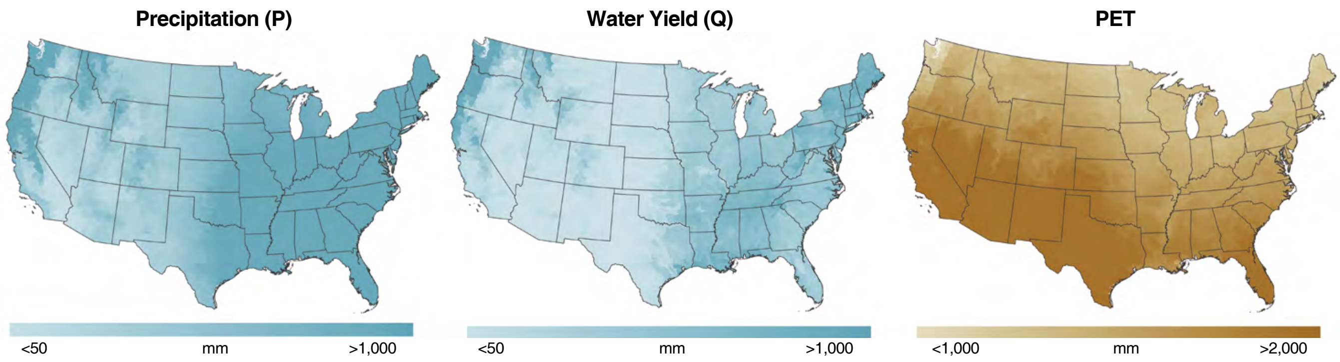


Figure 9-15. Spatial changes in 30-year average of annual precipitation in response to future climate change, from current (1986 to 2015) to mid-century (2041 to 2070) for: (a) RCP 4.5 and (b) RCP 8.5.

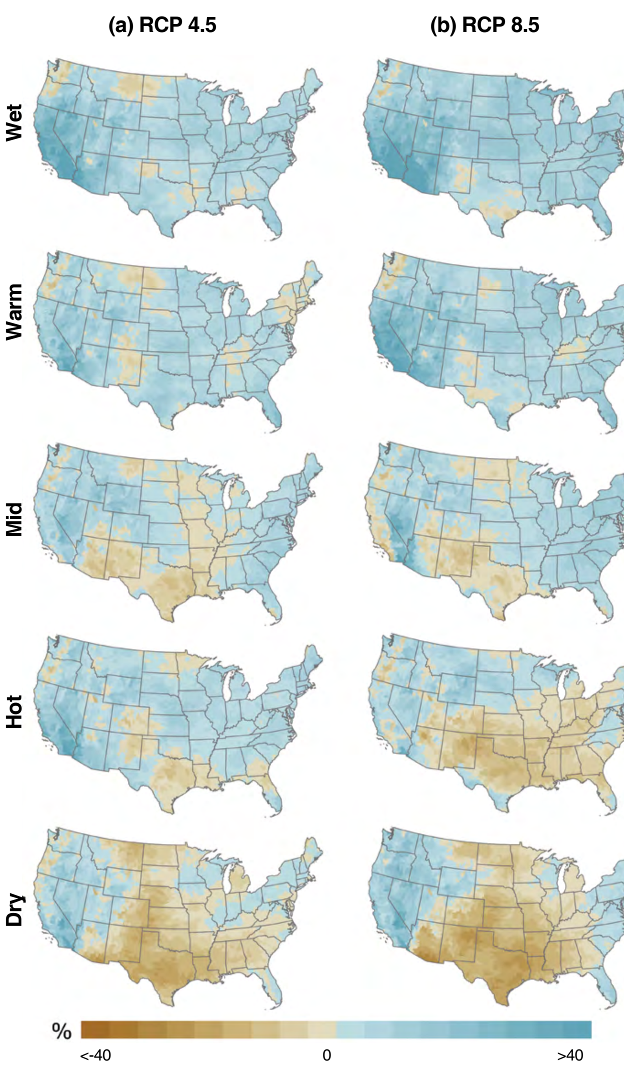
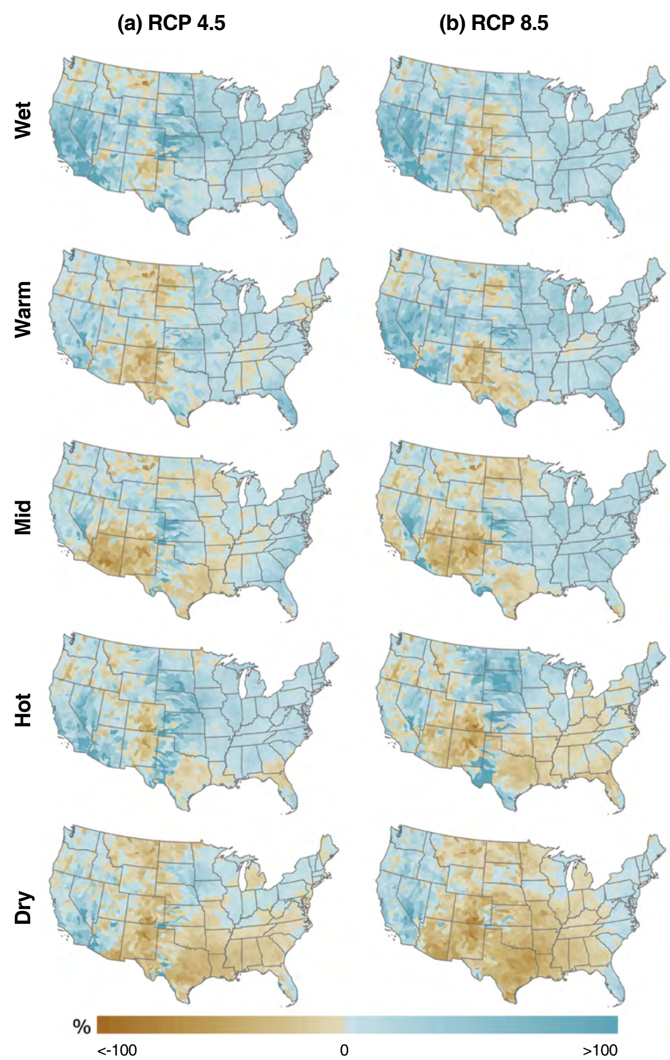
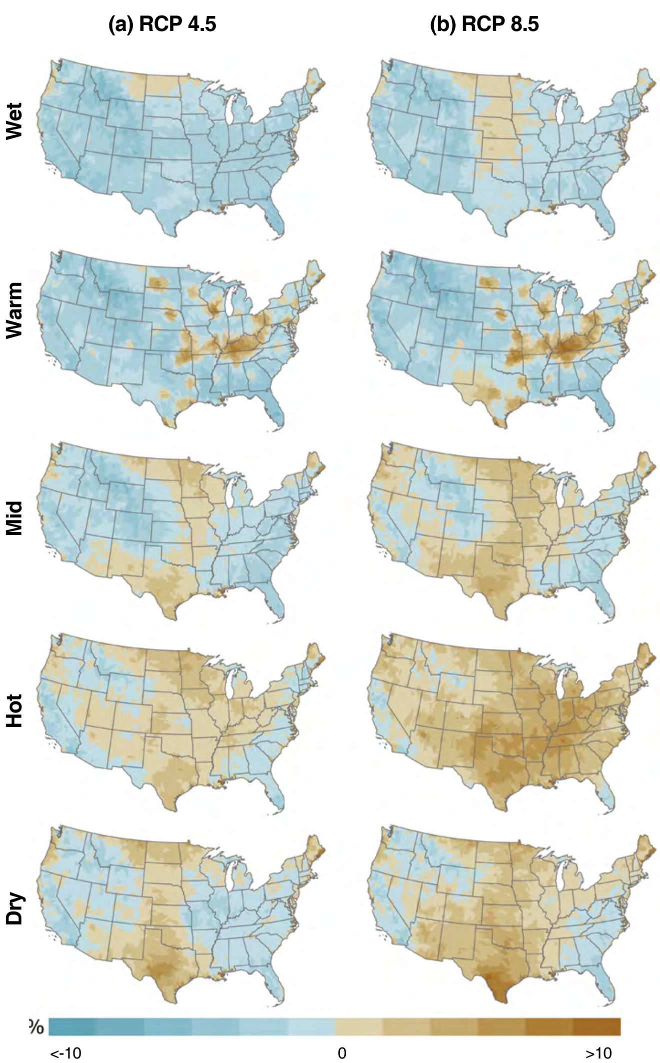


Figure 9-16. Spatial changes in 30-year average of annual water yield in response to future climate change, from current (1986 to 2015) to mid-century (2041 to 2070) for: (a) RCP 4.5 and (b) RCP 8.5.



for these same subregions. The most consistent results across projections are increases in precipitation and yield for much of the Western United States and decreases in water yield in the Southwest (figures 9-14 and 9-15). Much warmer temperatures in the South are projected to increase potential evapotranspiration more than for any other region, amplifying the effects of decreased precipitation and leading to further declines in water yield (figure 9-16). The majority of river basins in the Western United States are projected to experience a decrease in potential evapotranspiration under the wet and least warm climate projections but increases in potential evapotranspiration under the hot, dry, and middle projections. Large increases in potential evapotranspiration occur in the southern parts of the Great Plains and North Central Subregions.

Figure 9-17. Spatial changes in 30-year average of annual potential evapotranspiration (PET) in response to future climate change, from current (1986 to 2015) to mid-century (2041 to 2070) for: (a) RCP 4.5 and (b) RCP 8.5.



Vulnerability to Water Shortage and Socioeconomic Drought

- ❖ Extended dry spells turn short-term water shortages into intense long-term shortages.
- ❖ Under high future warming, droughts lasting more than a year are projected to occur four times more often and increase in intensity by 76 percent.
- ❖ Medium-intensity droughts will occur six times more often and severe droughts will be 76 percent more severe by 2070 under RCP 8.5, relative to current conditions.

Water shortage occurs when demands are partially or fully unmet, a condition also referred to as socioeconomic drought, or just drought, for the purposes of this chapter. Droughts are typically characterized by their magnitude, duration, frequency, and intensity. Magnitude is the cumulative deficit over the duration of the drought; duration is the number of consecutive periods in drought; frequency is the expected arrival time (i.e., return period) of the drought; and intensity is computed by its magnitude divided by its duration (essentially the average magnitude of the drought). The drought return period represents how likely a drought of that magnitude is in any given year. For example, a 10-year drought would be expected to occur about once every 10 years, or that there is a 10-percent chance of such a drought happening in any given year. Similarly, a 100-year drought would be expected to occur about once every 100 years, or that there is a 1-percent chance of such a drought happening in any given year. In terms of categorizations, 10-year droughts are considered medium intensity, whereas 100-year droughts are considered severe. Similar descriptions are commonly used for floods (that is, 100-year floods or 50-year floods) to create flood zone maps.

Methods for modeling water supply and shortage follow Brown et al. (2013). They rely on projections of consumptive water use (Brown et al. 2019), water yield (Heidari et al. 2020b), stream networks, reservoir storage capacity within each river basin, instream flow requirements, and trans-basin water systems and transfers. Water supply in this section differs from water yield in the above section in that water supply includes trans-basin diversions. Instream flow requirements are also included here as a demand requirement. Water is routed through stream networks and diversions using a Water Evaluation and Planning (WEAP) model for the conterminous United States (Sieber et al. 2002). The WEAP model is run at the monthly time scale, and shortage occurs when demand (the sum of consumptive use and instream flow requirements) exceeds water supply.

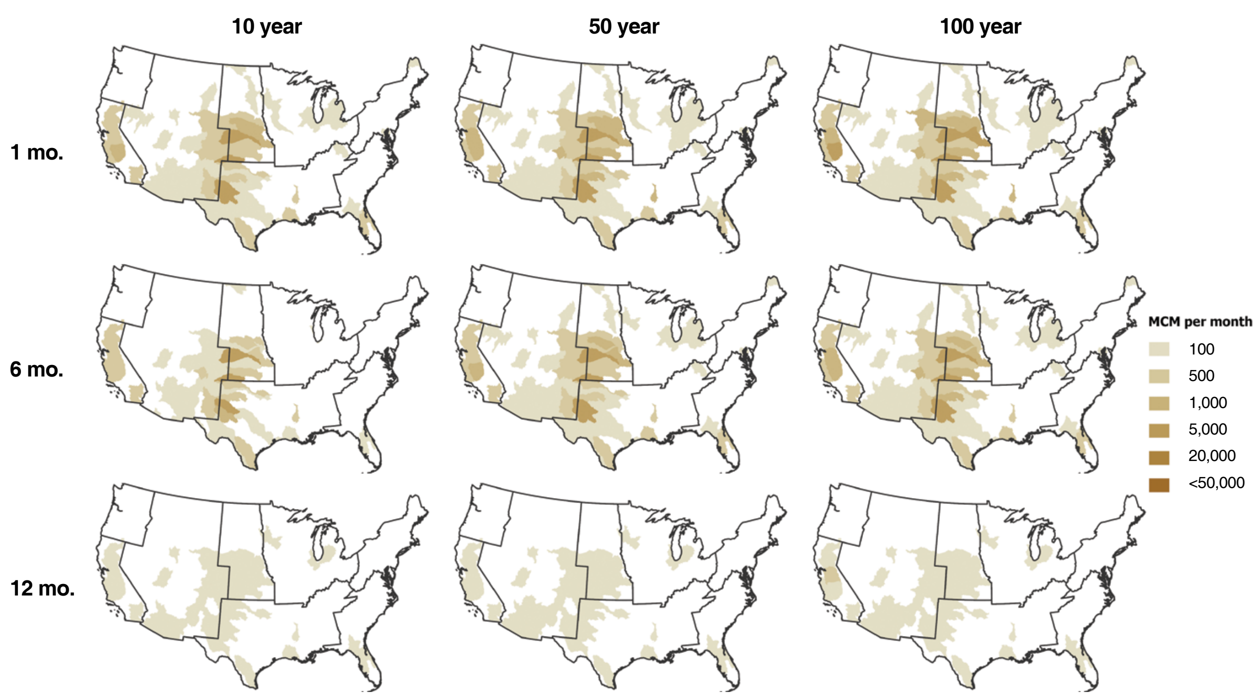
Distributions of shortages from the WEAP results are used to calculate statistical likelihoods of shortage and expected durations and frequency of drought following Heidari et al. (2020a, 2021). This analysis improves previous RPA water assessments by using a monthly rather than annual time step that allows analysis of droughts with duration less than a year (sometimes called flash droughts) and droughts with duration more than a year but not necessarily in annual increments.

Figure 9-18 shows current (1986 to 2015) shortage frequencies, durations, and intensities for HUC 4 basins across the country. Much of the United States currently experiences at least moderate shortages. The southern Great Plains and Rocky Mountain Subregions, southern California, and northern Florida already experience high-intensity shortages of less than a month in length as well as relatively less intense shortages with duration equal or greater than 6 consecutive months.

Future shortages for the lower and high-atmospheric warming futures (RCPs 4.5 and 8.5, respectively) using the dry climate projection are shown in figures 9-19 and 9-20; these projections represent a worst-case scenario for many regions of the conterminous United States. Under the dry climate projection, conditions worsen for much of the central United States. The most consistent increases in intensity and frequency of both within-year (duration less than 12 months) and over-year (duration great than 12 months) shortages occur in the southern portion of the Great Plains. In many places, extended dry spells turn short-term shortages into long-term intense shortages, including the middle Great Plains, Southwest, and South. This pattern extends into the southern Rocky Mountains with lower intensity, as well as the North Central Subregion, which currently only experiences low-intensity shortages. Conditions are projected to improve slightly for northern Florida under RCP 4.5 but deteriorate significantly under RCP 8.5, especially for extended shortages. Although climate projections were selected to represent conditions across the entire conterminous United States, precipitation under the RPA dry climate projection is expected to increase in much of the west coast, resulting in less frequent shortages.

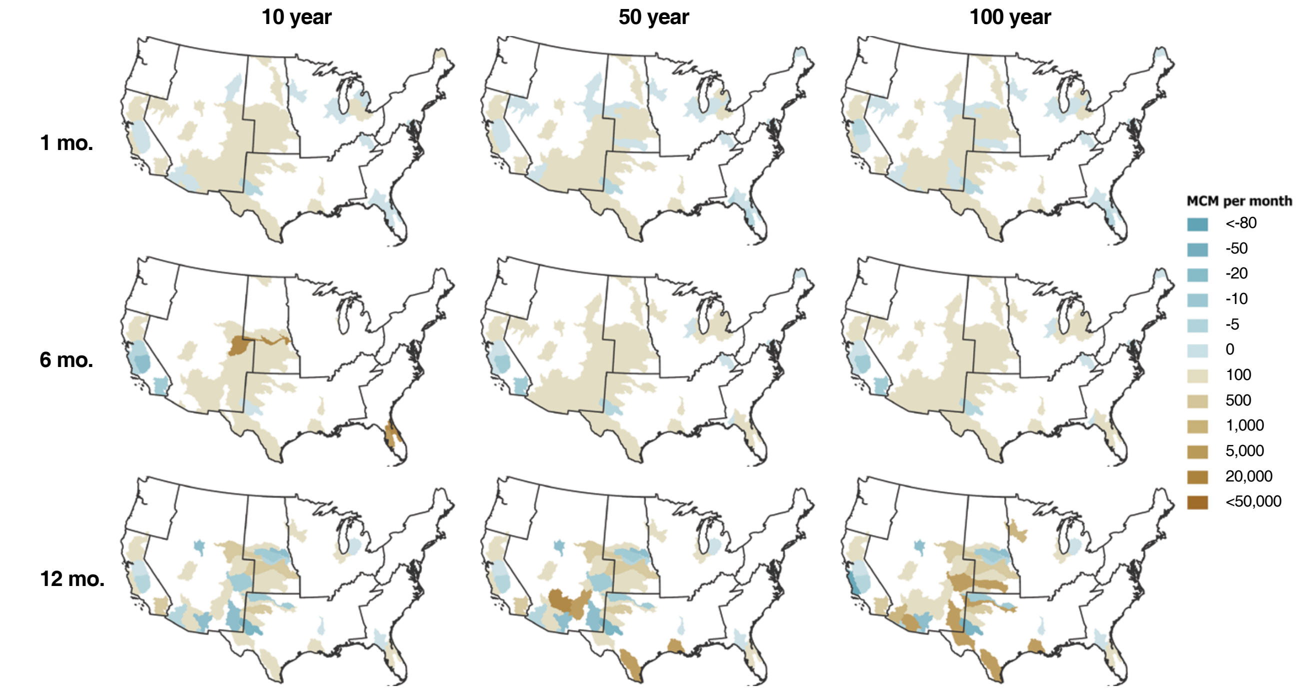
In many places, infrequent extreme droughts are projected to become more frequent, and the duration of droughts is projected to become longer. Droughts that currently last 1 month turn into 6-month droughts, and droughts that currently last 6 months turn into 12-month droughts. The intensity of droughts that are projected to occur in the future period every 10, 50, and 100 years also increases. What would currently be considered a 10-year drought is expected to occur 2.5 times more often under RCP 4.5 and 6 times more often under RCP 8.5, with increases in intensity and

Figure 9-18. Intensities of water shortage events under the current conditions (1986 to 2015) in million cubic meters per month. Shortage duration increases moving from top to bottom (duration greater than 1 month, greater than 6 months, greater than 12 months). Shortage return-period increases moving left to right (10-year drought, 50-year drought, 100-year drought).



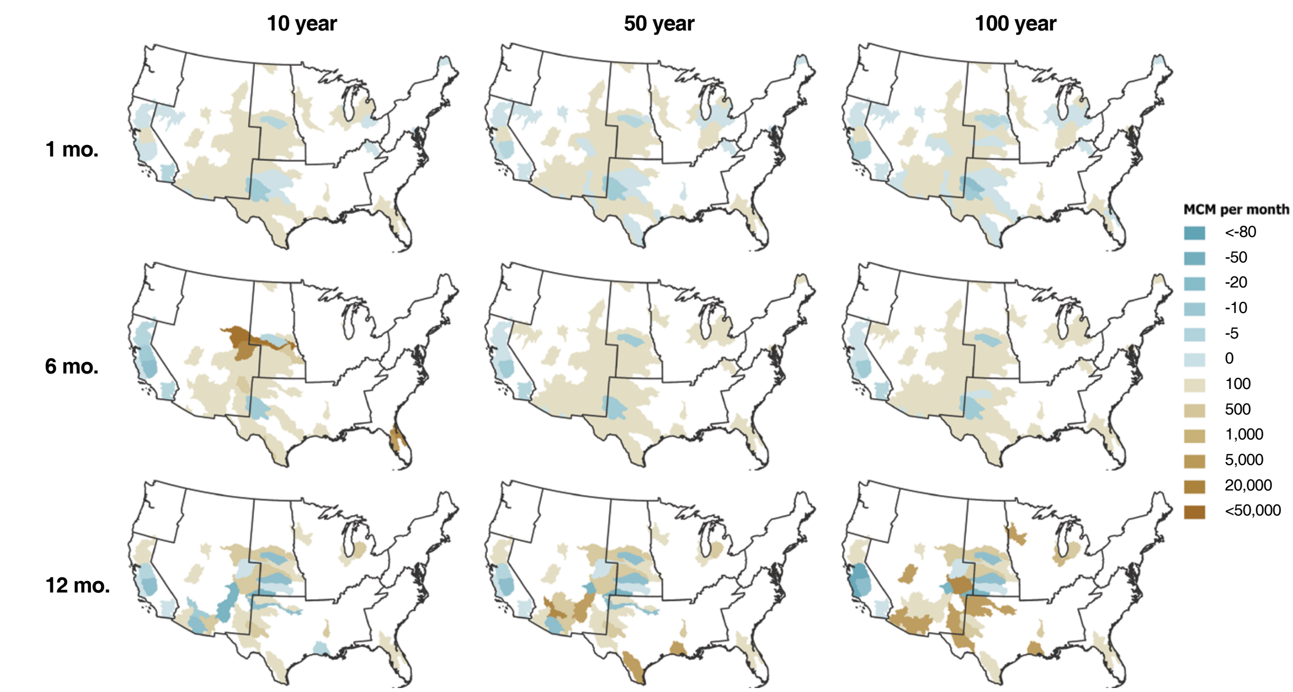
MCM = million cubic meters.

Figure 9-19. Changes in the intensities of water shortage events from current (1986 to 2015) to future (2041 to 2070) conditions under RCP 4.5. Shortage duration increases moving from top to bottom (duration greater than 1 month, greater than 6 months, greater than 12 months). Shortage return-period increases moving left to right (10-year drought, 50-year drought, 100-year drought). Locations mapped in brown are projected to experience increasing water shortage intensities, while locations mapped in blue are projected to experience decreasing shortage intensities relative to current shortage conditions.



MCM = million cubic meters; RCP = Representative Concentration Pathway.

Figure 9-20. Changes in the intensities of shortage events from current (1986 to 2015) to future (2041 to 2070) conditions under RCP 8.5. Shortage duration increases moving from top to bottom (duration greater than 1 month, greater than 6 months, greater than 12 months). Shortage return-period increases moving left to right (10-year drought, 50-year drought, 100-year drought). Locations mapped in brown are projected to experience increasing water shortage intensities, while locations mapped in blue are projected to experience decreasing shortage intensities relative to current shortage conditions.



MCM = million cubic meters; RCP = Representative Concentration Pathway.

frequency occurring in the Great Plains, Intermountain, North Central, South Central, and Southeast Subregions. Droughts decrease in frequency in parts of the Pacific Southwest due to the relative wetness of the dry climate projection in southern California. Hundred-year droughts (those with 1-percent likelihood in any given year) that last longer than a year are projected to increase in intensity by 27 percent under RCP 4.5 and by 76 percent under RCP 8.5.

Management Implications

In August 2021, the U.S. Department of the Interior declared the first-ever Colorado River Basin water shortage, triggering a series of water use reductions according to a drought contingency plan that was approved by Congress in 2019. Under the contingency plan, Arizona will lose 18 percent of its annual allocation of Colorado River basin water in the 2022 water year, representing 8 percent of the State's total water use; Nevada will lose 7 percent of its Colorado River basin water. These cuts fall heavily on agriculture in affected States, where farmers and ranchers rely on irrigation to support their livelihoods. In many cases, farmers have responded to water shortages and drought by increasing their use of groundwater, often at rates that exceed aquifer recharge rates (Hornbeck and Keskin 2014, Medellín-Azuara 2016). According to many of the projections in this assessment, such impacts on incomes, lifestyles, and other natural resources will become more common.

One of the key insights for management is that average future water yields are highly uncertain, but more frequent and intense droughts are likely. Based on these insights, we recommend that managers prepare for a more variable future, developing drought management plans and promoting conservation practices among water users. Our projections assume water use continues according to past trends, and thus highlight where adaptation may be needed as opposed to identifying where shortages may occur in the future. In regions where water becomes more scarce, economic pressure will likely shift water use between sectors and regions (Blanc et al. 2014). Longer term responses to climate change might require substantial transfers from agriculture to urban users, which could have serious negative impacts on rural communities (Brown et al. 2019, Warziniack and Brown 2019). Increasing reservoir storage might provide short-term relief but ultimately relies on sufficient water yield to fill the reservoirs, an increasing problem throughout the country (Brown et al. 2019). Reservoir levels may become low enough to affect hydroelectric power productions (Craig et al. 2018, Boehlert et al. 2016, Henderson et al. 2015).

Low flows in river systems due to climate change and human uses are already affecting aquatic biota and ecosystems, with compounding effects on water quality and temperature. More details on current and future conditions of aquatic species are discussed in the Biodiversity Chapter. The results from that chapter highlight the broad suite of risks to aquatic systems, from climate change, low flows, and development pressures, and point to the role Federal lands may play in preserving critical ecosystem services and providing refugia to threatened species.

Not all news related to water resources is bad. In many places, conservation efforts have reduced total water demand, even in areas with significant population increase. Innovative programs by local water managers have led to large reductions in household water use. Nevada, for example, recently passed a law restricting irrigation of lawns, or "nonfunctional turf" (Assembly Bill 356). Los Angeles' Metropolitan Water District offers $1 per square foot of lawn turf removed from residential properties. Similar policies that either impose restrictions or provide incentives to reduce turfgrass are likely to become more common.

Conclusions

Much of the country has made and will continue to make improvements in water use efficiency, leading to declines in total withdrawals. However, water use continues to increase in areas with rapid population growth and expanding agriculture. Many of these regions are already facing regular water shortages. Whether shortages increase in the future depends heavily on the climate outcome. Projected changes in national consumptive water use range from a 9-percent decrease to a 235-percent increase, with the largest impacts resulting from the needs of agriculture in response to changes in precipitation and aridity. These results highlight a conundrum associated with climate change and water use—a drier climate leads to increases in water demand. By mid-century, changes in aggregate water yield across the conterminous United States range from a 25.7-percent increase under the wet climate projection to a 10.9-percent decrease under the dry climate projection.

Water shortages are consistently projected to increase in intensity, frequency, and duration in the Southwest and Great Plains Subregions. If water yield decreases as projected due to climate change and shortages become longer and more frequent, these results suggest a mix of supply and demand adaptation measures may be needed. Common solutions like groundwater mining and transfers of water from the agricultural to the domestic sector will work in some but not all cases (Brown et al. 2019, Warziniack and Brown 2019). Novel adaptation methods may eventually be needed, such as increased use of recycled water, expanded use of precision agriculture, more efficient water pricing and transfers, and updated water infrastructure (Gleick 2016).

Projections of water use given here assume continuation of recent trends in economic production and water use efficiency. They are not bound by how much water is actually available nor do they consider changes in water scarcity and competition between sectors. Estimates of withdrawals and consumptive use are therefore likely to be larger than those produced with models that maximize the value of water subject to total water availability (e.g., Draper et al. 2003, Pulido-Velazquez et al. 2008) and models that estimate water requirements needed to maintain current practices in a future with climate change (e.g., Marston et al. 2020, Strzepek et al. 2012). Optimization models tend to reflect the best-case scenario and miss some of the forces already occurring in the economy that are likely to either magnify or alleviate some of the pains associated with climate change. Our approach highlights where the status quo is unsustainable and, therefore, where management actions are most needed.

Uncertainty exists around these projections, highlighted by the varied results for water yield across climate projections, but also due to underlying assumptions about socioeconomic factors like population growth and technological adaptation. Because demand cannot exceed supply, adjustments and mitigation measures may be needed. The RPA Assessment attempts to capture the full range of plausible future conditions to highlight where models agree and where large amounts of uncertainty exist, to help managers plan for the worst-case scenario.

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Chapter 10

Biodiversity: Wildlife and Aquatic Biota

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Biological diversity, or biodiversity, measures the variety of organisms and life forms in a specific area and is a key attribute of healthy ecosystems (Elmqvist et al. 2003). Biodiversity naturally varies across the United States in response to geologic history, tectonic activity, and ecoregional characteristics, yet areas of the country with naturally lower biodiversity still support species of regional ecological, cultural, and commercial importance and provide important ecosystem services. Significant declines in biodiversity have been documented globally across taxonimic groups (Garcia-Morena et al. 2014) and within the conterminous United States (e.g., in birds; see Rosenberg et al. 2019). Declining biodiversity is strongly linked to the anthropogenic actions that have modified ecosystems leading to declines in habitat quality, quantity, and connectity in marine, freshwater, and terrestrial settings. Tracking patterns in biodiversity, therefore, is key to informing management regarding places of particular vulnerability to current and emerging threats.

In this chapter of the Resources Planning Act (RPA) Assessment, we focus on patterns and threats to native wildlife and aquatic species biodiversity, measured as species richness. We present biodiversity information at multiple spatial and taxonmic scales, comparing current conditions with those presented in previous reports and adding new approaches for better addressing biodiversity conservation in the United States, with minimal representation of distributions and analysis for Alaska and Hawaii. We report geographic patterns of biodiversity, recent

- Trends from breeding bird surveys indicate population declines in at least 20 percent of all bird species across habitat types since the 1950s/60s, and in more than 50 percent of species that occupy grasslands or are ground nesting. These declines are linked to land use modifications of habitats as well as introduced species and loss of habitat connectivity.
- Concentrations of imperiled taxa with a listing status under the Endangered Species Act are found across the country, with particular concern in Peninsular Florida and Hawaii for birds, and in the RPA North and South Regions for fishes, crayfish, and mussels.
- Watersheds of the RPA North and South Regions are most vulnerable to compounded land use stress. Regardless of RPA region, development stands out as the largest overall land use stressor for native ecosystems.
- Areas of potential high climate stress were consistently found in mountainous areas of the RPA North, Rocky Mountain, and Pacific Coast Regions, with pockets of stress identified in arid regions of the Rocky Mountain Region.
- Federal lands with a lower risk of development or land conversion, such as those managed by the U.S. Department of Agriculture Forest Service and U.S. National Park Service, are projected to be under higher climate stress compared with other lands, potentially limiting their future ability to function as climate refugia for native biota.

historical trends in populations (particularly of birds), and patterns of species at risk of extinction as defined by their listing status under the Endangered Species Act (ESA). We also provide a discussion of threats to biodiversity including invasive species, pathogens, current land uses, and projected future climate change.

Patterns of Biodiversity

- The Mississippi River basin and Madrean Sky Islands/U.S.-Mexico border areas contain the highest terrestrial and aquatic biodiversity across the conterminous United States. These centers of biodiversity are linked to geologic history and the localized isolation of species (resulting in high rates of endemism).
- Population trends in migratory game birds (webless and waterfowl groups) since the 1950s/60s exhibit inter-annual variability, with harvest generally tracking overall population numbers. Over time, populations and harvest of ducks and geese tend to be increasing, while woodcocks and mourning doves are declining.
- Long-term population trends from breeding bird surveys report statistically significant declines in all groups of breeding birds, with at least half of all species of grassland or ground-nesting species showing significant population declines.

Biodiversity is in decline globally, with freshwater aquatic biodiversity declining at rates that exceed marine or terrestrial ecosystems (Tickner et al. 2020). In the United States, concern about species and their habitats has rallied diverse partners to unite in the shared goal of ecosystem protection and enhancement. In this section, we begin by presenting spatial patterns of terrestrial and aquatic biodiversity, followed by a presentation of status and trend information for avian species. We also present patterns of imperiled species as defined by their listing status under the ESA. We acknowledge that additional species may be imperiled across the United States that are not federally listed under the ESA. We primarily present ESA-listed species to provide direct information to land managers who have a responsibility to participate in the development of conservation plans.

Native Terrestrial Biota

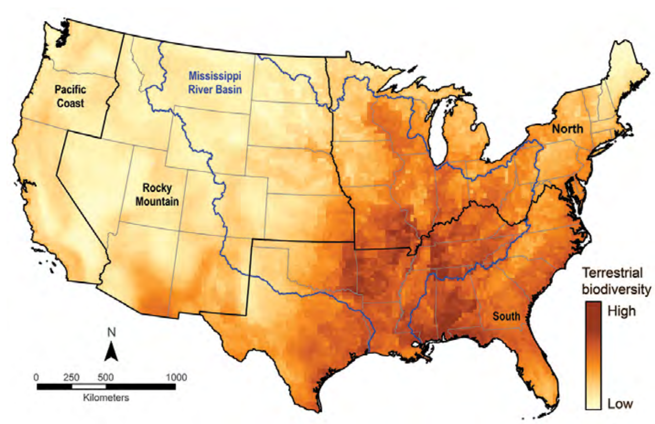
In order to assess geographic patterns of distribution, and for reference in vulnerability assessments described later in this chapter, we mapped terrestrial biodiversity across the conterminous United States. We acquired native terrestrial biodiversity datasets from NatureServe (https://www.natureserve.org), the organization that maintains the most comprehensive national data available on the taxonomy, distribution, and conservation status of native species. Individual species were counted for each 250-square-mile (647-km^2) grid from the NatureServe species dataset and displayed in map form (figure 10-1). The dataset includes 4,107 total species from across the country (inclusive of Alaska and Hawaii), capturing insects, birds, mammals, crustaceans, reptiles, and amphibians, among others. Of particular relevance for forest management are the subset of these species identified as forest-associated (see the sidebar Avian Species Associated with Forested Environments).

Across the conterminous United States, the highest biodiversity of terrestrial fauna is found in the eastern portions of the Mississippi River basin, in the Madrean Sky Islands, in the border areas between Texas and Mexico (consistent with findings of Van Devender et al. 2013), and in the south Atlantic- and Gulf-draining watersheds of Alabama, Florida, North Carolina, and South Carolina. Western States cover a geologically younger, less-dissected landscape than the eastern portion of the United States, leading to lower overall biodiversity in this area (Elkins et al. 2019).

Native Fish, Crayfish, and Freshwater Mussel Biodiversity

For the first time in an RPA Assessment, we are able to present species distribution data for native fish, crayfish, and mussels, allowing us to describe regional characteristics of aquatic species diversity. As for terrestrial biodiveristy, we acquired datasets of native aquatic species from NatureServe

Figure 10-1. Biodiversity of native terrestrial species (excluding plants) mapped at a resolution of 250 mi^2 for the conterminous United States, with RPA regional boundaries and the outline of the Mississippi River basin in blue. Invasive or introduced species are not included.

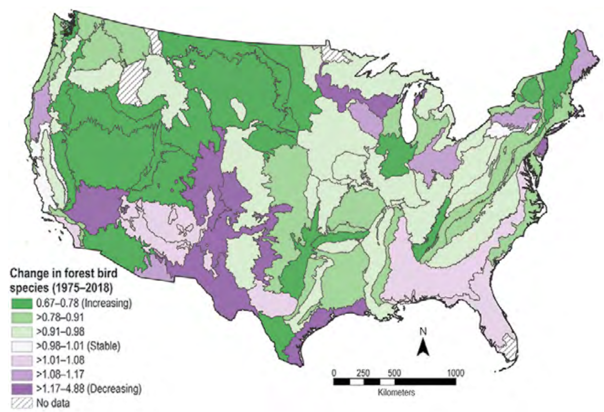


Source: NatureServe.

Avian Species Associated with Forested Environments

A closer look at long-term data available on forest-associated birds is available through the North American Breeding Bird Survey (BBS). Using BBS datasets, we found that long-term (1975 to 2018) trends in the number of bird species associated with forests varied among ecoregions of the conterminous United States (figure 10-2). The greatest increases in numbers of forest bird species were clustered in ecoregions of the northern Great Plains and Intermountain West, with additional gains scattered among the Cross Timbers and Arkansas Valley, Southern Texas Plains, Central Corn Belt Plains, Southwestern Appalachians, and Northeastern Highlands. The greatest declines were distributed among the Southern Rockies, Southwestern Tablelands, and Chihuahuan Deserts, and scattered among disjunct ecoregions of the Mojave Basin and Range, Western Gulf Coastal Plain, North Central Hardwood Forests, and Atlantic Coastal Pine Barrens (see Breeding Birds subsection of Avian Fauna section, figures 10-10, 10-11, 10-12, 10-13).

Figure 10-2. Estimated long-term change in the number of forest-associated bird species detected from 1975 to 2018. Change is measured as 1975 species divided by 2018 species number estimate, excluding exotic species. Values <1.0 indicate species numbers increasing (green shades); values >1.0 indicate species numbers decreasing (purple shades).



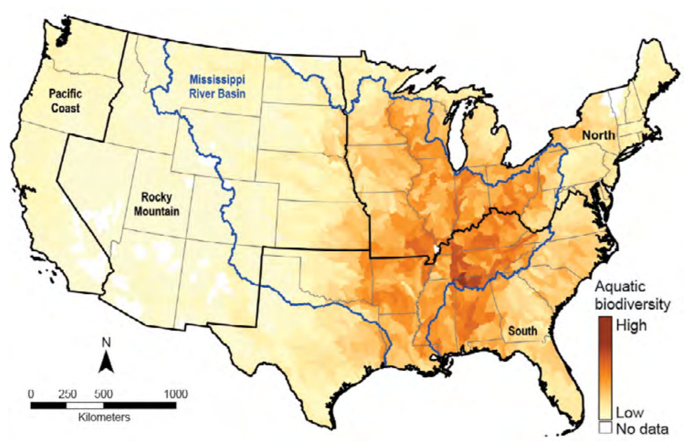
Source: USGS Breeding Bird Survey.

(https://www.natureserve.org/biodiversity-science/species-ecosystems) and mapped them at the 8-digit hydrologic unit code scale (HUC 8; https://water.usgs.gov/GIS/huc.html) across the conterminous United States (figure 10-3). We summarized individual species information per HUC 8 into counts to characterize biotic richness. A HUC 8 is intended to capture an entire subbasin from the headwaters to the mouth. In a large river system such as the Columbia River, there are multiple subbasins at the HUC 8 scale. The NatureServe aquatic biodiversity dataset contains 905 species of native fishes, 391 species of native crayfish, and 304 species of native mussels. All subspecies and populations were merged into species designations for mapping and tabular summaries. Nonnative or introduced aquatic biota are not included in this assessment. For example, introduced warmwater fish such as largemouth bass (*Micropterus salmoides*) in the Western United States are not included in the total count of native fish species in western areas.

Native aquatic species biodiversity and the distribution of individual species vary in response to a diversity of factors including geologic age, patterns of river connectivity, latitude and longitude, precipitation and thermal regimes, riparian habitat composition (see the sidebar Riparian Areas for more information regarding classification of riparian ecotone habitat for management applications), and human modifiers of the landscape such as land use and water management. The RPA South Region is a global hotspot in aquatic species biodiversity generally, and for crayfish in particular, and is the RPA region with the highest biodiversity of fish, crayfish, and mussels (table 10-1). Overall biodiversity of aquatic biota is lowest in the RPA Pacific Coast Region (table 10-1).

Biodiversity can be higher in areas with more endemic species. For this analysis, we defined endemism by RPA region: species endemic to a region occur only in that region. Because RPA regions do not follow watershed boundaries,

Figure 10-3. Aquatic biodiversity of the conterminous United States mapped at a HUC 8 watershed scale, with the Mississippi River basin outlined in blue.



HUC = hydrologic unit code.

Source: NatureServe.

Table 10-1. Native aquatic biodiversity and species endemic to each RPA region for fish, crayfish, and mussels. Numbers are species richness counts, with the number of endemic species in parentheses.

RPA region	Combined biodiversity	Fish	Crayfish	Mussels
	Total biodiversity (total endemic)			
North	560 (63)	354 (35)	91 (24)	115 (4)
South	1,353 (855)	702 (385)	360 (293)	291 (177)
Rocky Mountain	342 (59)	259 (57)	18 (2)	65 (0)
Pacific Coast	127 (67)	109 (63)	10 (2)	8 (2)

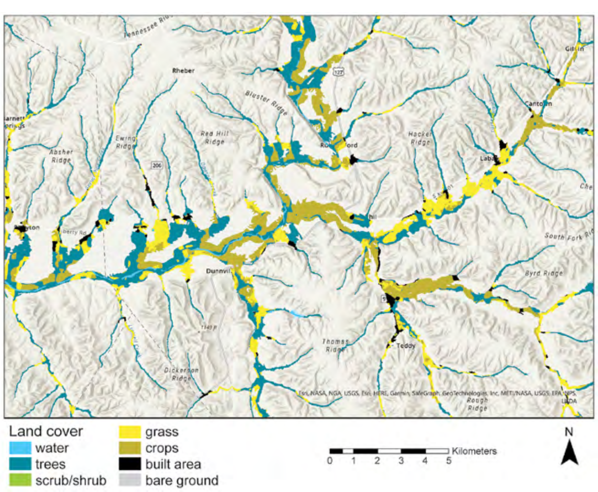
we assigned HUC 8 watersheds located along border areas to the RPA region that contained the majority of the HUC. All regions had high numbers of endemic species (table 10-1). The highest percentage of biodiversity identified as regionally endemic was found in the South Region (63 percent), followed by the Pacific Coast Region (53 percent) (calculated from table 10-1).

An accurate understanding of the distribution of species is important for both current and future management. This means having accurate maps not only for individual species, but also for abundance and diversity across the United States. Tracking patterns of overall and endemic species biodiversity can provide important information about ecosystem health broadly (Bonn et al. 2002), in addition to the potential resilience of local ecosystems (Burlakova et al. 2011). Detection of changes and patterns in biodiversity at a national scale associated with changes in the intensity and distribution of human uses may be found through examination of the entire suite of species present (e.g., Brown and Laband 2006), as well as by exploring the response of endemic species to human-mediated changes such as climate, land management, and human population growth. Endemic species have been identified as potentially more vulnerable to climate change than more widely distributed species (Malcolm et al. 2006) because many endemic species occur within a small and sometimes isolated geographic extent, leading to narrower habitat and environmental tolerances.

Riparian Areas

Riparian ecotones are an important natural resource, rich in biodiversity, ecological, and hydrological functions, supporting both aquatic and terrestrial biodiversity. Further, these ecotones contain specific vegetation and soil characteristics that play important roles in protecting water quality and stream ecosystem health and are very responsive to land management activities (Mitsch and Gosselink 1993, Naiman et al. 1993).

Figure 10-4. Percent riparian ecotone area per HUC 10 watershed in the National Riparian Areas Base Map in 2020.



HUC = hydrologic unit code.

Since the early settlement of the United States, riparian areas have experienced alterations resulting from urbanization, agricultural activities, and floodplain development that altered their extent and land cover condition (Brinson et al. 1981, Doppelt et al. 1993, Tockner et al. 2002).

The National Riparian Areas Inventory Project provides free tools and riparian datasets to facilitate riparian area delineation and quantification on multiple scales. These data support monitoring, riparian land cover classification, riparian conservation prioritization, and riparian areas management. The new National Riparian Areas Base Map uses the Riparian Buffer Delineation Model (Abood et al. 2012, www.riparian.solutions) to display riparian acreage, spatial distribution, and land cover at a national scale, where riparian areas are defined as streamside zones within the 50-year flood area of a stream. This Riparian Areas Base Map shows both the extent of riparian areas and the general riparian land cover composition, highlighting where riparian areas contribute disproportionately to biodiversity conservation compared to their abundance (figure 10-4).

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Avian Fauna

Although trends in terrestrial and aquatic biodiversity over time are not available at a national scale, species-specific temporal trends for some avian fauna are available and provide insights into their patterns of population abundance. Given increasing threats to fish and wildlife, examining patterns across both time and space helps us understand the potential consequences of management decisions and locate risks as well as potential refugia. We present status and trends in selected bird species using data collected by the U.S. Fish and Wildlife Service (FWS) and U.S. Geological Survey (USGS), in collaboration with States, Tribes, private landowners, nongovernmental organizations, and other Federal partners. These groups have responsibility for the conservation or monitoring of migratory species (e.g., waterfowl and neotropical migratory songbirds), federally listed species (endangered, threatened, and proposed for listing), and species with special designations like the golden eagle (*Aquila chrysaetos*) and bald eagle (*Haliaeetus leucocephalus*). This section describes population and harvest trends in migratory game birds as well as trends in populations of breeding birds. We present these results using the organizational units associated with the surveys and trend assessments associated with data collection rather than in relation to RPA regions, to preserve the statistical accuracy of the source information.

Migratory Game Birds

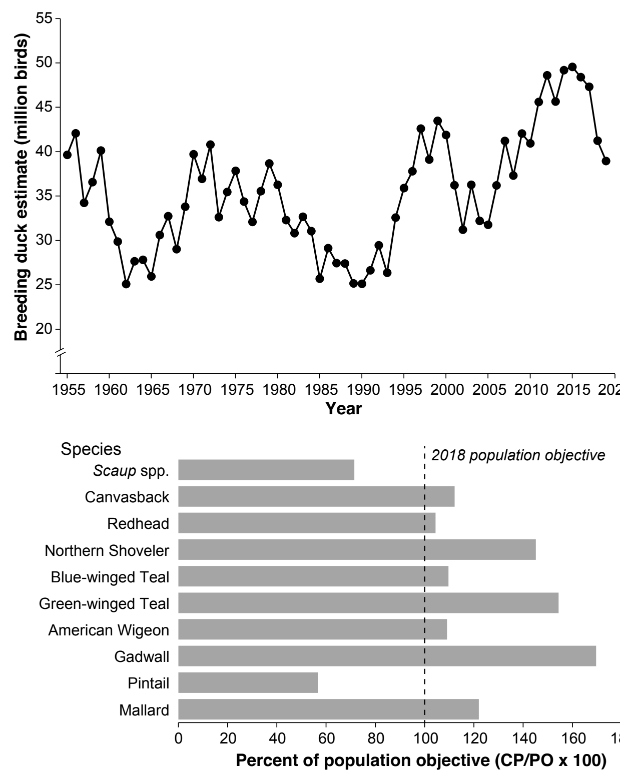
Migratory game birds reported here collectively refer to waterfowl (ducks, geese, and swans) and two additional species defined as webless migratory game birds: the mourning dove (*Zenaida macroura*) and American woodcock (*Scolopax minor*). Migratory game birds are economically important through recreational harvest and contribute to native ecosystems and biodiversity. These birds have a rigorous management history traceable to a series of international agreements to conserve them that were signed at the turn of the 20th century. This focused management led to the development of what many consider to be the leading monitoring system for conterminously distributed species (Nichols et al. 1995). Population flyways or management units have been established to achieve consistent monitoring and management of waterfowl, mourning doves, and woodcock. Waterfowl harvest regulation decisions are informed by population monitoring data (Nichols et al. 2007), so it is not surprising that harvest trends mirror breeding population trends (Flather et al. 2013).

Migratory Waterfowl—Ducks, Geese, and Swans

Trends in the populations of migratory waterfowl, including ducks, geese, and swans, vary over time. Breeding duck population estimates in 2019 were 2 percent lower than in 1955 and 10 percent higher than the long-term (1955 to 2019) average (figure 10-5). After falling to record lows in 1990 (25 million birds), duck populations increased to almost 50 million birds in 2015, with a subsequent decrease to nearly 39 million birds by 2019, amounting to a 55-percent net increase since 1990. Breeding population trends among the 10 most common duck species have been variable. Relative to population objectives established in the 2018 North American Waterfowl Management Plan, 8 of the 10 most common duck species (species grouped for lesser and greater scaup, *Aythya marila* and *A. affinis*, respectively) have 2019 breeding populations that exceeded population objectives, but pintail (*Anas acuta*) and scaup (greater and lesser combined) fell below objectives by 43 and 29 percent, respectively (figure 10-5). Gadwall (*Mareca strepera*) and green-winged teal (*Anas carolinensis*) both exceeded population objectives by more than 50 percent. Mallard (*Anas platyrhynchos*), the most abundant duck (9.4 million in 2019), exceeded its long-term population objective by 22 percent.

Duck harvest numbers across the United States increased from 5.1 million in 1961 to 9.7 million in 2019 (figure 10-6). During that period, harvest rates increased to exceed 15 million in the 1970s, decreased to below 5 million in the late 1980s, peaked above 17 million in the late 1990s, and then declined gradually to the current rate. The national pattern of harvest lows during the late 1980s is repeated in each of four flyways

Figure 10-5. Trend in the duck population from 1955 to 2019 (top); the relation between current (2019) duck population estimates (CP) for the 10 principal duck species (species grouped for greater and lesser scaup) with reference to the population objectives (PO) specified in the 2018 North American Waterfowl Management Plan, measured as percent of objective (bottom).

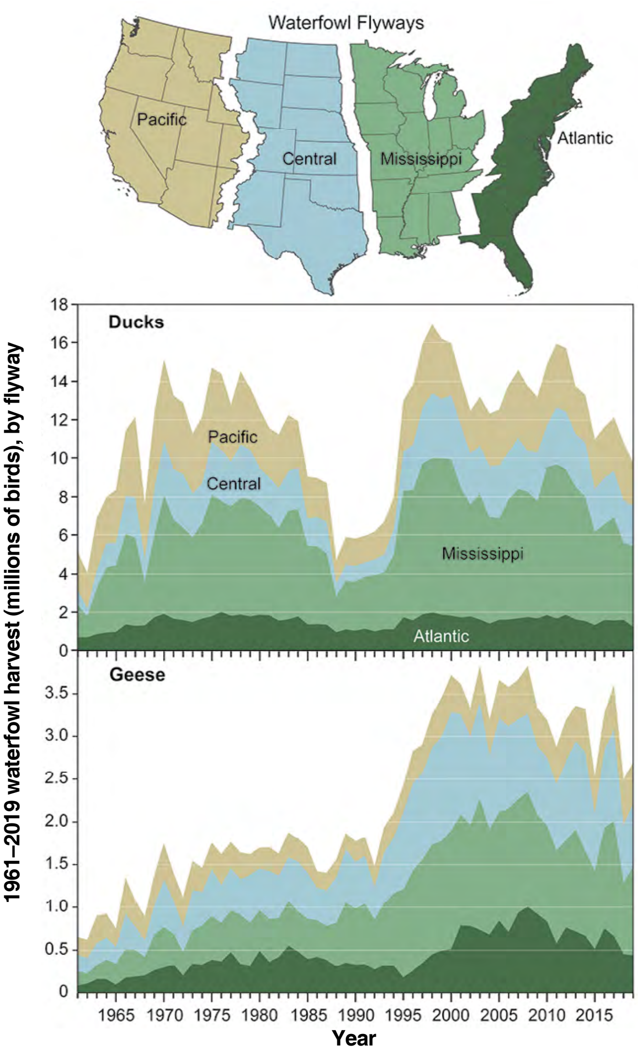


Source: U.S. Department of the Interior, U.S. Fish and Wildlife Service.

tracked by the FWS (i.e., Pacific, Central, Mississippi, and Atlantic) (figure 10-6). Similarly, goose harvest—including Canada geese (*Branta canadensis*), brant (*Branta bernicla*), snow geese (*Chen caerulescens*), Ross's geese (*Chen rossii*), emperor geese (*Anser canagicus*), and white-fronted geese (*Anser albifrons*)—increased slowly from 0.65 million in 1961 to 1.82 million in 1991, then increased substantially to 3.82 million in 2008. Since then, the harvest rate has been more variable, with a slightly decreasing trend through the 2019 harvest rate of 2.69 million birds (figure 10-6).

Swan populations (only tundra swans, *Cygnus columbianus*) are monitored by the FWS through surveys of many separate population segments of varying size. Population and harvest estimates are reported for Eastern versus Western U.S. regions. In 2019, the total swan population was estimated at 194,000 birds, nearly identical to the estimate of 193,000 birds from 1985. Fluctuations in populations ranged from a low of 158,000 in 1993 to a high of 270,000 in 2007 and 2008. Eastern and western populations exhibit similar total numbers and trends (figure 10-7). Swan harvest estimates have been variable, with increasing trends similar to populations from 1962 to 2019 (figure 10-7).

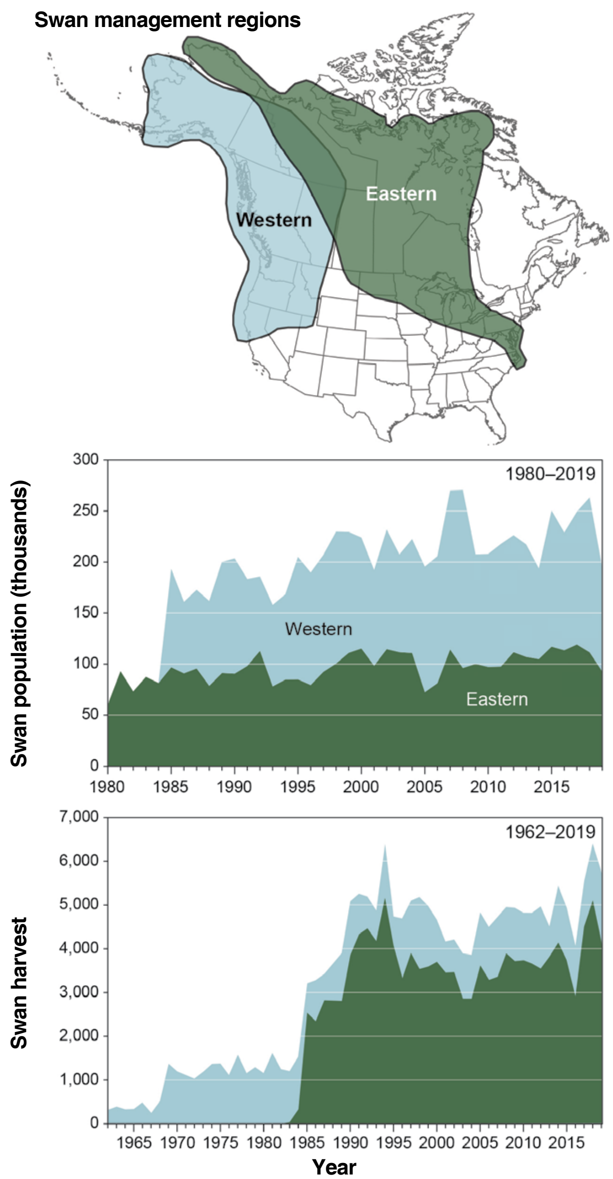
Figure 10-6. National trends across FWS administrative waterfowl flyway boundaries (top) for total duck harvest (middle) and total goose harvest (bottom), from 1961 to 2019.



FWS = U.S. Fish and Wildlife Service.

Source: U.S. Department of the Interior, U.S. Fish and Wildlife Service.

Figure 10-7. National trends for the western and eastern regions (top) for swan population from 1980 to 2019 (middle) and swan harvest from 1962 to 2019 (bottom).



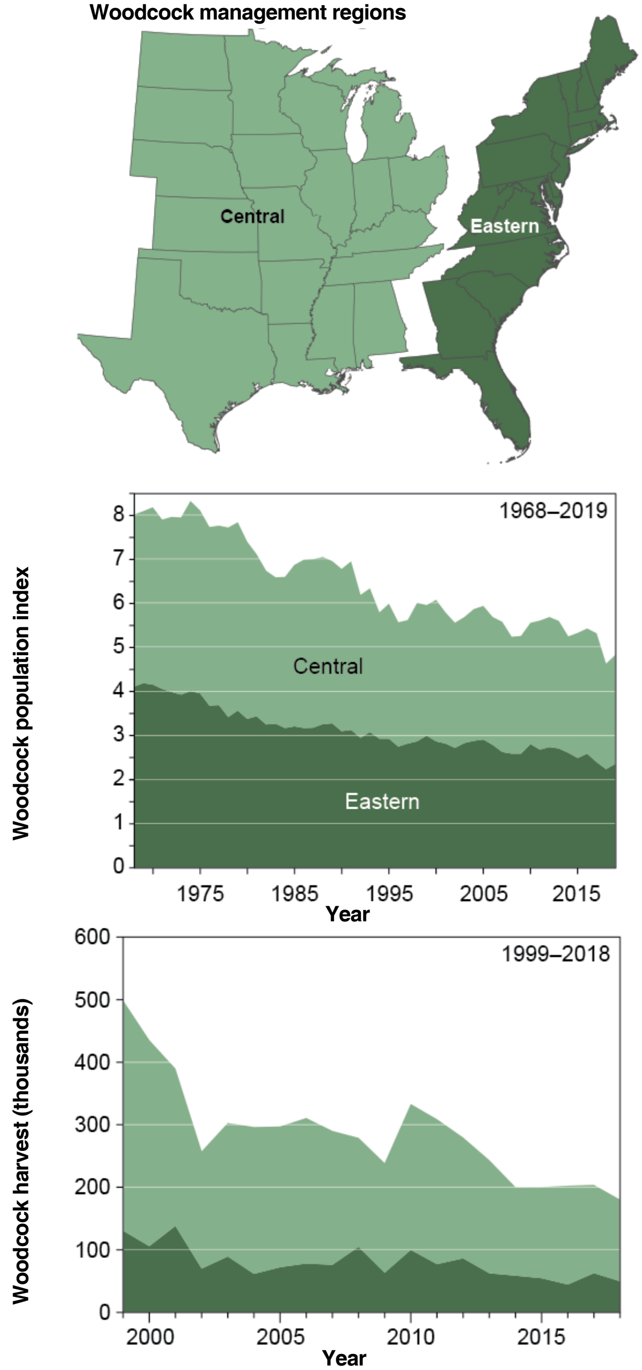
Source: U.S. Department of the Interior, U.S. Fish and Wildlife Service.

Webless Migratory Game Birds—American Woodcock and Mourning Dove

American woodcock populations and harvest have decreased over the past 50 years. American woodcock singing-ground surveys (SGS) have been conducted along permanent survey routes by the FWS each spring since 1968 (Seamans and Rau 2020), and populations are reported as an index of average numbers of birds detected per SGS route. Woodcock SGS indices have decreased consistently in both the Eastern and Central management regions (figure 10-8). On average, 4.0 woodcock were detected per SGS route in 1968, decreasing to 2.4 birds in 2019 (figure 10-8). Woodcock harvest rates have also decreased, from nearly 500,000 birds in 1999 to 180,000 birds in 2018, with harvests in the Eastern and Central management regions decreasing by similar proportions (figure 10-8). For the period during which both SGS and harvest rates are reported (1999 to 2018), the woodcock population index decreased from 3.0 to 2.3 birds per route.

Mourning doves have declined in abundance from 352 million doves in 2003 to 183 million doves in 2019, a 3.5-percent average annual rate of decline (figure 10-9) (contact chapter authors for extensive reference list of data sources). Average annual rates of change during this period were −3.3 percent in the Eastern, −0.5 percent in the Central, and −5.1 percent in the Western FWS management units (figure 10-9). Mourning dove harvests have also declined, from 24 million in 1999 to 10 million in 2019 (figure 10-9). For the period during which population estimates are reported (2003 to 2019), harvest rates changed at average annual rates of −3.5 percent in the Eastern, −2.0 percent in the Central, and −3.5 percent in the Western management units, for an overall decline of 2.8 percent per year.

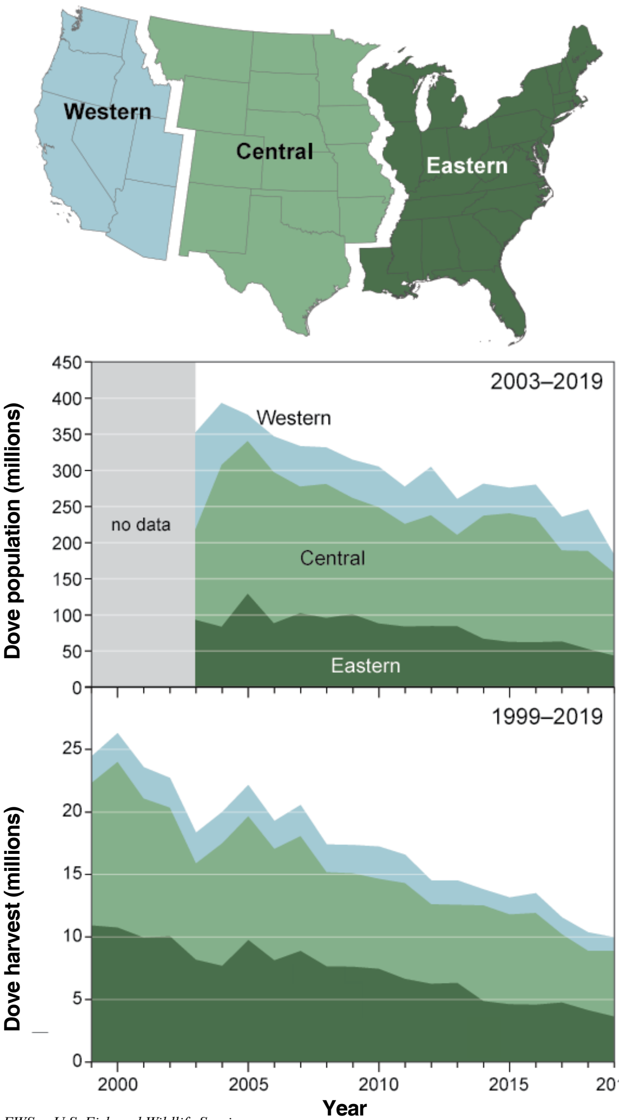
Figure 10-8. American woodcock FWS administrative management regions (top); population index from 1968 to 2019 (middle); and harvest trends from 1999 to 2018 (bottom).



FWS = U.S. Fish and Wildlife Service.

Source: singing-ground surveys (SGS) conducted by the U.S. Department of the Interior, U.S. Fish and Wildlife Service.

Figure 10-9. Mourning dove FWS administrative management units (top); population trends from 2003 to 2019 (middle); and harvest trends from 1999 to 2019 (bottom).



FWS = U.S. Fish and Wildlife Service.

Source: Population data from U.S. Department of the Interior, U.S. Fish and Wildlife Service.

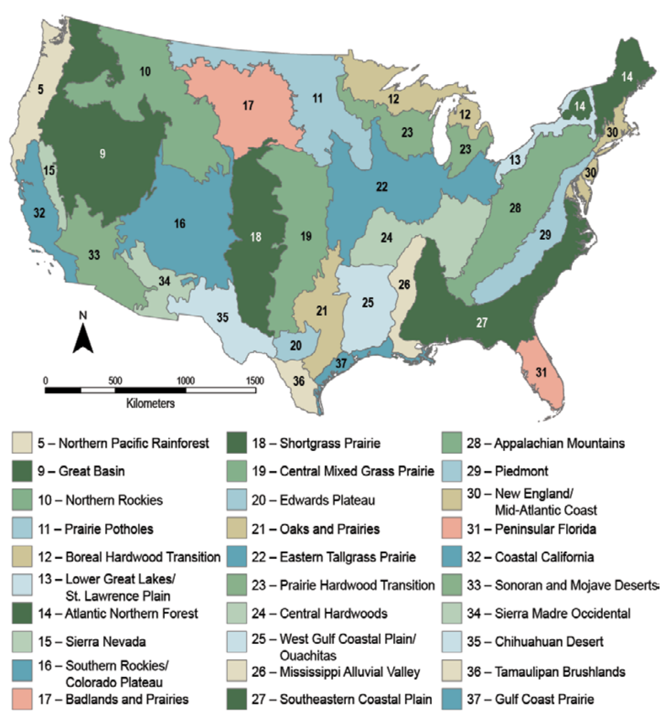
Breeding Birds

Wild bird populations have long been considered good indicators of environmental threats like landscape change because changes in habitat affect the abundance and diversity of bird species that occupy a particular region (Flather and Sauer 1996, Pidgeon et al. 2007). Given that North American bird populations have declined by 29 percent since 1970, a net loss of nearly 3 billion birds (Rosenberg et al. 2019), it is important to evaluate the status and trends among bird species throughout the country.

Reported breeding bird trends are based on the North American Breeding Bird Survey (BBS), an annual survey managed by the USGS that provides trends in the relative abundance of more than 400 bird species nationwide (Robbins et al. 1986). BBS population trends are summarized nationally and by individual Bird Conservation Regions (BCR; figure 10-10), which delineate ecologically distinct regions in North America with similar bird communities, habitats, and resource management issues. Thirty BCRs are located in the conterminous United States and are included in this report (https://nabci-us.org/resources/bird-conservation-regions/).

To obtain more detailed understanding of how birds respond to changes in their environments, we grouped bird species by breeding habitat type (grassland, successional-scrub, wetland, woodland), nest type and location (cavity, ground-low, midstory canopy, open cup), and migration status (neotropical, permanent, short distance). Details on data sources and methods are reviewed in Flather et al. (2013). Trends in abundance are reported for long-term (1966 to 2019) and short-term (1993 to 2019) time periods. Direction and statistical significance of population trends are labeled as having significant increase, nonsignificant increase, nonsignificant decrease, or significant decrease, based on a hierarchical modeling approach (Sauer and Link 2002) that provides a convenient framework for summarizing population change among regions. Long-term population trends from breeding bird surveys show declines in most categories of birds defined by habitat type.

Figure 10-10. Bird conservation regions of the United States.



Source: North American Bird Conservation Initiative (https://nabci-us.org/resources/bird-conservation-regions/).

Long-Term Abundance Trends

From 1966 to 2015, statistically significant decreases in bird populations exceeded significant increases for species in grassland and successional-scrub habitats; species that build ground-low, midstory, and open-cup nests; and species with neotropical or short-distance migration patterns (figure 10-11). Grassland bird species had the greatest declines in long-term trends, with 54 percent of species showing significant decreases while only 4 percent had significant increases. The remaining 42 percent of grassland birds experienced population changes that were not statistically significant. The cavity nesting category contained the largest percentage of species with statistically significant increasing populations (37 percent), but this was mostly offset by significantly decreasing populations (29 percent). Other categories where significantly increasing populations exceeded decreasing populations included wetland habitat users and permanent residents.

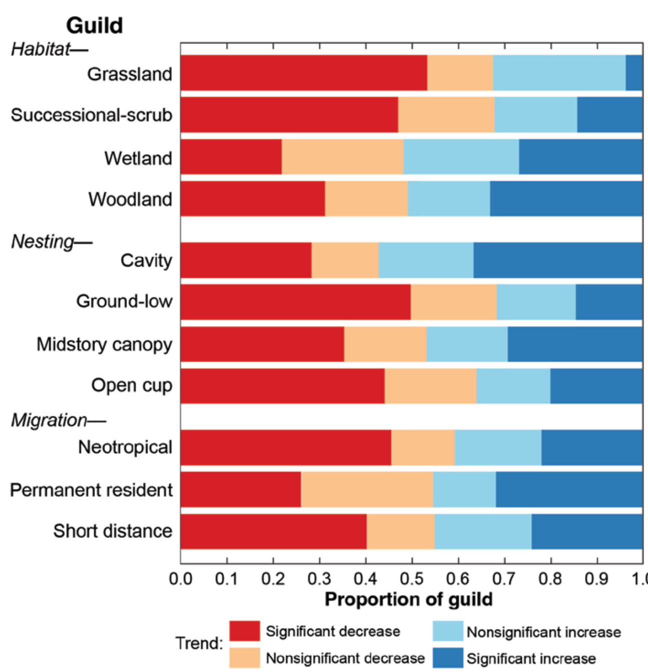
Short-Term Abundance Trends

Patterns of species populations over the 2005 to 2015 period mirror longer term trends; however, smaller proportions of species have statistically significant increasing or decreasing populations (figure 10-12). This may be partially explained by smaller sample sizes available during shorter periods. Trends for midstory canopy nesters and neotropical migrants differed from longer term trends; these groups had more species with statistically significant increasing populations in the short term (figure 10-12).

Trend Comparisons

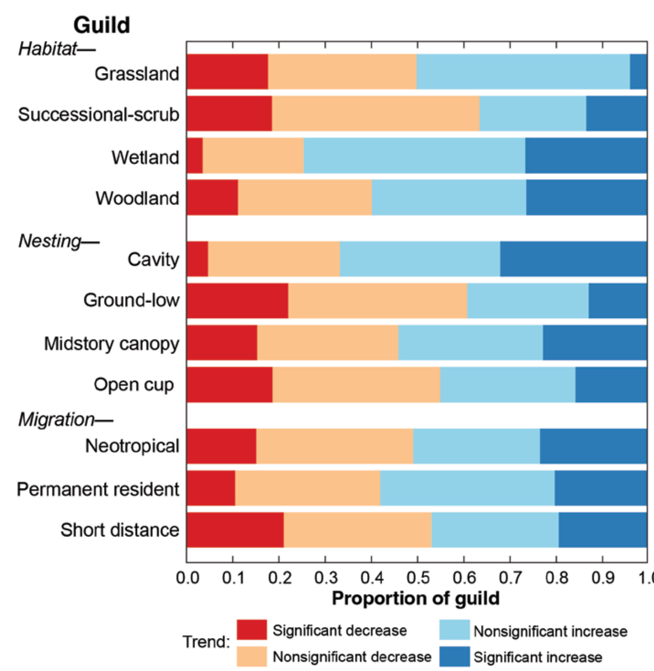
Across all the habitat affinity groupings, all BCRs had at least one bird species that showed statistically significant population gains over both the long term (1966 to 2019) and the short term (1993 to 2019) (see “All” in figure 10-13). When examining individual habitat affinity groups, patterns of increasing or decreasing populations varied. Grassland species are almost universally in decline over both long- and short-term assessments (figure 10-13). Successional-scrub-associated species in the North Region and Southeast Subregion also experienced population declines over both time periods. Some increases in wetland species in the north-central portion of the United States

Figure 10-11. Long-term increases and decreases in proportions of native bird populations in the conterminous United States, 1966 to 2015. Long-term proportion of native bird species with decreasing populations shown in red and increasing populations shown in blue. Changes that are statistically significant appear in a dark shade; nonsignificant changes appear in a light shade. Species populations are analyzed based on major habitat affinity, nesting position, and migratory status.



Source: USGS Breeding Bird Survey.

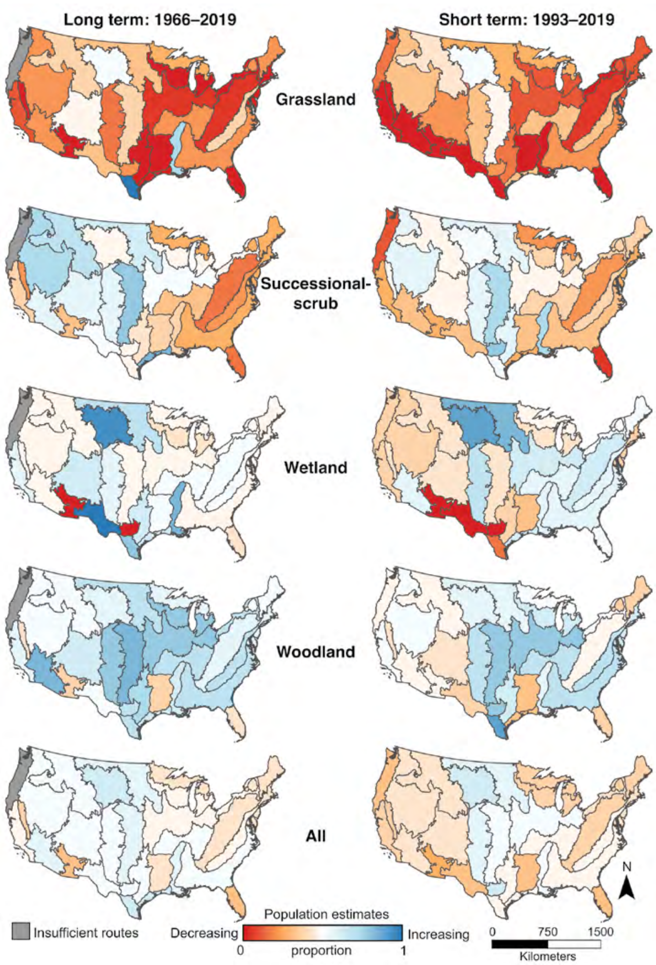
Figure 10-12. Short-term increases and decreases in proportions of native bird populations in the conterminous United States, 2005 to 2015. Short-term proportion of native bird species with decreasing populations shown in red and increasing populations shown in blue. Changes that are statistically significant appear in a dark shade; nonsignificant changes appear in a light shade. Species populations are analyzed based on major habitat affinity, nesting position, and migratory status.



Source: USGS Breeding Bird Survey.

are noted (figure 10-13). Wetland species in the Texas borderlands region experienced significantly decreasing populations in the short term, alongside increasing populations over the long term (figure 10-13).

Figure 10-13. Decreasing or increasing native bird populations in the conterminous United States, by Bird Conservation Region. Proportion of native bird species with decreasing (red) or increasing (blue) populations estimates, by major habitat affinity, over the long term (1966 to 2019; left) and short term (1993 to 2019; right). Gray areas denote where there were insufficient routes for observing species.



Source: USGS Breeding Bird Survey and North American Bird Conservation Initiative.

Imperiled Animal Species

- ❖ Concentrations of ESA-listed birds are documented in Peninsular Florida and Hawaii, whereas listed mammals and fish are widely distributed, with regional concentrations across multiple areas.
- ❖ Regionally constrained ESA-listed distributions were identified for amphibians (Coastal California), crustaceans (Coastal Mountains and Dry Steppe), mollusks (Upper Midwest, Southern Appalachia, and Interior Highland Hills and Plateau), and reptiles (Gulf Coast and Peninsular Florida).

The protection of native biota to avoid decline and the conservation of species already in decline are both primary goals of State and Federal agencies. This important work addresses changes in habitat and environmental conditions resulting from a variety of causes that affect some of our most iconic and culturally important species (see the sidebar Pacific Trout in the Conterminous United States). In this section, we describe patterns in the distribution of federally identified imperiled species listed under the ESA because their conservation status is linked to applied management actions within the United States. We also present hotspots for taxonomic groups and describe taxa identified as Species of Greatest Conservation Need from across the set of federally mandated State Wildlife Action Plans, which guide biodiversity management and conservation actions at the State level.

Federally Listed Imperiled Species

Federal listing demonstrates both empirical evidence of species-specific long-term population-scale trends, as well as political will in support of listing decisions. We focus on ESA-listed species, specifically species listed as federally endangered, threatened, proposed endangered or threatened, candidate, species of concern, or listed threatened because of similarity in appearance to another species (definition of these species codes can be found at: https://www.fws.gov/endangered/about/listing-status-codes.html). We refer to this broad assemblage of species as imperiled throughout this chapter. Species assigned G1 or G2 conservation status by NatureServe are not included in this analysis because they are not federally listed under the ESA, but these species are included in the sidebar Forest-Associated Species at Risk of Decline.

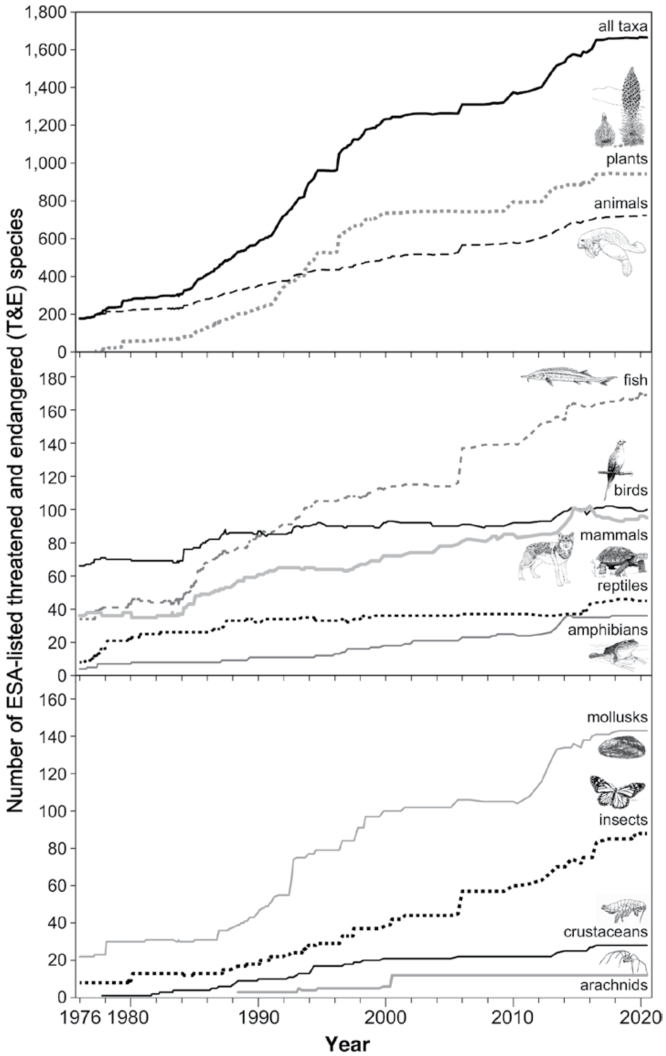
Distributions of ESA-listed taxa vary geographically, with some portions of the country containing higher numbers of listed species than others. Hawaii has the largest number of listed species (499; mostly flowering plants), nearly double the second highest State, California (286). States with the fewest listed species include Washington, DC (3), Vermont (6), North Dakota (8), and Alaska (8) (https://ecos.fws.gov/ecp/report/species-listings-by-state-totals?statusCategory=Listed). For this assessment, species distributions across the United States were mapped onto an equal-area grid (250 square miles [647 km^2]) to eliminate area effects of State or county size (figure 10-14). Imperiled birds are widely distributed, with notable hotspots in Hawaii and Peninsular Florida (figure 10-14). Imperiled mammal and fish species are also widely distributed, but with multiple regional areas of concentration (figure 10-14). More regionally constrained distributions are evident for imperiled amphibians (Coastal California), crustaceans (Coastal Mountains and Dry Steppe), mollusks (Upper Midwest, Southern Appalachia, and Interior Highland Hills and Plateau), and reptiles (Gulf Coast and Peninsular Florida) (figure 10-14).

The total number of ESA-listed species are tracked by the FWS, Environmental Conservation Online System (https://ecos.fws.gov/ecp/report/boxscore). We plotted this information from July 1976 through October 2021 and saw a steady rise in the overall number of federally listed imperiled species, with sharp increases in aquatic taxa (e.g., fish, mussels) and insects (figure 10-15). With few species being delisted, current patterns of distribution reflect cumulative counts of species that have been federally listed over time.

Figure 10-14. Geographic distributions of plant, mollusk, coral, bird, crustacean, insect, arachnid, mammal, fish, amphibian, and reptile species formally listed under the Endangered Species Act as endangered, threatened, proposed endangered or threatened, candidate, species of concern, or listed threatened because of similarity in appearance to another species. Alaska and Hawaii are displayed at a different scale for presentation purposes.

Source: NatureServe.

Figure 10-15. Cumulative number of species listed as endangered or threatened under the Endangered Species Act (accounting for delistings) from 1 July 1976 through 4 October 2021 for plants and animals (top), vertebrate groups (middle), and invertebrate groups (bottom). Increases in a given year are additional species added, making the total number of species in a given year cumulative over time.



ESA = Endangered Species Act.

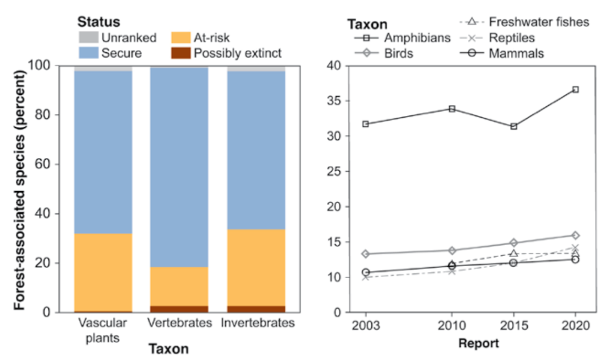
Source: FWS Environmental Conservation Online System (https://ecos.fws.gov/ecp/report/boxscore).

Forest-Associated Species at Risk of Decline

Forest-associated species are tracked by NatureServe through a habitat matrix domain table developed for each species (NatureServe Central Databases, metadata on file with Michael S. Knowles, Rocky Mountain Research Station). We examined forest-associated species that were classified by NatureServe with conservation status G1 (critically imperiled), G2 (imperiled), or G3 (vulnerable). This list includes, but is not limited to, federally listed ESA species. Among forest-associated species of vascular plants, vertebrates, and select invertebrates, 111 (~1 percent) were determined to be presumed or possibly extinct; 5,328 (31 percent) were determined to be at risk of extinction (includes species classified as critically imperiled, imperiled, or vulnerable to extinction); and 12,025 (69 percent) were determined to be apparently secure or were unranked.

At-risk species associated with forest habitats are concentrated geographically in Hawaii, the arid montane habitats of the Southwest, the chaparral and sage habitats of Mediterranean California, and in the coastal and inland forests of northern and central California. The number of possibly extinct and at-risk species is proportionately greatest among vascular plants (32 percent) and select invertebrates (34 percent)—nearly double the percentage observed among vertebrates (19 percent) (figure 10-16, left). Among forest-associated vertebrates, the greatest proportion of possibly extinct and at-risk species is found among amphibians (37 percent). Birds (16 percent), reptiles (14 percent), freshwater fishes (13 percent), and mammals (12 percent) show substantially lower percentages of forest-associated species considered to be at risk (figure 10-16, right).

Figure 10-16. The percent of vascular plant, vertebrate, and select invertebrate species associated with forest habitats determined to be possibly extinct, at risk of extinction, secure, or unranked (left). Change in the percent of forest-associated amphibian, bird, freshwater fish, reptile, and mammal species classified as at-risk using NatureServe global conservation status (G1, G2, G3) as described in the National Report on Sustainable Forests from 2003, 2010, 2015, and 2020 (right).



Source: NatureServe and multiple sustainability reports.

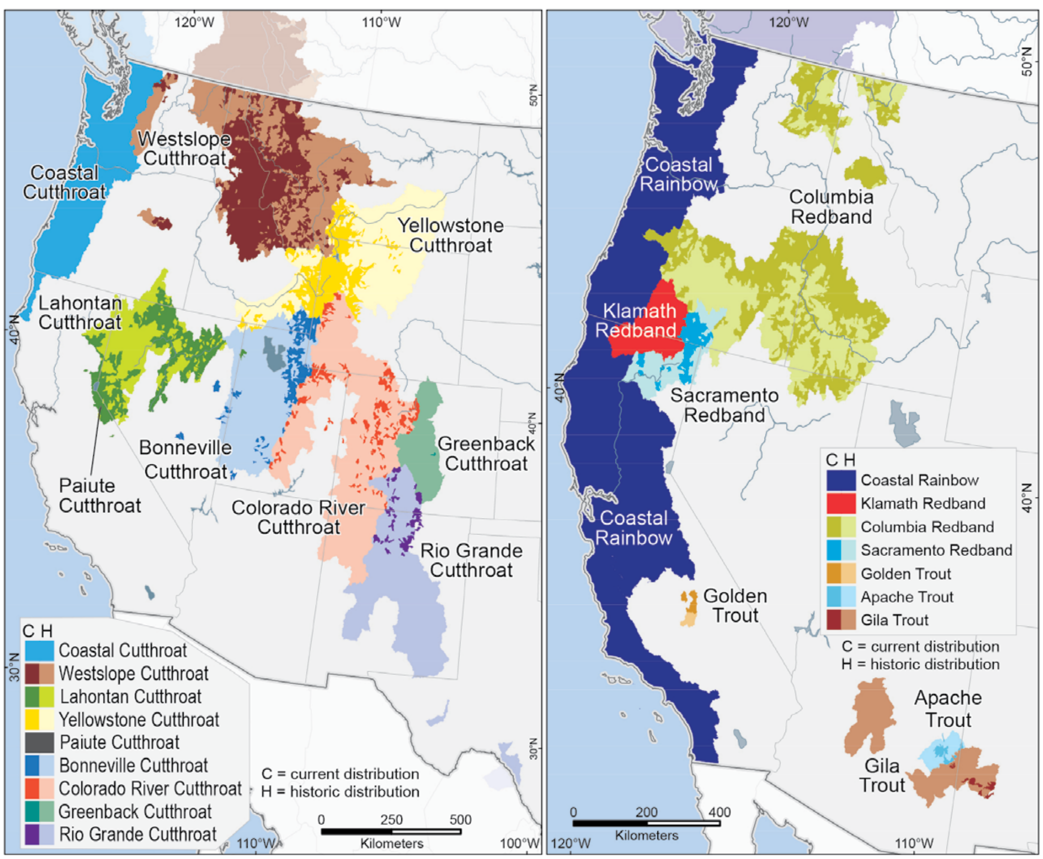
Pacific Trout in the Conterminous United States

Pacific trout (*Oncorhynchus* spp.) are ecologically, socioeconomically, and culturally important. Substantial declines in abundance and contractions in distribution across Pacific trout species and subspecies have led to substantial research and conservation efforts (figure 10-17). Population declines of at least two-thirds from historical levels for some populations have led to elevated Federal protection (under the ESA) and by State management agencies in all or part of their range. Two cutthroat trout subspecies, the Alvord cutthroat trout (*O. clarkii alvordensis*) and the yellowfin cutthroat trout (*O. clarkii macdonaldi*), are considered extinct.

Human influences leading to declines in Pacific trout began with Euro-American colonization of North America (Penaluna et al. 2016). The decline of Pacific trout over recent decades and, in some cases, the last century, reflects the challenges of balancing societal values with natural resources and wild places under a changing climate. Legacies of past overfishing and land-use activities have led to habitat degradation (e.g., from forest harvest, agriculture, cattle grazing, mining, migration barriers, nonnative species, climate change, land development, water withdrawal, etc.). Fortunately, Pacific trout have evolved characteristics including genetic, phenotypic, and life-history diversity, along with long-distance migration to be resilient to large-scale natural disturbances (e.g., wildfire, flood). These characteristics may be the keys to their future persistence. Scientists and managers can work together to consider social pressures that increase vulnerability of Pacific trout and find opportunities to restore species diversity through flexible management.

Brooke Penaluna, USDA Forest Service, Pacific Northwest Research Station

Figure 10-17. Historical and current distributions of Pacific trout in the conterminous United States, with distributions of *Oncorhynchus mykiss* spp. and other Pacific trout (left), and *O. clarkii* spp. (right). Historical distributions (faded colors), represent areas that are no longer occupied.



Source: Modified from Penaluna et al. 2016.

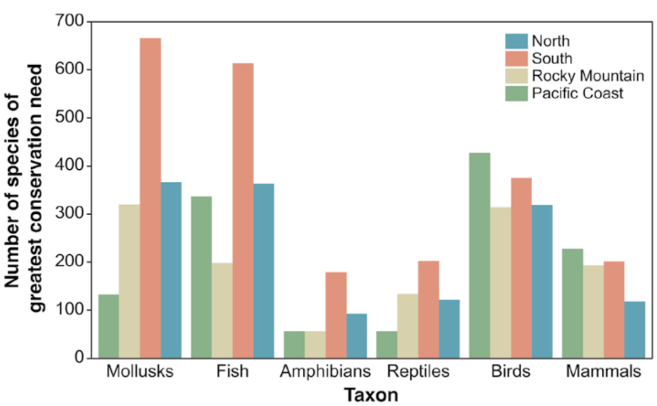
State-Level Species of Concern

In addition to Federal agencies, individual States and Tribal governments also conduct wildlife and fish management conservation. Maintaining an approved State Wildlife Action Plan (SWAP; https://www.fishwildlife.org/afwa-informs/state-wildlife-action-plans) is a prerequisite to receiving FWS State and Tribal Wildlife Grant Program funding. All States completed initial SWAPs in 2005 and updated SWAPs in 2015. Each SWAP identifies Species of Greatest Conservation Need (SGCN) within a State—many of which are not federally listed—as well as their key habitats and threats, and actions needed to conserve them. To illustrate the diversity of species of importance to each State, we report the numbers of SGCNs by taxonomic group, State, and RPA region, based on a USGS compilation of SWAP data.

Not all States considered all taxonomic groups, nor did they consider all species within taxonomic groups when designating SGCN. For example, few States included plant species. Therefore, we present information for amphibians, fish, mollusks, reptiles, birds, and mammals for more consistent comparisons among States.

A compilation of SWAPs across all 50 States and 5 territories revealed 4,723 SGCN in 2005 and 4,484 SGCN in 2015, resulting in 5,525 distinct SGCN. The 2015 SWAP taxonomic breakdown included 289 amphibians, 865 birds, 1,180 fish, 518 mammals, 1,253 mollusks, and 379 reptiles. The RPA South Region had nearly twice as many SGCN compared to each of the other three major RPA regions (figure 10-18). The South Region also had the most SGCN for amphibians, fish, mollusks, and reptiles; bird and mammal SGCNs were most numerous in the Pacific Coast Region (figure 10-18).

Figure 10-18. Count of species of greatest conservation need listed in State wildlife action plans by RPA region, 2015.



Data collected by U.S. Fish and Wildlife Service and compiled by U.S. Geological Survey.

Threats to Biodiversity

- ❖ The aggregate index of land use stress shows the stark difference in pressure in eastern compared with western watersheds. Eastern watersheds face compounded pressures from mining, energy development, nitrogen deposition, and roads, whereas high-risk watersheds in the Western United States face pressure mainly from development in large metropolitan regions.
- ❖ Although the Pacific Coast and Rocky Mountain Regions exhibit low levels of aggregate land use stress, pockets of high stress occur in the human population and agricultural centers of Washington, Idaho, and California, and areas of the Rocky Mountains that are experiencing rapid population growth.
- ❖ Areas of high climate stress were found in all RPA regions. A majority of our climate change models project future high climate stress in the mountains of the Pacific Coast, Rocky Mountain, and South Regions, as well as in large areas from New York to Maine in the North Region. Lower elevation lands in southern New Mexico, southern Arizona, Oklahoma, and Texas are also projected to experience high climate stress.
- ❖ USDA Forest Service and U.S. National Park Service lands are projected to experience higher future climate stress than all other lands, likely due to their location in vulnerable higher elevation areas. These results suggest that the ability of these lands to serve as climate refugia for native biota and ecosystems may be limited.
- ❖ Overlays of climate stress and terrestrial or aquatic biodiversity indicate that places of high climate stress and high biodiversity are commonly found in the North and South RPA Regions, although pockets of high stress and higher biodiversity are also found in the Pacific Coast Region.

Native species have experienced significant losses in habitat owing to a wide variety of threats derived from human-driven land use and management (Foley et al. 2005) that will likely be compounded in the future as the stress on native ecosystems increases under a changing climate (Manytka-Pringle et al. 2015). In this section, we describe ongoing stressors affecting native ecosystems, including invasive species, pathogens, and land use alteration—with a focus on urban areas, agriculture, mining, pipelines, and energy development. We also include a section examining ecosystem stress related to climate projections under future scenarios. Finally, we overlay existing land use stress with modeled climate stress and consider climate stress relative to distributions of native terrestrial and aquatic biota. These comparisons highlight the different stressors currently affecting specific regions, and places of future concern, particularly considering biodiversity distributions.

Biological Drivers of Change

Invasive species and pathogens are significant drivers of change in biodiversity across the United States and are anticipated to increase in influence as individual species respond to anthropogenic drivers of land use and climate change. Neither of these topics have been addressed in prior RPA reports. In this report, we introduce these two drivers of ecological change, and describe some of the mechanisms through which they alter ecosystems. We did not model either invasive species spread or pathogens but acknowledge that such efforts would be highly informative for local, regional, or national management planning and implementation.

Invasive Species

Invasive species in the United States are highly diverse and represent every taxon. More than 6,500 invasive species have been documented as currently established (see USGS, https://www.usgs.gov/programs/invasive-species-program; OTA 1993), and each species' level of impact is as varied as the organism. Invasive species are defined here as plentiful, nonnative organisms that negatively affect the area they inhabit (Beck et al. 2008, Colautti and MacIsaac 2004). Invasive individuals and species compete for resources and predate native species (Doherty et al. 2016, Doody et al. 2009, Dugger et al. 2011, Salo et al. 2007), and may also interbreed and hybridize with related native organisms (Huxel 1999, Muhlfeld et al. 2017). Invasive species contribute to habitat change and destruction, which can lead to changes in trophic structure or disturbance regimes (Johnson et al. 2009, Sousa et al. 2009, Mack and D'Antonio 1998, Vitousek 1990). In the most severe cases, introduced

Herpetofauna Diversity and Threats

Aquatic-dependent herpetofauna enrich freshwater, riparian, and moisture-rich ecosystems. There are more than 300 amphibian species in the United States, with 70 percent being endemic. Notably, the United States is the global hotspot for salamander biodiversity (198 species), with Appalachian and Pacific Northwest forests having particularly unique communities. Among the world's largest salamanders are the awe-inspiring hellbenders (*Cryptobranchus alleganiensis*) (to ~29 inches) and common mudpuppy (*Necturus maculosus*) (to ~17 inches) of Eastern U.S. waters, and the northwest stream-breeding Pacific giant salamanders (*Dicamptodon* spp.), the largest terrestrial-occurring salamander (to ~12 inches). Of the more than 300 U.S. reptiles, freshwater-dependent species include turtles, snakes, and alligators. The United States is second in the world in freshwater turtle biodiversity, with most of its 57 species occurring in the Southeast. Both amphibians and reptiles are centrally positioned as both predators and prey in food webs, being critical cogs of complex trophic systems, cycling energy and nutrients between water and land. Some amphibians play a role in carbon sequestration from the atmosphere (Best and Welsh 2014, Semlitsch et al. 2014), and both amphibians and reptiles have been pivotal for biomedical research. Their ecosystem services span a variety of aesthetic, cultural, educational, recreational, food, medicine, and other product categories.

Herpetofauna epitomize the ongoing sixth mass-extinction event on Earth (Wake and Vredenburg 2008), with 40 percent of world amphibians (IUCN 2020a) and over half of world turtles and tortoises (Stanford et al. 2020) threatened with extinction. Although U.S. herpetofauna are faring better, about 27 percent of freshwater turtles, 21 percent of salamanders, and 13 percent of frogs and toads are threatened (IUCN 2020b). Although habitat loss is pervasive, diseases and climate change are emerging threats that are gaining conservation concern for management action (Bletz et al. 2022, Olson and Pilliod 2022, Wogan et al. 2022). Snake fungal disease, snake lung parasites, turtle shell disease (fungal pathogen), turtle aural abscesses, turtle and amphibian ranavirus infections, amphibian chytridiomycosis, and trematode infections are among leading concerns (NWDC 2021, PARC 2021). Forestalling human-mediated disease transmission is a top biosecurity priority, especially for aquatic pathogens that are also invasive species such as the chytrid fungi (Julian et al. 2020; NWCG 2017, 2020; Olson 2022). For aquatic herpetofauna in the United States, climate change is projected to alter amphibian, reptile, and pathogen habitat macro- and micro-refugia, generally moving optimal conditions northward and higher in elevation, raising concerns for rare species already threatened by habitat loss and fragmentation, and requiring proactive retention of predicted habitat strongholds and corridors for dispersal (Olson 2022).

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species can lead to local extirpation or extinction of native species (Clavero and Garcia-Berthou 2005, Huxel 1999): Impacts of invasive species were important in 68 percent of the extinctions of North American freshwater fishes in the past 100 years (Miller et al. 1989).

The damage invasive species inflict on economic and ecosystem services humans use is also extensive (Born et al. 2005, Charles and Dukes 2008, Poland et al. 2021). The monetary cost of invasive species management is estimated at approximately $120 billion each year (Pimentel et al. 2005), with the crop damage from European starlings alone estimated at $800 million in the year 2000 (Linz et al. 2007). Understanding of invasive species is both incomplete and important for management of natural systems of the United States (Rahel et al. 2008). Invasive species are anticipated to increase in the future, as will their compounded interactions with climate change, increased human pressures on natural systems, and other forces (Muhlfeld et al. 2014, Rahel and Olden 2008).

Pathogens

Pathogens are a serious risk to fish, game, and wildlife in the Nation's forests (Wobeser 2007, Woo et al. 2006). In addition to direct impacts on individuals and species, disease can interact with human-caused environmental changes and alter ecosystems (Brearley et al. 2013, Daszak et al. 2001, Hilker and Schmitz 2008, Tompkins et al. 2011). Disease pathogens are defined here as any fungal, bacterial, or viral microorganism causing dysfunction in structure or function of the body (Balloux and van Dorp 2017, Scholthof 2007) as well as trematode parasites that can cause limb malformations in anurans (Johnson et al. 2002).

There are a variety of ways that pathogens interact with wildlife communities. Endemic or preexisting diseases may change in rate or intensity (Price et al. 2019, Rachowicz et al. 2005). Diseases that have not previously been seen in a population or species may arrive via transmission from another group, or by evolving into a new pathogen (Daszak et al. 2000, Kock et al. 2010, Rachowicz et al. 2005). These new pathogens vary in the rate of transmission and spread within and between wildlife populations (Gallana et al. 2013, Van Hemert et al. 2014, see the sidebar Herpetofauna Diversity and Threats). These patterns are influenced by human activities such as land management and the interactions of domesticated and wild animals (Bradley and Altizer 2007, Brearley et al. 2013, Daszak et al. 2001) because of the potential for disease transmission between these groups (Daszak et al. 2000, Miller et al. 2017, Pedersen et al. 2007). The existence of multiple hosts, parasites, and life stages, however, can complicate transmission (Rachowicz et al. 2005, Van Hemert et al. 2014).

The effects of disease on wildlife can range from mild to catastrophic. Although some individuals may reproduce and live long lives with few symptoms of a disease, these carriers can be responsible for extensive disease transmission (Artois et al. 2009, Garwood et al. 2020). On the other end of the spectrum, some pathogens have led to entire species becoming endangered or even extinct (Pedersen et al. 2007, Skerratt et al. 2007, Smith et al. 2006). For example, White Nose Syndrome, caused by the fungal pathogen *Pseudogymnoascus destructans*, has decimated populations of bats in the conterminous United States (Cheng et al. 2021, Hoyt et al. 2021). Severe disease outbreaks may influence the workings of entire ecosystems or influence disturbance regimes (Hilker and Schmitz 2008, Tompkins et al. 2011).

The severity of disease is predicted to increase in the future as introduced species bring novel pathogens into native populations, climate change influences species ranges (including those of pathogens), and human alterations to landscapes increase disease transmission (Brearley et al. 2013, Hemert et al. 2014, Price et al. 2019, Wilkinson et al. 2018, Young et al. 2017). The wildland-urban interface and other areas of increased interaction between humans, domestic animals, and wildlife are especially likely to lead to increased transmission of disease (Bradley and Altizer 2007, Deem et al. 2001, Miller et al. 2017, Wilkinson et al. 2018). Given these compounding factors, research is currently lacking on the full complexity of these interactions (Ryser-Degiorgis 2013, Stallknecht 2007) that could help managers prepare for projected increases in outbreaks and severity (Buttke et al. 2021).

Anthropogenic Drivers of Change

Connection and interconnection within and among habitats are crucial for the long-term persistence of native biota. Native species are adapted to the disturbance processes most prominent on a landscape (such as wildfire), assuming they occur within the natural range of variability (Johnstone et al. 2016). Disturbances associated with human land use and development (including wildfire suppression), however, have extensively altered the availability and patterns of habitats at landscape scales, leading to extirpation of some species. Vulnerability to extinction currently exists for hundreds of species, far beyond those listed under the ESA (Harris et al. 2012). The existing landscape will likely be further stressed in complex ways as the effects of climate change provide an additional layer of stress on native ecosystems (Mantyka-Pringle et al. 2015). This section provides modeling work addressing the effects of land use and climate change on native biodiversity, individually and together.

Land Use

Human use and development of landscapes directly affect both terrestrial and aquatic biodiversity. Drivers of biodiversity loss associated with human activities include long-term land cover change, degraded and homogenized wildlife habitats, and the creation of pathways for introduction of nonnative species (Allan 2004, Flather et al. 1998, Howard et al. 2020, Regetz 2003, Wilcove et al. 1998). To assess where future development and expansion may cause increasing stress on native ecosystems, we explored changing patterns of three key themes related to land use change: human population growth and urban development; agriculture; and energy development and mining.

For each of the themes, we created stress indices for HUC 10 watersheds throughout the conterminous United States using principal component analysis (PCA) of variables shown in table 10-2, using the *prcomp* function in the *stats* package in R (R Core Team 2021). PCA is a data-reduction technique that simplifies datasets with many, sometimes-correlated variables, into fewer dimensions (called principal components) to draw out trends and patterns—in this case, to more clearly show variation in the combination of stressors among watersheds. We performed PCA on variables associated with each of the themes individually and for all the variables together (the aggregate index), providing stress indices for each HUC 10 watershed, shown in figure 10-19. Results allow more refined discussion of watershed threats, examining the major drivers and how they vary by region.

Population Growth and Urban Development

The U.S. population is projected to grow between 24 and 44 percent from 2010 through 2070 under intermediate scenarios (Shared Socioeconomic Pathways 1, 2, and 4; Wear and Prestemon 2019). Although much of that growth is expected to be centered on metropolitan regions, the fastest areas of development are on the urban fringe, as large metropolitan regions expand their exurban and wildland interface areas (see the Land Resources Chapter, also Beale and Johnson 1998, Hjerpe et al. 2020, Kirk et al. 2012, Radeloff et al. 2018). Such expansion threatens native ecosystems with habitat fragmentation and decreases in native species diversity. Indirect effects of development include increased amounts of impervious surfaces, roads, noise, and light. Impervious surfaces and roads increase sedimentation and pollutant runoff into streams and modify regional hydrology. Roads also lead to direct mortality of animals, disrupt dispersal and migration, and serve as pathways for invasive species (Bennett 2017, Regetz 2003, Siemers and Schaub 2011). Anthropogenic noise and light pollution have also been linked to declines in wildlife and alterations in behavior (Barber et al. 2010, Carral-Murrieta et al. 2020, Kerth and Melber 2009, Shannon et al. 2016, Siemers and Schaub 2011).

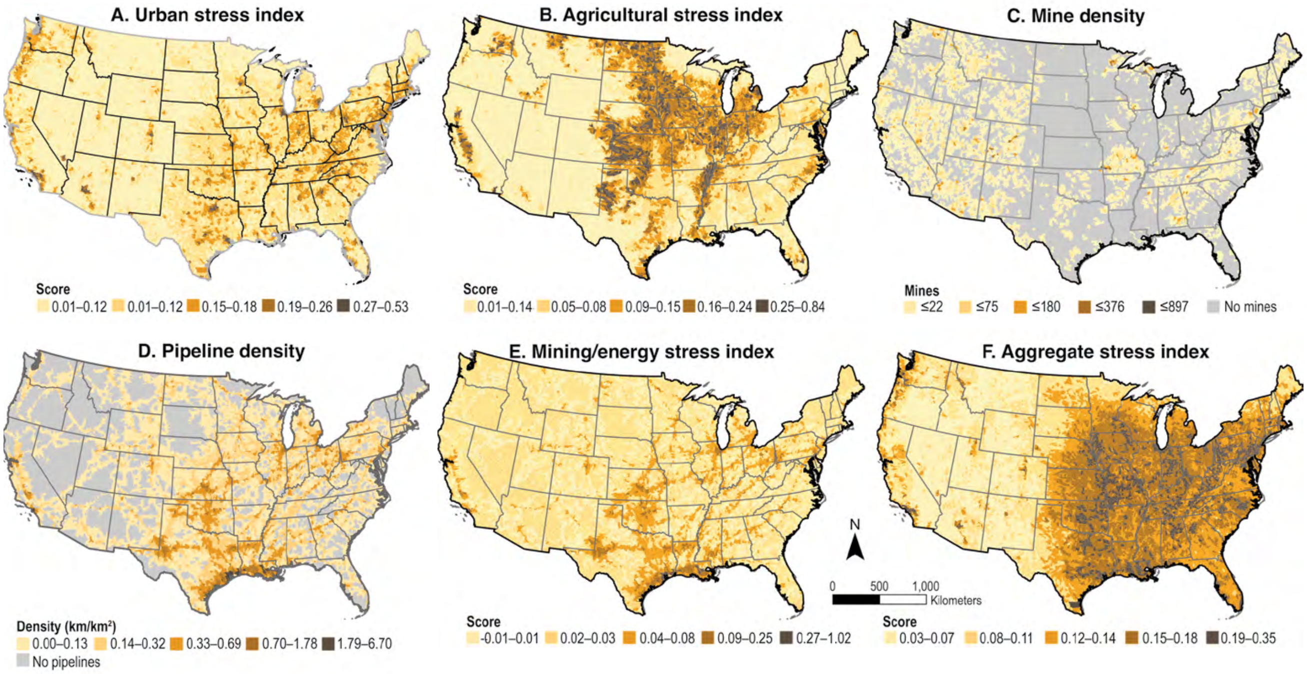
The stress index used for population growth and urban development focuses on housing density, population, and roads (figure 10-19a). PCA for these variables reduced the data to three principal components. The first principal component, accounting for 47 percent of the variation among watersheds, is heavily weighted toward population density and roads, identifying watersheds near cities and large metropolitan regions. Watersheds affected by human activity outside of cities, namely roads in steep areas and crossing streams, explain 18 percent of the variation. Roads fragment habitat by creating barriers to aquatic organism passage, and lead to increased sedimentation of waterways. These high-stress watersheds occur frequently in the southern Great Plains, central Arizona, and mountainous areas across the United States, with particularly high stress in the Appalachians stretching from western North Carolina to Pennsylvania.

Table 10-2. Variables and data sources used in stress indices.

Variables	Data sources
	Urban development and population growth
Developed land use	30-m NLCD 2011 Land Cover (2011 Edition, amended 2014); National Geospatial Data Asset Land Use Land Cover
Housing density (population per km^2) **Population change** **Population density**	SILVIS Lab, Dept. of Forest & Wildlife Ecology, University of Wisconsin-Madison (2017)
Road density **Road stream crossings** **Roads on steep slopes**	U.S. Census TIGER 2015 Roads National Geodatabase; USGS 2018 Quarterly National Hydrography Dataset high-resolution (1-to-24,000 or better) stream coverage
	Agriculture
Cultivation on gentle slopes	30-m NLCD 2011 Land Cover (2011 Edition, amended 2014); National Geospatial Data Asset Land Use Land Cover USGS 7.5-minute (~30-m) National Elevation Dataset
Cultivation on highly erosive soils	National Cooperative Soil Survey Web Soil Survey
Mean deposition of N, dry	~4-km National Atmospheric Deposition Program (2018). Total Deposition Maps, v2018.01.
	Energy development and mining
Oil wells	Homeland Infrastructure Foundation-Level Data (2018). Retrieved from https://hifld-geoplatform.opendata.arcgis.com/datasets/oil-and-natural-gas-wells/data. Downloaded 3 Dec 2020.
Pipeline density	National Pipeline Mapping System (2004). U.S. Dept. of Transportation. Pipeline and Hazardous Materials Safety Administration. Washington, DC

NLCD = National Land Cover Database
USGS = U.S. Geological Survey

Figure 10-19. Land use stress at watershed scales from (a) population growth and urban development; (b) agricultural expansion; (c) density of mines; (d) density of pipelines; (e) mining/energy; and (f) aggregate stress across all sectors (at HUC 10 scale). Higher scores indicate greater stress.



The third principal component, explaining 14 percent of the variation in the data, represents watersheds with new residential developments, reflecting trends in urbanization around cities, and for rapidly growing urban areas (e.g., southern California, western Washington and Oregon, central Arizona, Colorado Front Range, central Texas). This factor also captures growth in rural areas, such as parts of the Wasatch Range, Rocky Mountains, and Appalachian Mountains, where amenity-driven growth has led to expansion of housing in the wildland-urban interface, with significant impacts on wildlife habitat.

Agriculture

In human-dominated ecosystems, established agricultural areas can host an abundance of species, including pollinators (Devictor et al. 2008, Krauss et al. 2003, Westphal et al. 2003), but agricultural expansion also converts complex landscapes into simple managed ecosystems, intensifies resource use, and increases pollutants via fertilizer and pesticide application (Donald et al. 2001, Dudley and Alexander 2017, Robinson and Sutherland 2002, Tscharntke et al. 2005). The stress index for agriculture uses variables related to cultivation, erosion potential, and nitrogen deposition (table 10-2). The PCA results for agriculture do not differentiate watershed types as clearly as the development PCA, perhaps because there is more variation in degrees of development than agriculture. The first principal component captures 74 percent of the variation among watersheds and mostly distinguishes watersheds with heavy concentrations of agriculture from those without heavy concentrations. The second principal component, which is almost entirely composed of watersheds without cultivated crops but with high levels of nitrogen deposition, explains 21 percent of the variation in the data and identifies the downstream impacts of agriculture on watersheds. The two principal components together explain 95 percent of the variation in the data and provide a fuller description of risk to watersheds associated with agriculture (figure 10-19b), namely those with agriculture in the watershed and those that experience the indirect effects of runoff from upstream watersheds. Agriculture-related stress is high throughout the Great Plains, Mississippi River basin, eastern Washington, and central California.

Energy Development and Mining

Stress on watersheds from mining activity derives from acid rock drainage, increased movement of pollutants such as metal sulfides following heavy rainfall and floods, and impacts on wildlife populations and movements. Watersheds containing active or abandoned mines are affected by complex interactions of surface and subsurface flows that introduce acidity and metals to the receiving stream. These influences may also emanate from natural sources in the underlying bedrock. Even in areas without active mining, some ecosystems have not completely recovered from mining that took place in the 19th century and continues to impact stream channels, sedimentation, and release of toxic chemicals (Schmidt et al. 2012, Wohl 2006, Wohl et al. 2015). Short-term impacts related to the construction of

Southeastern Crayfish Diversity and Threats

Crayfish are found in a wide range of habitats, including permanent and seasonal riverine and lacustrine habitats, freshwater caves and springs, and terrestrial burrows. Crayfish play a significant role in these ecosystems by processing detritus and macrophytes, which increases the availability of nutrients and organic matter to other organisms; digging burrows, which manipulates and mobilizes substrate, making nutrients and habitat available to other stream organisms; and serving as prey for, or predators on, numerous aquatic animal species, especially some game fishes such as bass and catfish (Holdich 2002, Reynolds et al. 2013). Thus, crayfish influence multiple aspects of ecosystem structure and function. They also serve as a profitable and popular food resource (Larson and Olden 2011).

Globally, crayfish reach their highest level of diversity in the United States (~400 species and subspecies versus 500+ in the world [65 percent]) (Taylor et al. 2019). In the United States, crayfish diversity reaches its pinnacle in the Southeast (~200 species; notably Tennessee, Alabama, and Mississippi) (Richman et al. 2015). Crayfish have a high level of endemism, with over two-thirds of Cambaridae species (the family of 99 percent of North American crayfishes) endemic to the Southeastern United States (Simon 2011). Crayfish are imperiled over much of their range, with 50 percent of all U.S. species at some level of conservation concern (Taylor et al. 1996, 2007) and 22.5 percent listed in threatened or higher concern categories (Taylor et al. 2019). Although interest in crayfish conservation is rapidly growing, basic biological and ecological information is lacking, severely hindering our ability to assess crayfish status and manage crayfish populations (Barnett 2017, Loughman and Fetzner 2015, Moore et al. 2013).

Crayfish imperilment is often attributed to small range sizes and degradation of habitats through pollution, urban development, and dams/water management (Crandall and Buhay 2008, Richman et al. 2015); however, there is a paucity of studies that directly assess these threats to southeastern crayfishes. Existing studies assessing dams/water management show that small dams shift the relative abundance of stream crayfishes (Adams 2013, Barnett and Adams 2021, Barnett et al. 2022) and large dams decrease the density and diversity of stream crayfishes when compared to streams without dams (Barnett 2019, Barnett and Adams 2021, Barnett et al. 2022). Dams have also caused genetic fragmentation of stream crayfish populations (Barnett et al. 2020, Barnett and Adams 2021). Similarly few studies have assessed the impacts of threats to crayfish—the Comprehensive Everglades Restoration Plan is the only well-known major restoration initiative that focuses on crayfishes (Taylor et al. 2019). Because of their important role as ecosystem engineers and both predator and prey in aquatic and terrestrial ecosystems, crayfish conservation also protects other organisms of conservation concern, as well as critical ecosystem functions (Boyle et al. 2014, Reynolds et al. 2013, Wolff et al. 2015).

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wells and pipelines include increased turbidity, modification of aquatic habitats, and opportunities for fuels and chemicals to enter the system during the construction stage (Maloney et al. 2018, Reid and Anderson 1999, Reid et al. 2003). Oil and gas wells, as well as development and roads, have also been shown to alter wildlife movements and migration patterns across broad spatial scales (Jakes et al. 2020). Long-term impacts of oil and gas development include channel incision and lateral movement, along with the potential for catastrophic impacts from a future spill. Pipelines might make hundreds or thousands of stream crossings and intersect a wide variety of habitats (Levy 2009), with the potential for spills to move contaminants through large river systems. Even small releases of oil and gas have been shown to injure and kill wildlife (Ramirez 2010, Ramirez and Mosley 2015). Levy (2009) found that there were 762 pipeline failures per year on average in Alberta, Canada over a 15-year period. In the United States, there were 614 pipeline incidents of some kind reported in 2019 (FracTracker.org, accessed 26 January 2021). An analysis of about 7,000 U.S. onshore liquid pipeline incidents that occurred from 1985 to 2012 found 5.5 percent of all incidents were triggered by natural hazards, 28 percent led to releases into water bodies, and more than 20 percent resulted in fires (Girgin and Krausmann 2016).

The PCA for energy development and mining aggregates the mining, well, and pipeline data into one threat index, identifying parts of the country that have significantly more energy and mining activity than the rest of the country. Mining is widespread throughout the West, the Ozarks, parts of the Great Lakes, and the Appalachians stretching into the Northeast (figure 10-19c), whereas the density of pipelines increases toward the Gulf Coast of Texas and Louisiana, although pipelines also crisscross much of the Eastern United States (figure 10-19d). The mix of mines and pipelines leads to stress related to energy development distributed throughout the United States, with hotspots occurring in the West, Ozarks, and Southeast (figure 10-19e)—areas that have experienced impacts on terrestrial and aquatic species (Allert et al. 2009, Jakes et al. 2020). Of note are the large parts of the country where data are missing. Availability of data on mines and wells is limited, collected inconsistently by States. Lack of availability of data is a serious limitation to assessing the impacts the energy sector might have on watersheds and wildlife.

Aggregate Index of Land Use-Driven Stress

We calculated an aggregate PCA using all the variables in the individual indices. The first three principal components of this aggregate index cumulatively account for about 55 percent of the variation in watershed stressors, with the individual components accounting for 31, 14, and 10 percent of variation in the data, respectively. The aggregate index shows the stark difference in pressures faced by eastern and western watersheds. Although mining might have significant impacts on the watersheds in which it occurs, energy development is not widespread enough to score high at a large regional scale, especially compared to impacts from development and agriculture. The largest source of variation between watersheds comes from nitrogen deposition and roads; collectively, they affect most of the watersheds in the Eastern United States (figure 10-19f). High-risk watersheds in the Western United States are mainly near the large metropolitan regions. The Pacific Coast and Rocky Mountain Regions generally score low on aggregate stress, but increased stress exists in the population and agricultural centers of Washington, Idaho, and California, and pockets of the Rocky Mountains that are experiencing rapid population growth.

Climate Change

Climate change is affecting terrestrial and aquatic vertebrate species in the United States, resulting in large-scale shifts in their range and abundance (Howard et al. 2020, Lipton et al. 2018). At the scale of the conterminous United States, annual average temperature has increased 1.8 °F (1.0 °C) over the period 1901 to 2016 and is projected to rise by about 2.5 °F (1.4 °C) by 2050 under all plausible futures (USGCRP 2017). Projected changes in total annual precipitation vary geographically. In addition, climate change is projected to continue altering natural disturbances such as wildfire (see the Disturbance Chapter). The total area of the country affected by wildfire has increased annually and this increase is projected to continue under climate change (Westerling 2016). Wildlife habitat will be affected by the interaction of changes in climate and natural disturbances (Weiskopf et al. 2020).

Model Inputs

We explore the potential effects of climate change on wildlife habitat at the scale of the conterminous United States using the 10 climate projections developed for the RPA Assessment, two disturbance treatments (fire suppression and no fire suppression), and the MC2 dynamic global vegetation model. The Scenarios Chapter describes the development of the climate projections using the two climate scenarios from the Intergovernmental Panel on Climate Change (RCPs 4.5 and 8.5, representing lower and high atmospheric warming, respectively) and five climate models identified for use in the RPA Assessment. Climate projections under RCP 4.5 and 8.5 were drawn from the downscaled climate dataset for each of the five climate models, resulting in 10 unique climate projections. The core set of five climate models were selected from the available models based on their ability to capture the range of temperature and precipitation change at mid- and end-century under RCP 4.5 and 8.5 (table 10-3, also see the Scenarios Chapter for more information).

Future vegetation biomass and shifts in vegetation types were assessed by the dynamic global vegetation model MC2—a model that projects vegetation response to changes in temperature, precipitation, and disturbance (fire, drought) based on biogeographic and biogeochemical processes in ecosystems (Bachelet et al. 2016, Klemm et al. 2020). Two disturbance treatments—fire suppression and no fire suppression—were analyzed using the MC2 model under each of the 10 climate projections, resulting in a total of 20 plausible future projections. Wildfire is a disturbance of concern because it can change a landscape in a short period of time, in contrast with gradual changes in mean climate. The "no fire suppression" disturbance scenario decreases the fire-return interval and allows for a potential full range of changes in future fire dynamics, whereas

Table 10-3. Five climate models selected to reflect the range of the full set of 20 climate models in the year 2070. Each model was run under RCP 4.5 and RCP 8.5, providing a range of different U.S. climate projections.

	Least warm	Hot	Dry	Wet	Middle
Climate model	MRI-CGCM3	HadGEM2-ES	IPSL-CM5A-MR	CNRM-CM5	NorESM1-M
Institution	Meteorological Research Institute, Japan	Met Office Hadley Centre, United Kingdom	Institut Pierre Simon Laplace, France	National Centre of Meteorological Research, France	Norwegian Climate Center, Norway

RCP = Representative Concentration Pathway
Source: Joyce and Coulson 2020.

the “fire suppression” scenario can extend the mean fire-return interval in some ecosystems (Sheehan et al. 2015). The conterminous climate and MC2 base data were converted to equal-area grids at 4-km resolution.

The MC2 model assesses the effects of climate and disturbance; historical vegetation is assumed to be potential vegetation. Land use change was not included in the MC2 runs, meaning that the inevitable future land use change linked to socioeconomic changes (see the Land Resources Chapter) was not analyzed here. Areas of open water, developed, and barren land cover—as defined by the USDA Natural Resources Conservation Service (Homer et al. 2020) and approximating 11 percent of the conterminous area—were removed from the analysis. Changes in land use will likely result in added stress on terrestrial and aquatic ecosystems in the United States as urban landscapes expand and rural refuges disappear. We address the implications of this omission in our caveats.

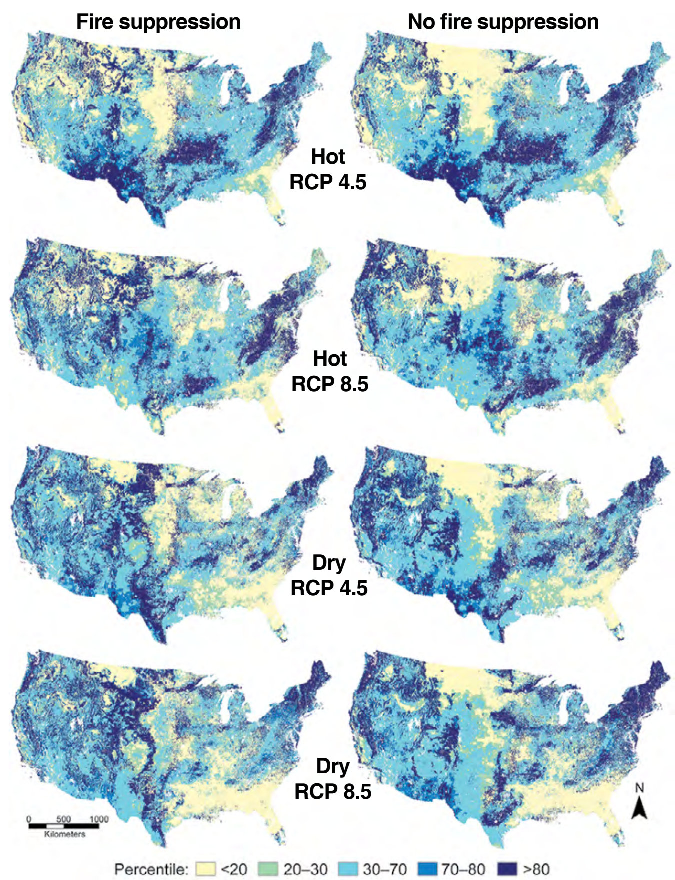
Terrestrial Climate Stress Index

The Terrestrial Climate Stress Index (TCSI) is used to simultaneously explore changes in annual mean temperature (°C), total annual precipitation (cm), and annual vegetation production (grams carbon per m^2) between historical (1951 to 2000) and future (2050 to 2099) periods for each of the 20 projections. Deviations in location and variance between historical and future distributions are captured by calculating Bhattacharyya distance (Bhattacharyya 1946), where larger distances equate to larger differences between the historic and future periods. We use the Bhattacharyya distances as the TCSI scores to rank the relative differences. We define high stress as the 20 percent of cells with the highest TCSI score (most difference between time periods) for each of the 20 projections, similar to many classifications of drought. This index therefore describes the magnitude of departures from historical conditions and identifies where future high stress is projected across the conterminous United States. Exploration of an individual projection (e.g., the hottest or the driest of the suite of projections) highlights areas where that particular stressor may result in challenges to natural resources under those plausible futures, whereas the TCSI based on all projections portrays consistency in projected future high-stress locations across the conterminous United States (see following section).

High Terrestrial Climate Stress Areas Under the Hot Projections

The hot climate model was run for RCP 4.5 and RCP 8.5, under the two disturbance treatments (fire suppression, no fire suppression) to identify areas of high stress under a hot future (figure 10-20). High stress is defined as a TCSI value greater than the 80th percentile (i.e., top 20 percent). Because these scores are relative to each projection, the shifts demonstrate how stress changes depending on the RCP scenario and disturbance treatment. Comparing the results across these four hot-model

Figure 10-20. Terrestrial Climate Stress Index (TSCI) scores ranked by percentile. High stress is a TCSI score greater than the 80th percentile (dark blue). Projections shown are under the hot model (top two rows) and dry model (bottom two rows). Projections include two RCP scenarios (RCP 4.5 and 8.5) and two disturbance treatments (fire suppression: left column, and no fire suppression: right column).



RCP = Representative Concentration Pathway.

projections suggests that although there are common areas of high stress across the four treatments (Appalachian Mountains in the South Region), individual RCPs and disturbance treatments can influence the location of high stress across the conterminous United States.

The northern area of the Rocky Mountain Region is projected to be in high stress under the fire suppression treatment (both RCPs); however, few grid cells are projected to be in high stress under no fire suppression (both RCPs). Historical fire regimes in this area have restricted the advance of woody species. Without future fire suppression, wildfire will continue to minimize woody species advances. The addition of fire-suppression treatments, however, could enable the advance of woody species and result in higher future stress (also found by Klemm et al. 2020). Wildfire management may need to consider the shifting changes in fire regimes under climate change and the future role of prescribed fire under those changes.

A noticeable difference between the RCP 4.5 and 8.5 scenarios occurs in the southwestern area of the Rocky Mountain Region. High stress is found in this southwestern area under RCP 4.5 (both disturbance treatments) but not under RCP 8.5 (both disturbance treatments), suggesting that atmospheric warming has a greater influence on stress in these areas than fire-suppression treatments.

High Terrestrial Climate Stress Areas Under the Dry Projections

The dry climate model was run for RCP 4.5 and RCP 8.5, under the two disturbance treatments (fire suppression, no fire suppression) to identify areas of high stress under a dry future (figure 10-20). Comparing the results across these four projections suggests that although common areas of high stress are visible across the four projections (northeastern area of the North Region), individual RCPs and disturbance treatments can influence the locations of high stress across the conterminous United States.

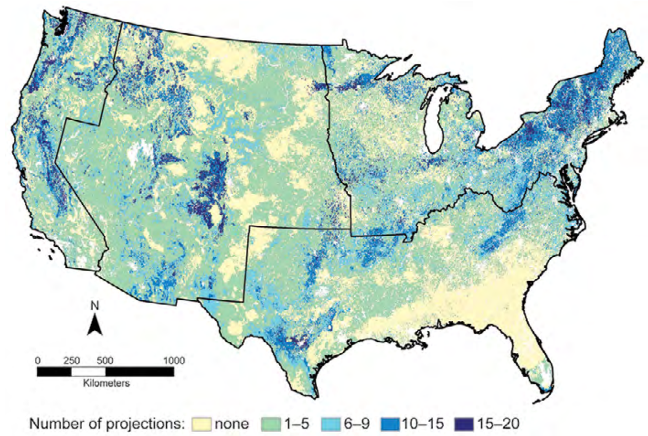
The high-stress projections under the dry model are similar to the results of the hot model for the Rocky Mountain Region: high stress in the northern part of the region is projected for both RCPs under fire suppression (covering a larger area than under the hot model) and relatively low stress is projected under no fire suppression. Changes in fire regimes under climate change may be an important consideration for resource management in these areas. All four projections predict future high stress in the northeastern area of the North Region. In contrast to the hot-model projection, where high stress was seen in the Appalachian Mountains (extending into the northeastern area but not including Maine), high stress in the dry model intensifies in the far northeastern area across all four projections. Further exploration of drought in this area may be valuable for local resource planning. Also common to all four projections is the relatively large area without high stress in the southern parts of the South Region. Stress is still evident, but when compared to other areas, this relatively wet region is projected to have few areas of high stress under the dry-model projections.

Consistent with the hot-model projections, areas of high elevation are projected to experience high stress under the dry-model projections. These common areas of high stress include the mountains throughout the Pacific Coast and Rocky Mountain Regions. Higher elevations in the eastern part of the conterminous United States appear to experience more stress under hot projections than dry projections.

High Terrestrial Climate Stress Trends Across Projections

Grid cells that are consistently ranked as high stress across the projections denote areas that are most likely to experience high stress in the future, based on this suite of plausible futures. Figure 10-21 shows the number of

Figure 10-21. The cumulative number of projections that identify future high stress for every cell, based on the set of 20 projections. Barren area, open water, and developed areas (white on the maps) are not included in the analysis.



projections that identify future high stress in each cell, out of the 20 total projections. For the conterminous United States, we define areas of concentrated stress (hotspots) as occurring where 10 or more projections identify high stress.

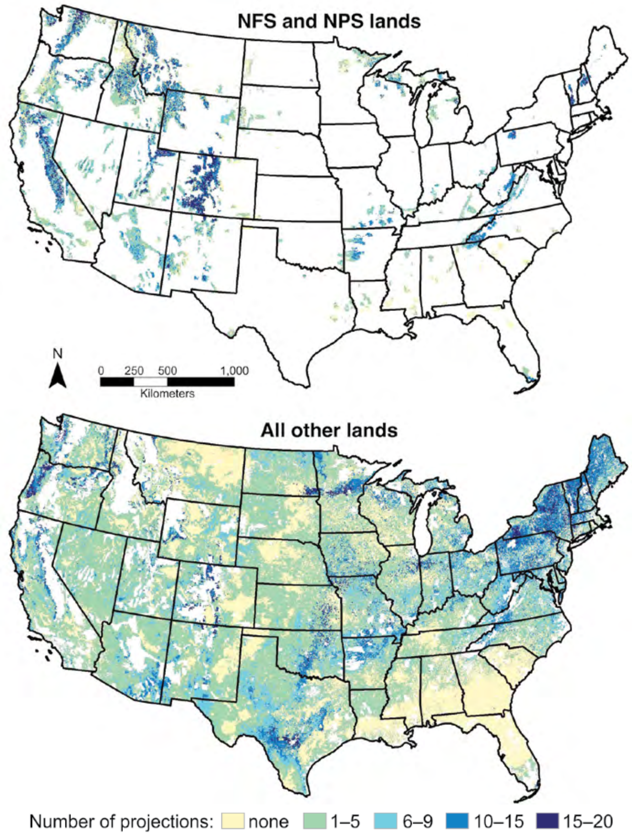
Areas of concentrated high stress occur in all RPA regions. High-elevation areas are consistently ranked as high stress, including the mountains of California, Oregon, and Washington in the Pacific Coast Region; the Rocky Mountains (Montana through Colorado) in the Rocky Mountain Region; areas in the Appalachian Mountains and Ozarks in the South Region; and northeast mountains in the North Region. Scattered arid lands in southern Arizona and New Mexico in the Rocky Mountain Region consistently show high stress. Areas in eastern Oklahoma and parts of Texas, and central Minnesota also see high stress.

Stress Projection Comparisons: National Forests and U.S. National Park Service Lands, Compared with All Other Lands Across the United States

Land management under Federal ownership includes a variety of objectives including both conservation and resource extraction, but these lands are less vulnerable to development or land conversion compared with other land ownerships. Federally owned lands therefore have the potential to play an important role as climate refugia when considering climate vulnerability. To better understand how climate change may affect Federal lands and their potential to serve as climate refugia, we compared stress projections for National Forest System (NFS) and U.S. National Park Service (NPS) lands with stress projections for all other lands (both public and private, but not necessarily set aside as protected) in the conterminous United States (figure 10-22).

Looking at the TCSI results for NFS and NPS lands shows high stress areas across these networks (figure 10-22, top). Concentrated high stress is seen in the Rocky Mountain and Pacific Coast Regions, notably the central/southern Rocky

Figure 10-22. The number of cumulative projections that identify future high stress for (top) National Forest System and U.S. National Park Service lands, and (bottom) all other lands, based on the set of 20 projections.



NFS = National Forest System; NPS = U.S. National Park Service.

Mountains, northwestern Utah, parts of Montana, and the Sierras in California. High stress on all other lands occurs as isolated areas of high stress across the country and concentrated in the northeastern area of the North Region, southern Texas, and the Coast Range in Oregon (figure 10-22, bottom).

We averaged TCSI for all 20 projections (1) across NFS and NPS lands and (2) across all other lands (not part of the NFS or NPS) and tested for differences using a paired t-test. Future stress is significantly greater for NFS and NPS lands than for all other lands, based on changes in climate and disturbance (p-value <0.0001; t = 5.07, df = 19).

Because elevation is confounded with temperature, future warming temperatures mean that higher elevation areas are more likely to be in high stress. NFS and some NPS lands largely exist in the mountainous regions of the country at higher elevations than other lands (mean elevation of 1542 m versus 709 m), a driving factor for the significantly higher stress found in these lands. However, the correlation between elevation and the number of projections identifying a cell in high stress across the conterminous United States is weak (r = 0.15), suggesting that other factors including wildfire suppression also contribute substantially to this result.

Implications of Terrestrial Stress

Climate change has already had negative impacts on many threatened wildlife species (Pacifici et al. 2017), and it will likely continue to adversely affect many more species as projected increases in temperature and variation in precipitation lead to changes in vegetation and fire regimes. As in our previous assessments, these results also suggest that the historical influence of fire on vegetation is an important consideration. The effect of a changing climate and a changing fire regime differs depending on the management of wildfire, particularly where fire regime has been a major influence in sustaining a specific vegetation type (e.g., grasslands). Large, high-severity fires can lead to more heterogeneous landscapes that provide a mosaic of habitat types facilitating greater biodiversity (e.g., grassland birds; Fuhlendorf et al. 2006). However, there are many feedback cycles associated with fire and confounded with climate change. For example, cheatgrass (*Bromus tectorum*), an invasive plant species of particular concern in the Great Basin owing to its negative impact on wildlife species in sagebrush ecosystems, has been shown to have a positive feedback cycle with fire (Coates et al. 2016). The mountain pine beetle (*Dendroctonus ponderosae* Hopkins) is another example in the Rocky Mountains where warming temperatures have altered the beetle's lifecycle, leading to emergence of more individuals simultaneously, which in turn leads to more successful attacks and more dead trees that are more likely to result in large crown fires (Logan and Powell 2001). These cascading effects threaten trophic interactions that have adapted to historical norms and are rapidly changing at a pace wildlife species may not be able to keep up with.

Federal lands are expected to serve as future refugia if surrounding lands are converted to other land uses. Although our study did not incorporate land use as a factor affecting vegetation, our finding that NFS and NPS lands are projected to experience higher future climate stress than all other lands suggests that the ability of these lands to serve as refugia may be limited by climate stress. Nevertheless, Federal lands may offer important landscapes through which wildlife can disperse in response to changing environmental conditions resulting from climate change.

We identified several areas where a majority of the plausible futures predict high stress: mountains in the Pacific Coast, Rocky Mountain, and South Regions; large areas from New York to Maine in the North Region; and lower elevation lands in southern New Mexico, southern Arizona, Oklahoma, and Texas. The consistency of high stress in these areas suggests that wildlife managers will likely see changes in wildlife habitat and wildlife distributions. For example, decreased ranges for wildlife that are particularly vulnerable to heat stress, such as marten (*Martes americana*) and lynx (*Lynx canadensis*), may lead to associated population declines (Carroll 2007). Other indirect effects such as increased parasitic vulnerability could also contribute to population declines in many wildlife species, such as winter ticks (*Dermacentor albipictus*) on moose (*Alces alces*) (Rodenhouse et al. 2009).

The local exploration of different individual climate projections (least warm, hot, dry, wet, middle) may assist resource managers in identifying the significant impacts on wildlife and wildlife habitat with respect to a particular plausible future (Lawrence et al. 2021). There is value in examining individual projections, as vegetation sensitivity to changes in climate varies across the conterminous United States. In our examination of the hot and dry projections, it was apparent that atmospheric warming (RCP 4.5 versus RCP 8.5) can have more influence than disturbance treatments on high-stress projections and vice versa. The notable example is fire suppression in the northern part of the Rocky Mountain Region, where woody species expanded under fire suppression but not under no fire suppression. Assessing the potential changes in wildfire regimes will be important in planning natural resource management in the future, as will tailoring strategies to the circumstances that characterize various landscapes. Given the large range of habitat types identified to be under high stress, climate change will likely be an important component of future habitat management plans, specifically addressing possible mitigation strategies that are tailored to individual conservation needs.

Combining Stressors

Interactions among individual stressors that affect ecosystem health can compound vulnerability of already altered ecosystems and the biodiversity they support. In the previous sections of this report, we described the modeling and mapping of stressors from land use and climate change. Here, we combine land use stress, future climate stress, and biodiversity data in order to visualize overall distributions of current and future risk to ecosystems across the conterminous United States. Future climate stress in these sections is the aggregate of all the climate prediction models (n = 20) that identified a specific cell as high stress, as described above in the Terrestrial Climate Stress Index section.

Anthropogenic Stressors

Our assessment of anthropogenic drivers of change (described in detail above) captures current stressors on the landscape resulting from (1) land use and associated human activities and (2) changing environmental conditions resulting from climate change. The land use stressor assessment identified the Eastern United States as highly vulnerable to several individual stressors, and with greater overall stress than the Western United States. In contrast, several areas of high stress in response to future climate conditions were identified in the Western United States. To visualize the interaction between these forms of ecosystem stress representing current and future conditions, we combined the datasets using the Plus tool in ArcGIS Pro 2.8.3. Combining these two indices allows us to see where both identify similar geographic patterns and which areas of the conterminous United States are likely to experience compounding stressors. The resulting map identifies areas of high combined stressors in the North Region, along with areas of concentrated combined stress in much of Colorado, southern Texas, and the Sierra Nevadas of California (figure 10-23).

Figure 10-23. Stress presented as an index for: future climate vulnerability—defined as the number of climate models that identified an individual cell as high stress (map in upper left); current aggregate land use impacts (map in upper right); and a combination of the two indices developed using the Plus tool in ArcGIS Pro 2.8.3 (map in lower center).

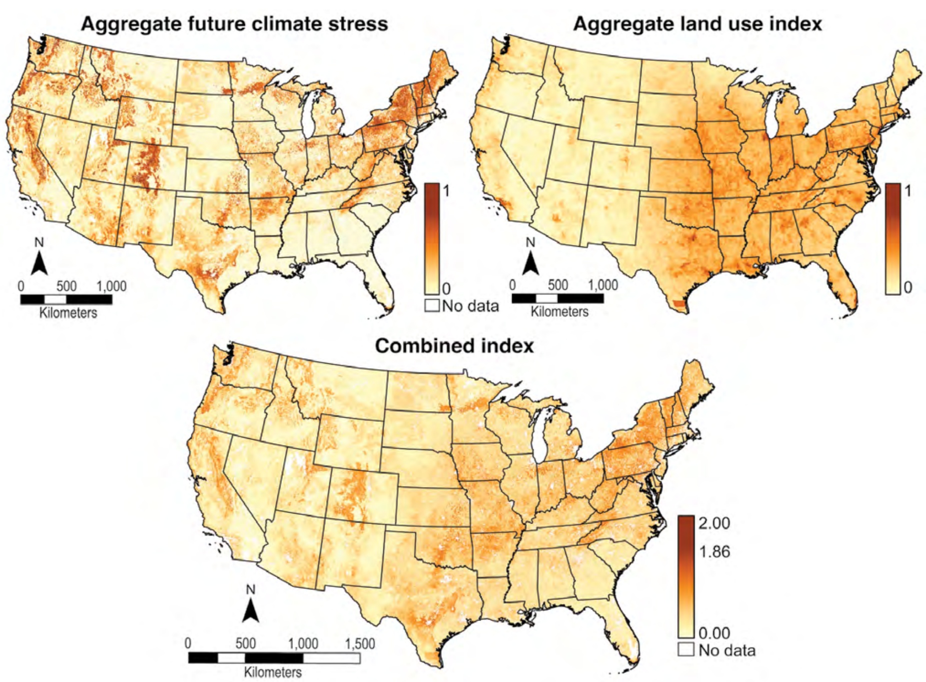


Figure 10-24. Hotspots with both high terrestrial biodiversity and a likelihood of high future stress. Overlaying an index of future climate change (map in upper left)—defined as the number of climate models that identified an individual cell as high stress—on terrestrial biodiversity (map in upper right) results in a map that identifies hotspots with both high terrestrial biodiversity and a likelihood of high future stress (map in lower center). Future climate stress and source information for biodiversity map described in prior sections of the chapter.

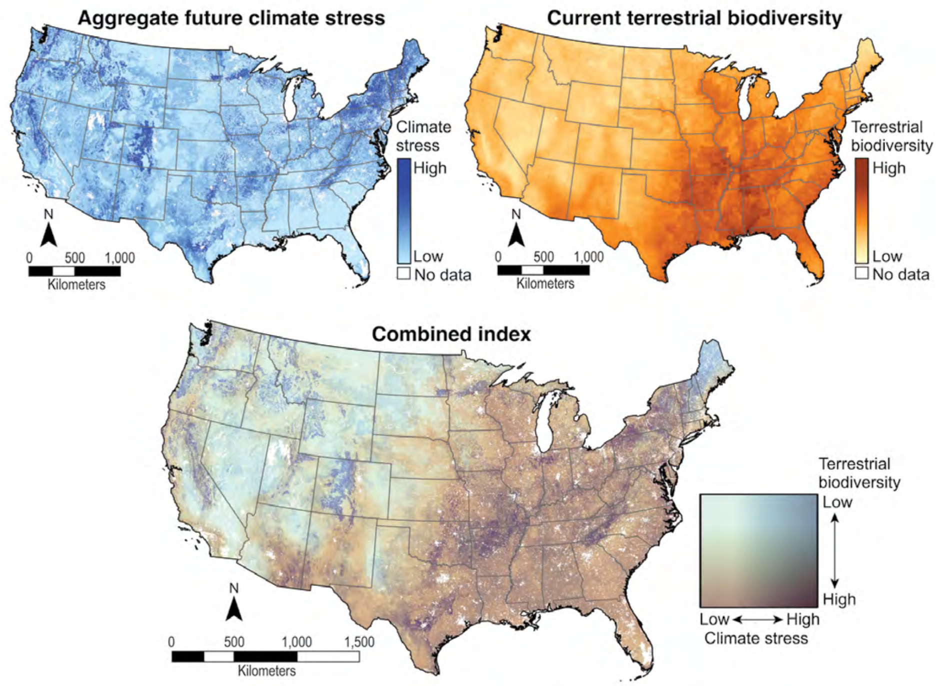
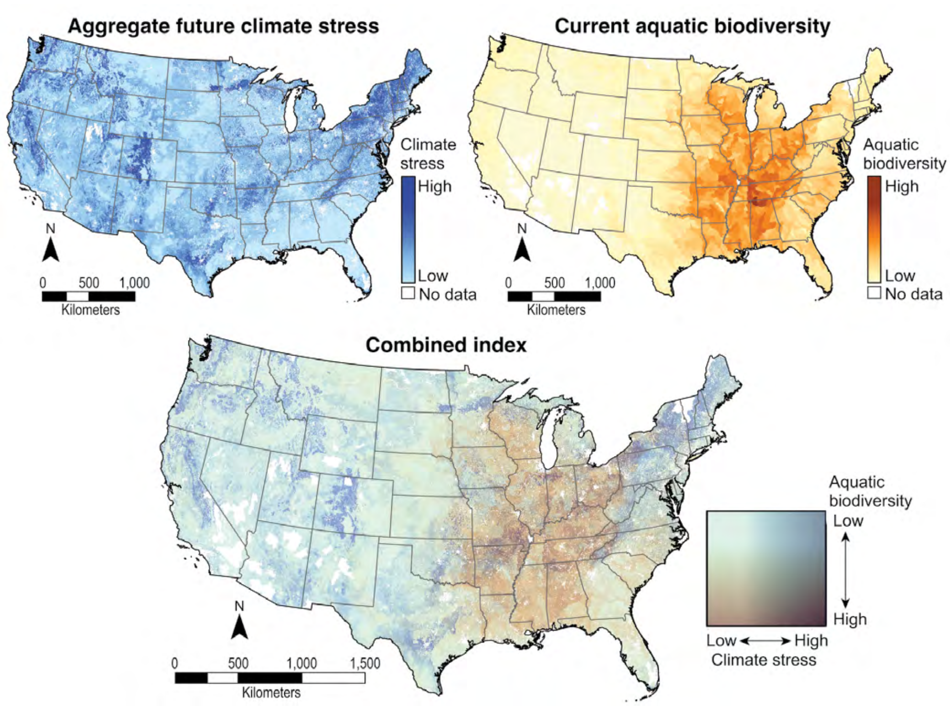


Figure 10-25. Hotspots with both high aquatic biodiversity and a likelihood of high future stress. Overlaying an index of future climate change (map in upper left)—defined as the number of climate models that identified an individual cell as high stress—on current aquatic biodiversity (map in upper right) results in a map that identifies hotspots with both high aquatic biodiversity and a likelihood of high future stress (map in lower center). Future climate stress and source information for biodiversity map described in prior sections of the chapter.



Future Climate and Biota

The potential effects of future climate on terrestrial and aquatic biota are relevant to management decisions being made today. We therefore examined how future climate stress could intersect terrestrial and aquatic biodiversity patterns by overlaying the future climate stress map onto our biodiversity maps.

The eastern portion of the country contains the areas of highest terrestrial and aquatic biodiversity. When overlaid with climate stress, we see some similar overall patterns. For terrestrial biota, the overlap with climate stress shows areas of high vulnerability in the Appalachian and Ozark Mountains, as well as in the Madrean Sky Islands. Additional areas of both high terrestrial biodiversity and high climate stress are found in southern Texas and in the Northeast (figure 10-24). Vulnerability of aquatic biodiversity to climate stress is also centered in the Appalachian and Ozarks Mountains (figure 10-25). Areas of high climate stress but low biodiversity are found throughout the Western States. Although these areas may have lower overall biodiversity, they support important ecosystems, making identification of areas of high climate stress important for management decisions.

Management Implications

The observed ongoing decline in long-term biodiversity and increases in ESA listing status across taxa signal continued biotic and anthropogenic threats to native biodiversity across the conterminous United States. The vulnerability of native biota, particularly to land use and projected climate change, highlights the importance of prioritizing habitat conservation actions in response to local and regional threats. Federal lands, including national forests and national parks, can play a role in providing long-term refugia as landscapes transition into novel future ecosystems.

Different regions of the country experience specific and uniquely interacting threats. For example, compounded land use stressors dominate the Eastern United States, while development is the primary land use stressor of habitats in the West. Climate change stress, however, is expected to be highest in higher elevation areas, but also creates a mosaic of high stress across the country where it interacts with disturbance processes such as wildfire. Because these stressors contribute to biodiversity loss, land managers in different regions will face unique combinations of stressors.

Non-Federal lands in the RPA North and South Regions are projected to be highly vulnerable to compounded land use stress in the coming decades, increasing the importance of Federal lands to serve as refugia for biodiversity. The amount of federally owned land in these regions is limited, however, and the fact that they are the most biodiverse regions in the conterminous United States highlights the difficulty for managers seeking to conserve and protect biodiversity. Collaboration across both public and private lands therefore offers the best path for biodiversity conservation and protection in the Eastern United States.

In the Western United States, stress is patchier in distribution than in the East and derives primarily from development and climate change. The higher proportion of the land in Federal ownership in the West presents an opportunity for biodiversity conservation at broad spatial scales commensurate with climate stress and wildfire. While collaboration with partners and non-Federal entities can enable the maintenance of ecological processes and habitat connectivity, there may be opportunities to track and facilitate migration of ecosystems and species into habitats more conducive to survival as climate and landscapes shift. Management could benefit from additional consideration of climate vulnerability planning that supports change as ecosystems transition in response to climate reality (West et al. 2009), including resilience to disturbances such as wildfire (e.g., Ager et al. 2020).

Conclusions

The diversity of animal life described in this chapter contributes to our well-being, our livelihoods, and our national identity. Our analysis demonstrates that ecosystems across the country are vulnerable to a variety of factors including land use change, climate change, and biological invasions. Our analysis also demonstrates that threats vary across the country, with different combinations of threats associated with different underlying topographic, climatic, and settlement patterns. These combined drivers have contributed to the current mosaic of intersecting land uses and native ecosystems that define different regions across the country.

Our analysis projects that land use pressures—including land conversion, human population growth, expansion of agricultural areas, and development of energy infrastructure and mining—will be most pronounced in the North Region, as well as areas of the South, driven in large part by population growth. Land use change has been identified as a threat to species persistence (Smith-Hicks and Morrison 2021), particularly in terrestrial systems (Sala et al. 2000), owing to a variety of impairments to habitats including reductions in quantity, quality, and connectivity (Powers and Jetz 2019). For example, endemic species that are specialized and regionally isolated are inherently vulnerable to shifts in land cover and human population pressure or climate (Malcolm et al. 2006), reflecting a potentially limited adaptive capacity to survive as conditions change. Land use changes compromise and reduce local habitat availability and/or quality and may have a more immediate effect on endemic species compared with broadly distributed species for which some portion of the population may be able to find refuge on Federal or other protected lands. Highly migratory species are also uniquely vulnerable to climate change, as their life stages are linked to specific habitat conditions at specific times (e.g., phenology). Decoupling of these linkages as climate and land use changes in different ways in different places along their migratory journey may increase their overall vulnerability (Robinson et al. 2009). The high concentration of land use stress in the RPA North and South Regions highlights the conservation role of limited Federal lands in the East, which also coincide with the areas of highest terrestrial and aquatic biodiversity in the conterminous United States.

Climate-driven stress is highest in the Pacific Coast Region and parts of the Rocky Mountain Region—areas that have a large share of Federal lands including NFS, NPS, and FWS lands—along with the North Region. Our modeling indicates that climate change may compromise the ability of federally managed lands to provide refugia to native biota. Protection of native ecosystems (that will likely morph into novel ones as they migrate in response to a changing climate) will likely require collaboration and cooperation from public and private lands. In addition, management approaches that are based on past and current climate may benefit from updates to consider different future climates and the potential for greater numbers of discrete and compound stress events (e.g., drought, heat, and wildfire) (Hagerman and Pelai 2018, IPCC 2021).

In addition to biotic and anthropogenic stressors varying across regions, biota in different parts of the country will likely also experience different types of stresses over short and long timescales. Although projections look to the future, the documented changes already occurring make climate change both a short-term and long-term issue with broad management consequences (IPCC 2014). Shifts in the distribution patterns of vegetation (e.g., Joshua Tree National Park with fewer Joshua trees (*Yucca brevifolia*), Sweet et al. 2019) and landscape features (e.g., retreating glaciers in Glacier National Park, Hall and Fagre 2003) have been occurring for decades. As the existing capacity of individual species to survive in more constricted environmental conditions declines, the threshold between survival and imperilment will likely narrow. Greater vulnerability to climate change is anticipated for long-lived species that adapt more slowly to environmental changes (Hetem et al. 2014) or for species with small range sizes who have fewer migration opportunities (Morueta-Holme et al. 2010, Schloss et al. 2012). For species with broader distributions, portions of the population may experience climate stress, rather than the entire population (i.e., coho salmon, *Oncorhynchus kisutch*, in the Pacific Northwest, Flitcroft et al. 2019), or specific seasons may be more stressful than others (i.e., seasonal temperatures and vegetation, Wang et al. 2011). The important role that protected lands can play into the future is likely to become even more critical. The ability of forest managers to maintain and enhance variability of terrestrial and aquatic habitats within their jurisdictions may provide a critical link for the persistence of native biota.

Observed patterns in the listing status of imperiled species under the ESA show some overlap between areas of high biodiversity and locations containing larger numbers of listed species. However, ESA listing bias towards large-bodied charismatic species for which long-term data often exist, suggests that current patterns of imperiled species may not necessarily reflect species-specific threats across the country (e.g., amphibians, Gratwicke et al. 2012). In recognition of the changes to the environment that are stressing native biota, it is important to look for additional vulnerable populations of biota that are not currently targeted for conservation. Additional Federal listing decisions for species of concern could occur as climate and land use continue to affect habitats across the United States.

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Chapter 11

Outdoor Recreation and Wilderness

White, Eric M.; Askew, Ashley E.; Bowker, J.M. 2023. Outdoor Recreation and Wilderness. In: U.S. Department of Agriculture, Forest Service. 2023. Future of America's Forest and Rangelands: Forest Service 2020 Resources Planning Act Assessment. Gen. Tech. Rep. WO-102. Washington, DC: 11-1–11-37. Chapter 11. https://doi.org/10.2737/WO-GTR-102-Chap11.

Forests and rangelands, along with other natural resources and open space, provide opportunities for U.S. residents and visitors to participate in outdoor recreation. In this Resources Planning Act (RPA) Assessment chapter, we focus on outdoor recreation that is nature-based—specifically, those activities where natural resources, such as forests, rivers, and rangelands, are central to the recreation experience. Recreation is a primary means through which people in the United States interact with these natural resources. Recreational use of forests, water, rangelands, and other natural resources is considered here, just as we consider the use of natural resources to provide for timber, grazing, or carbon sequestration elsewhere in the RPA Assessment. In this chapter we describe (1) the current supply of recreation opportunities in the United States and how future population and land use changes may influence that supply, (2) recent patterns of outdoor recreation across the United States, and (3) projected future patterns in outdoor recreation in the conterminous United States under a range of future scenarios that integrate socioeconomic and climatic change.

Key Findings

- Publicly managed recreation resources, at all levels of government, provide most opportunities for outdoor recreation.
- Per capita participation in outdoor recreation activities has been relatively stable in recent years, but population growth has led to an increase in the number of participants.
- Forest recreation resource availability, per capita, is expected to continue to decline in future decades for locations experiencing population growth.
- Greater income and population growth generally result in higher rates of per capita participation in outdoor recreation.
- Continued population growth results in a greater number of outdoor recreation participants, even potentially offsetting any declines in per capita participation.
- Greater atmospheric warming is projected to have a negative influence on recreation engagement in many activities and little positive influence.
- Projections of consumption, measured as annual days of recreation, show increases across most activities, with the greatest numbers of recreation days in activities of a general or broadly accessible nature, i.e., day hiking, viewing nature, developed site use, and developed site camping.

Outdoor Recreation Resources

- ❖ Forests and other natural resources offer abundant public and private outdoor recreation opportunities.
- ❖ Data on the number and types of recreation resources in the United States are limited, especially for local-government-managed lands and privately owned forests and rangelands.
- ❖ Federal lands and Wilderness are disproportionately located in the West, offering greater acreage under public management for outdoor recreation, especially in dispersed settings, undeveloped experiences unique to designated Wilderness, and national parks and associated areas managed by the U.S. National Park Service.
- ❖ Private lands can offer unique recreation opportunities, but those opportunities are often available only to owners and their friends and relatives or those who can purchase access.
- ❖ Increased frequency and severity of disturbance resulting from climate change may reduce the availability and condition of recreation opportunities.

Forests, rivers, rangelands, and other natural resources provide settings conducive to outdoor recreation. Just as current and projected forest conditions define the potential supply of timber, wildlife habitat, and carbon sequestration, the extent and characteristics of natural resources, now and in the future, define the opportunities that people have (and will have) to engage in outdoor recreation. Outdoor recreation pursuits are diverse, with the environments and conditions necessary for engaging in outdoor recreation equally variable. Some activities, such as fishing and canoeing, require a specific type of resource (water) while other activities, such as hiking or viewing nature, can take place in a range of settings (e.g., forests, rangelands, and urban open space). In addition to the diversity in resource needs for outdoor recreation, outdoor recreationists themselves are diverse in their desires for various settings to recreate. We characterize recreation supply across a variety of land ownerships and natural resource types in order to recognize this diversity.

Public Land Resources

From town parks to State parks to national forests, public lands for recreation are provided at every level of government: local, county, State, and Federal. In the United States, we often look to publicly owned lands as primary providers of places for outdoor recreation. The recreation opportunities offered by governments differ in their natural settings, locations relative to population centers, and types.

Local—There is no comprehensive enumeration of the extent or location of outdoor recreation resources managed by local governments. These public lands can range from small "pocket parks" that provide for short respites, to larger urban parks where people picnic, walk/hike, or relax, to county park systems that offer a myriad of recreation opportunities. Among public lands, those managed by local governments are typically the closest to population centers. For those living in or visiting urban and peri-urban areas, these public lands generally offer the most-accessible spaces for nature-based outdoor recreation. Local government public lands typically offer opportunities to engage in the most-popular outdoor recreation activities, such as walking/hiking, viewing nature and wildlife, and simply relaxing in the outdoors, and often accommodate those with a wide range of skills and abilities.

The most extensive data on outdoor recreation opportunities managed by local governments come from The Trust for Public Land's annual City Park Facts. Those data provide insight into the characteristics of park and open-space resources in the 100 most-populated U.S. cities. In 2020, there were slightly more than 2 million acres of parks and open space in the 100 most-populated U.S. cities—many of those acres managed by State or Federal government agencies. In 2020, about 835,000 acres of parks and open space in the most populated U.S. cities were managed by local governments (The Trust for Public Land 2020). That land area has remained steady since 2017. Owing to a change in how City Park Facts data are collected, examination over a longer timeframe is not possible. The size of urban open spaces ranges widely, but most are relatively small. The median size of parks and open space in the 100 most-populated cities was 3.8 acres (The Trust for Public Land 2020). Seventy percent of the populations in the largest cities live within a 10-minute walk of an urban park (The Trust for Public Land 2018).

State—A variety of agencies in State governments manage lands and waters available to the public for outdoor recreation. Although outdoor recreation is central to the missions of State park agencies, other State-level agencies that focus on forestry, wildlife, land conservation, or other natural resource uses also often provide public recreation opportunities. However, the acres available for recreation and the types of recreation opportunities offered by those other agencies are not well documented nationally. In general, our best understanding of recreation opportunities provided by State agencies comes from State parks and State forestry agencies.

In 2017, State park systems across the United States managed 18.7 million acres (Smith and Leung 2019). Among RPA regions (see figure 2-1 for RPA region designations), the North Region contains the greatest State park acreage (8.2 million), followed by the Pacific Coast

Region (5.3 million) (table 11-1). Across the entire United States, the area of State park systems has increased steadily since the mid-1980s (Smith and Leung 2018). Between 2009 and 2017, the acreage of State park agencies increased by about 33 percent (Smith and Leung 2019); however, that increase primarily reflects mergers of other State agencies into State park systems, rather than movement of lands into public ownership or changes in public access. The greatest increases in State park agency acreage have taken place in the RPA Rocky Mountain Region (1.4 million acres, 102 percent) and the RPA North Region (3 million acres, 57 percent). For the Rocky Mountain Region, the increase in acreage traces primarily to an approximately 1-million-acre increase following the merger of Colorado State Parks and Colorado Division of Wildlife. In the North Region, the increase in acreage is driven by a 2.9-million-acre increase in the State park system of New York State, between 2013 and 2015, that resulted from changes in agency reporting. Expenditures for operating State park agencies in the United States totaled $2.6 billion in 2017 (Smith and Leung 2018). Although that is greater than the spending in the mid-1980s (after adjusting for inflation), the expenditures in support of State park operation have been declining year over year since the mid-2000s (Smith and Leung 2018).

State forestry agencies often have responsibility for managing recreation opportunities on State forests and other State lands. There are about 76 million acres of State-owned forests in the United States, and this acreage has remained steady to slightly increasing in recent years. Although there are a substantial number of acres managed by State forestry agencies, the workforce dedicated to managing recreation is limited. In 2018, across all State forestry agencies, fewer than 500 seasonal positions were dedicated to managing recreation (National Association of State Foresters 2019). Agencies in the RPA North Region accounted for the greatest numbers of seasonal positions focused on recreation. The number of seasonal employees dedicated to recreation has remained steady in recent years. In 2018, State forestry agencies spent about $43 million on recreation programs (National Association of State Foresters 2019), with State agencies in the North Region accounting for more than half of expenditures in support of recreation.

Federal—Seven Federal agencies provide the majority of recreation opportunities on federally managed lands. The diversity of recreation opportunities provided on Federal lands parallels the diversity of the managing agencies' missions and origins. In general, Federal lands are most common in the West (Vincent et al. 2020) but are prominent in every RPA region (table 11-2). The U.S. Bureau of Land Management (BLM), with lands almost exclusively in the West, manages the largest land area of any Federal agency. Although there are important exceptions, in general the recreation resources of the BLM focus on dispersed recreation in rangeland settings with limited or lightly developed recreation facilities and infrastructure. The U.S. Department of Agriculture (USDA), Forest Service is the next largest Federal provider of lands for recreation. The USDA Forest Service manages a range of recreation resources that support a wide variety of recreation activities and settings. Lands managed by the USDA Forest Service are located across the United States but are more common in the West. The U.S. National Park Service (NPS) is widely recognized by the public as a provider of keystone recreation opportunities. In addition to national parks, the NPS manages numerous national historic sites, national monuments, national recreation areas, national seashores, and other units. Although the majority of NPS lands are in the West, a greater relative share of lands managed by the NPS are in the East, compared to the USDA Forest Service and BLM. The NPS provides diverse recreation settings and opportunities, including highly developed facilities and interpretive sites.

Four other Federal agencies provide the remaining Federal recreation opportunities. The U.S. Fish and Wildlife Service

Table 11-1. Acres in State park systems by RPA region.

Year	Pacific Coast	Rocky Mountain	North	South	Grand total
			(acres)		
2009	5,176,228	1,395,813	5,183,851	2,217,453	13,973,345
2010	5,203,469	1,188,091	5,366,119	2,239,543	13,997,222
2011	5,227,872	1,298,298	5,215,357	2,256,921	13,998,448
2012	5,250,954	1,070,932	5,230,013	2,370,263	13,922,162
2013	5,255,256	2,283,562	5,242,108	2,366,587	15,147,513
2014	5,275,180	2,456,972	3,892,200	2,318,864	13,943,216
2015	5,262,699	2,597,620	8,135,730	2,376,461	18,372,510
2016	5,271,493	2,818,660	8,117,502	2,389,873	18,597,528
2017	5,306,258	2,822,394	8,165,824	2,400,094	18,694,570
Total region area	**415,728,000**	**538,203,520**	**743,325,440**	**574,086,400**	**2,271,343,360**

Although subsequent modeling and simulations examine the RPA Pacific Coast Region as defined within the conterminous United States, this table presents summaries on the State park systems relative to the entire country, including Alaska and Hawaii.

Sources: Smith and Leung 2019, Vincent et al. 2020.

Table 11-2. Area of Federal land and percentage (relative to combined States' total acreage) by RPA region and Federal land manager in 2018.

RPA region	Total Federal acreage (1000s)	Total acreage in RPA region (1000s)	Federal acreage (%)
North	15,963	415,728	3.8%
BLM	5		
USDA Forest Service	12,300		
FWS	1,468		
NPS	1,381		
ACOE	809		
South	25,363	538,204	4.7%
BLM	29		
USDA Forest Service	13,391		
FWS	3,424		
NPS	5,122		
ACOE	3,397		
Rocky Mountain	260,558	743,325	35.1%
BLM	141,692		
USDA Forest Service	99,265		
FWS	6,319		
NPS	10,985		
ACOE	2,297		
Pacific Coast	89,930	204,499	44.0%
BLM	31,268		
USDA Forest Service	45,824		
FWS	1,036		
NPS	9,644		
ACOE	2,158		

ACOE = U.S. Army Corps of Engineers; BLM = U.S. Bureau of Land Management; FWS = U.S. Fish and Wildlife Service; NPS = U.S. National Park Service.

U.S. Bureau of Reclamation facilities are not presented here.

Pacific Coast Region does not include Alaska or Hawaii.

Source: Vincent et al. 2020.

(FWS) provides a variety of recreation opportunities, although with primary recreation focus on wildlife-related recreation. The U.S. Army Corps of Engineers (ACOE) and U.S. Bureau of Reclamation (BOR) primarily provide recreation opportunities centered on waterways and flood- and irrigation-control facilities. The ACOE has facilities located across the United States, while the BOR facilities are nearly exclusively in the South and West. In addition to the land-focused Federal agencies, the National Oceanic and Atmospheric Administration's Office of National Marine Sanctuaries manages a system of 15 national marine sanctuaries and 2 marine national monuments that provide for shore- and ocean-going recreation within the ocean and Great Lakes.

Numerous specially designated areas, identified through Congressional legislation, and proclaimed areas, established by the Executive Branch, are present within Federal recreation lands. These resources include Wilderness, national wild and scenic rivers, national scenic areas, and national monuments. Designated Wilderness areas are established under the Wilderness Act of 1964 and constitute the National Wilderness Preservation System (NWPS). Wilderness areas are designated to preserve lands without human development and with natural processes as the centerpiece. In Wilderness, recreation is limited to non-mechanized opportunities and occurs in dispersed settings. Wilderness is generally thought to supply some of the best opportunities for solitude and remoteness. Although Wilderness areas tend to be far from population centers, many are readily accessible to populated places. The NWPS extends across 44 States with over 109 million acres that are managed by four Federal recreation agencies (Carlson et al. 2016) (table 11-3). The NPS manages the greatest number of NWPS acres (44 million), accounting for more than half of the NPS land base (Hoover 2014). The USDA Forest Service manages the second-greatest number of NWPS acres (36 million), but those lands amount to less than one-fifth of USDA Forest Service-managed lands. Nearly 95 percent of the Wilderness acres managed as part of the USDA Forest Service National Forest System (NFS) are in the West, with nearly equal amounts located in the RPA Rocky Mountain and Pacific Coast Regions (18 and 16 million acres, respectively). The RPA South Region has less than 1 million acres of Wilderness, while the North Region has about 1.5 million acres. This distribution reflects, in part, the presence of land that met the requirements for designation under the Wilderness Act. The spatial distribution of NFS Wilderness means that those living in the West have markedly greater access to Wilderness compared to those living elsewhere.

Table 11-3. Acres (1,000s) in the National Wilderness Preservation System by Federal agency and RPA region, circa 2012.

RPA region	USDA Forest Service	NPS	FWS	BLM	Region total
North	1,432	179	64	0	1,675
South	754	1,487	470	0	2,711
Rocky Mountain	18,188	1,349	1,465	4,611	25,614
Pacific Coast	15,777	40,885	18,704	4,089	79,455
Federal agency total	36,151	43,900	20,703	8,701	109,455

Pacific Coast Region does not include Alaska or Hawaii.

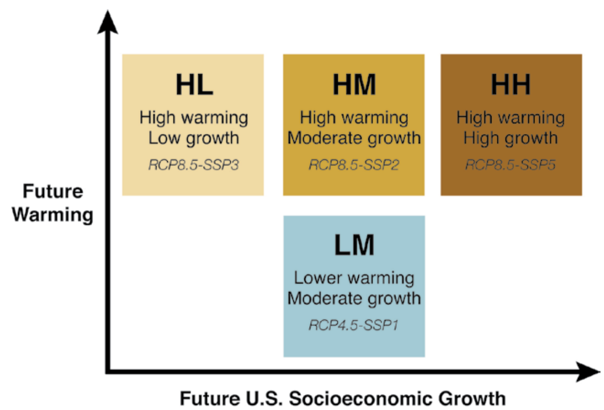
Source: Hoover 2014.

RPA Scenarios

The RPA Assessment uses a set of scenarios of coordinated future climate, population, and socioeconomic change to project resource availability and condition over the next 50 years. These scenarios provide a framework for objectively evaluating a plausible range of future resource outcomes.

The 2020 RPA Assessment draws from the global scenarios developed by the Intergovernmental Panel on Climate Change to examine the 2020 to 2070 time period (IPCC 2014). The RPA scenarios pair two alternative climate futures (Representative Concentration Pathways or RCPs) with four alternative socioeconomic futures (Shared Socioeconomic Pathways or SSPs) in the following combinations: RCP 4.5 and SSP1 (lower warming-moderate U.S. growth, LM), RCP 8.5 and SSP3 (high warming-low U.S. growth, HL), RCP 8.5 and SSP2 (high warming-moderate U.S. growth, HM), and RCP 8.5 and SSP5 (high warming-high U.S. growth, HH) (figure 11-1). The four 2020 RPA Assessment scenarios encompass the projected range of climate change from the RCPs and projected quantitative and qualitative range of socioeconomic change from the SSPs, resulting in four distinct futures that vary across a multitude of characteristics (figure 11-2), and providing a unifying framework that organizes the RPA Assessment natural

Figure 11-1. Characterization of the 2020 RPA Assessment scenarios in terms of future changes in atmospheric warming and U.S. socioeconomic growth. These characteristics are associated with the four underlying Representative Concentration Pathway (RCP) – Shared Socioeconomic Pathway (SSP) combinations.



Source: Langner et al. 2020.

Figure 11-2. Characteristics differentiating the 2020 RPA Assessment scenarios. These characteristics are associated with the four underlying Representative Concentration Pathway (RCP) – Shared Socioeconomic Pathway (SSP) combinations.

RPA Scenario (RCP-SSP)	Global Temperature Rise	U.S. Population Growth	U.S. Economic Growth Rate	Bioenergy Demand	Energy Sector Focus	Global Energy Usage	International Trade Openness
LM Lower warming Moderate growth *RCP4.5-SSP1*	Lower	Medium	Medium-High	High	Renewables	Low	Medium
HL High warming Low growth *RCP8.5-SSP3*	High	Low	Low	Low	Fossil fuels	Medium	Low
HM High warming Moderate growth *RCP8.5-SSP2*	High	Medium	Medium	Medium	Mixed	Medium	Medium
HH High warming High growth *RCP8.5-SSP5*	High	High	High	High	Fossil fuels	High	High

resource sector analyses around a consistent set of possible world views. The Scenarios Chapter describes how these scenarios were selected and paired; more details are provided in Langner et al. (2020).

The 2020 RPA Assessment pairs these four RPA scenarios with five different climate models that capture the wide range of projected future temperature and precipitation across the conterminous United States. An ensemble climate projection that averages across the multiple model projections is not used because of the importance of preserving individual model variability for resource modeling efforts. The five climate models selected by RPA represent least warm, hot, dry, wet, and middle-of-the-road climate futures for the conterminous United States (table 11-4); however, characteristics can vary at finer spatial scales. Although the same models were selected to develop climate projections for both lower and high-warming futures, there are distinct climate projections for each model associated with RCP 4.5 and RCP 8.5. The Scenarios Chapter describes how these climate models were selected. Joyce and Coulson (2020) give a more extensive explanation.

Throughout the RPA Assessment, individual scenario-climate futures are referred to by pairing RPA scenarios with selected climate projections. For example, an analysis run under "HL-wet" assumes a future with high atmospheric warming and low U.S. population and economic growth (HL RPA scenario), as well as a wetter climate for the conterminous United States (wet climate projection).

Table 11-4. Five climate models selected to reflect the range of the full set of 20 climate models in the year 2070. Each model was run under RCP 4.5 and RCP 8.5, providing a range of different U.S. climate projections.

	Least warm	Hot	Dry	Wet	Middle
Climate model	MRI-CGCM3	HadGEM2-ES	IPSL-CM5A-MR	CNRM-CM5	NorESM1-M
Institution	Meteorological Research Institute, Japan	Met Office Hadley Centre, United Kingdom	Institut Pierre Simon Laplace, France	National Centre of Meteorological Research, France	Norwegian Climate Center, Norway

Source: Joyce and Coulson 2020.

RCP = Representative Concentration Pathway.

Private Land Resources

The approximately 459 million acres of forests owned by individuals and families, private businesses, and land trusts and community-owned forests provide recreation opportunities for many in the United States. However, data are limited on the use of some of these lands for recreation and their availability to the public for recreation. Recreation opportunity on forests owned by individuals and families (272 million acres across the country) is almost exclusively available only to the owners' families and friends (Butler et al. 2020). Approximately 56 percent of the land owned by these individuals has been used in recent years for recreation by the owners, while 46 percent has been used by the owners' children and 41 percent by owners' friends (Butler et al. 2020). Individual and family forest parcels greater than 10 acres in size are more likely to be used for recreation by owners, family/friends, or the public (Butler et al. 2016, Butler and Snyder 2017). Owners identify recreation as a "very important" or "important" reason for owning about half of the forest land acres owned by individuals and families (Butler et al. 2020). Although recreation was often viewed as an important reason for owning land, only a small share of that forest land is managed to improve recreation opportunity. Approximately 25 percent of individual and family forest land acres (and 14 percent of ownerships) are part of holdings that have had trail improvements, and about 35 percent of acres (13 percent of ownerships) are part of holdings that have undergone management to improve wildlife habitat in the last 5 years (Butler et al. 2020).

Another source of recreation opportunity is the many forest industry corporations that make their lands at least partially available to the public. Many large corporate forest landowners (i.e., those owning more than 45,000 acres) provide a mix of free and fee-based recreation opportunities. In a survey of these owners, 74 percent reported allowing public recreation access for free and 85 percent for a fee (Sass, personal communication). In general, recreation is a low-priority management objective of corporate landowners (Sass et al. 2021). Somewhere between 15 and 75 percent of corporate owners (depending on company type) reported hunting as an ownership objective, while less than 40 percent reported recreation (more generally speaking) as an ownership objective (not mutually exclusive categories) (Sass et al. 2021).

Local, State, and national land trusts and community forests provide recreation opportunities on many lands they manage. In 2015, land trusts were responsible for conservation efforts on about 56 million open space acres across the United States and owned about 8 million of those acres (Land Trust Alliance 2016). More than 70 percent of lands managed by land trusts nationally are open for recreation. Like many landowners, land trusts often specify which recreation activities are permitted on lands they manage. For example, recreation activities may be limited to those that are non-consumptive and non-mechanized. Community forests—often owned by a nonprofit organization or local government—where management goals are guided by community boards, are also often open to recreation. Like land trusts, community forests can have restrictions on the types of recreation activities allowed on the lands they manage. The area managed as community forests across the United States is unknown (in part because what constitutes a community forest is poorly defined in the United States) but is less than the area managed by land trusts.

Changes Influencing Recreation Resources

Land Use and Ownership Change—Changes in land use and land ownership can alter the availability of both private and public land recreation resources. Conversion of private land from open space to developed uses, such as housing, businesses, or infrastructure, can reduce recreation opportunities that were historically available. This conversion can result in a reduction in the total area available for recreation and increased pressure on public land recreation resources, assuming the recreation engagement that historically happened on private land is displaced to public land—for example, an annual hunting trip to privately owned land that now occurs on State land. Although conversion to developed land uses is less common on publicly owned lands, changes in management or land designation can alter the availability of publicly owned land for recreation. Such changes can both increase (e.g., designation of lands where recreation opportunity is the primary focus) or restrict (e.g., expanding area designated for resource extraction or implementing a cap on the number of visitors) recreation opportunity.

Beyond land use changes, changes in property ownership can also alter access to recreation opportunities. In some cases, such as a land trust purchasing a property, recreation access may increase because of an ownership change. In other cases, changes in ownership can reduce recreation opportunities when new landowners restrict access that was previously granted.

How projected land use change may alter the availability of non-federally owned forests for recreation can be explored by examining the joint projections of future land use (described in the Land Resources Chapter) and population (described in the Scenarios Chapter) under the 2020 RPA Assessment scenarios (see the sidebar RPA Scenarios). Looking toward 2040 (and using the middle climate projection for illustration of potential scenario differences), many areas of the United States are projected to experience modest change in per capita non-federal forest area (figure 11-3). Under the moderate population and economic growth RPA scenario (LM), slight or moderate declines in forest area are most typical for 2040. In contrast, if population and economic growth is lower (the HL scenario), per capita non-Federal forest area declines are projected to be less and in some cases forest area may increase. When gains in per capita non-Federal forest area are projected, they are most commonly in northern areas of the RPA North and Rocky Mountain Regions. Gains in per capita non-Federal forest area become less common under moderate growth (LM) and almost nonexistent under a high-growth scenario (HH) as land use conversion rates increase. In the low-growth scenario, projected losses in per capita non-Federal forest area are mostly confined to the RPA South and southern Rocky Mountain Regions. Under the greater growth in the LM and HH scenarios, projected losses in per capita non-Federal forest area are found in every region and are most significant in the far north of the North Region, the northern portions of the Pacific Coast Region, and the southern portions of the Rocky Mountain Region. We use the lower atmospheric warming (LM) and the higher atmospheric warming (HL, HH) scenarios here to explore the range of potential forest land use changes under the middle climate projection and different atmospheric warming levels. However, these results can also differ with different climate projections (see the Land Resources Chapter for discussion of how a climate model influences land use projections).

Looking to 2070, the projected changes in per capita non-federal forest area are similar in pattern to those found in the 2040 projections (figure 11-4). Modest changes in per capita non-Federal forest area are still projected for multiple locations in each RPA region. When changes are projected, they are of greater magnitude in 2070 than in 2040. For example, gains in per capita forest area in the HL scenario and losses in per capita forest area in the HH scenario more frequently approach 5 percent.

Climate Change—Climate change can alter natural resource and environmental conditions in ways that change their desirability for recreation. Changing climate conditions can affect the frequency of natural disturbances (e.g., wildfire and flooding) with potential for dramatic, rapid changes in resource conditions, necessitating such managerial actions as limiting access to recreation resources. Changes in resource and

Figure 11-3. Differences in non-Federal forest acres per capita, 2012 to 2040. Differences are computed as the ratio of acres (hundreds) to population (tens), for RPA scenarios (a) Low Medium (LM), (b) High Low (HL), and (c) High High (HH) under the middle climate projection. Blue/purple areas have increasing per capita non-Federal forest lands, while red areas have decreasing per capita non-Federal forest lands. Areas shaded in gray (N/A) have no non-Federal forest lands or lack projections due to insufficient land use transition data.

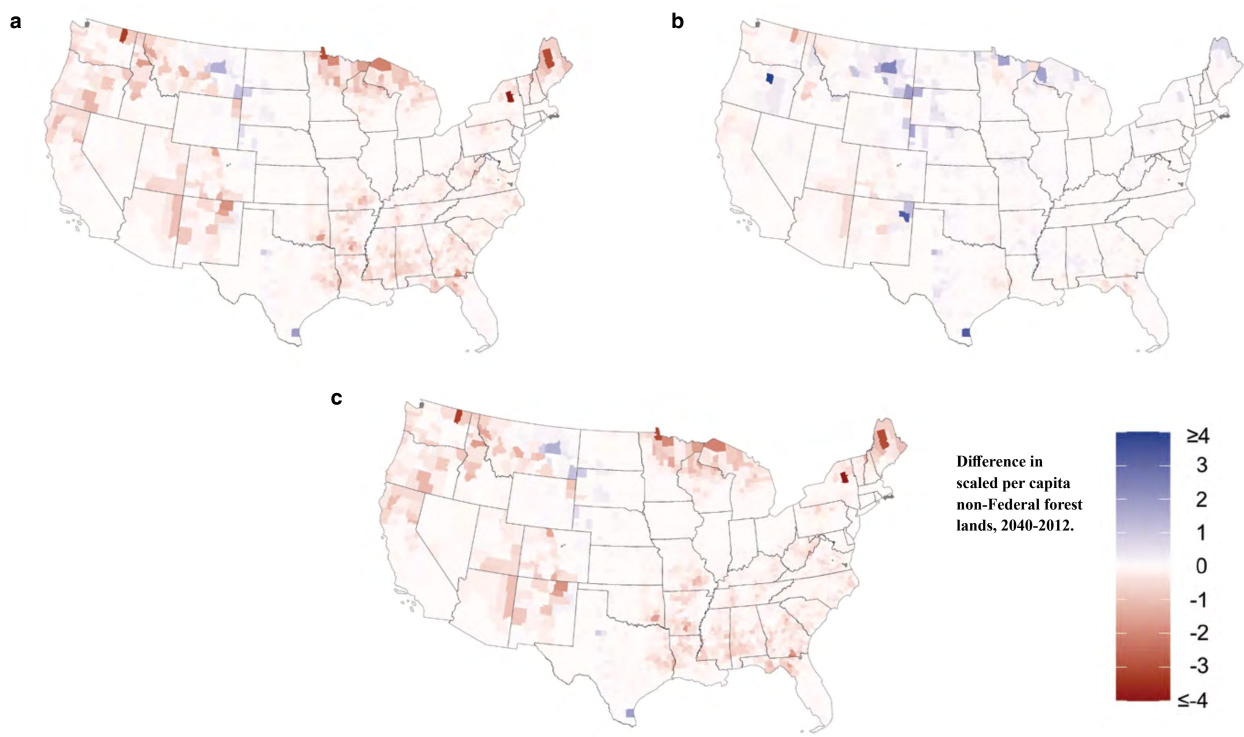
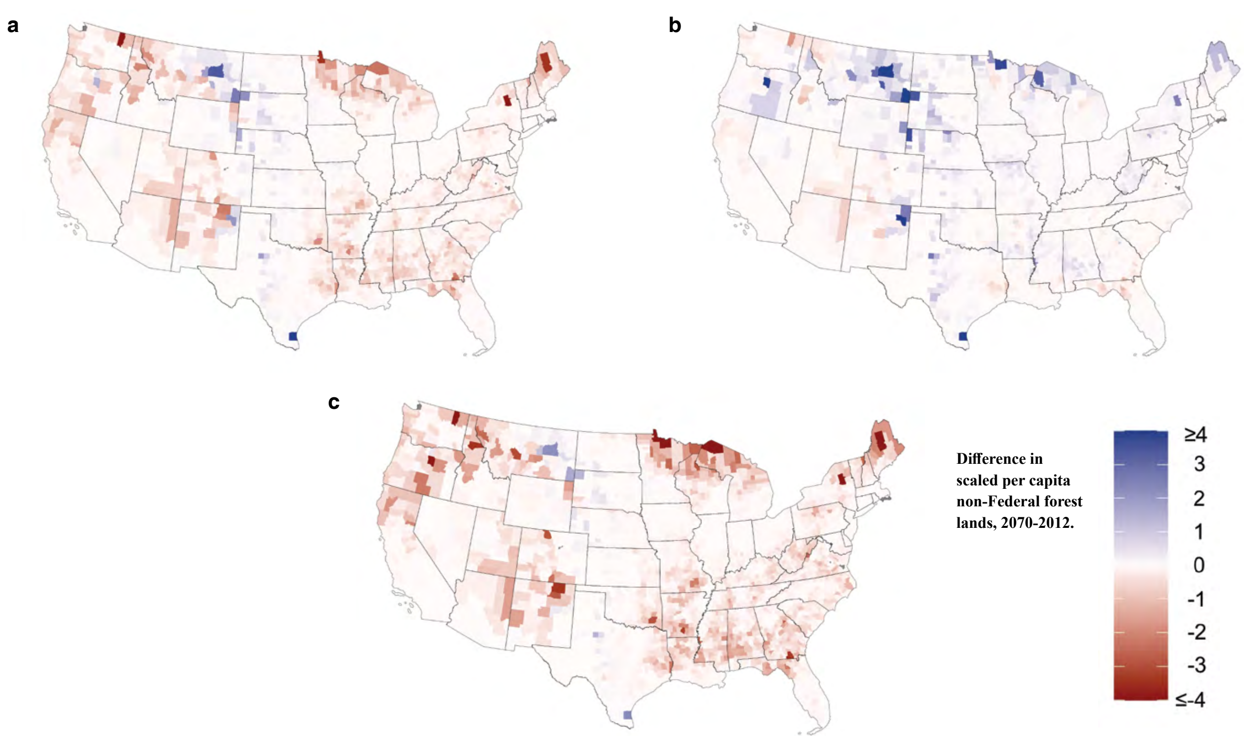


Figure 11-4. Differences in non-Federal forest acres per capita, 2012 to 2070. Differences are computed as the ratio of acres (hundreds) to population (tens), for RPA scenarios (a) Low Medium (LM), (b) High Low (HL), and (c) High High (HH) under the middle climate projection. Blue/purple areas have increasing per capita non-Federal forest lands, while red areas have decreasing per capita non-Federal forest lands. Areas shaded in gray (N/A) have no non-Federal forest lands or lack projections due to insufficient land use transition data.



environmental conditions can include those that make recreating more or less pleasant (e.g., temperatures that are too hot or not as cold as typical) or that change the feasibility or desirability of recreation (e.g., low water levels, changes in numbers or timing of flowers, shifts in bird migration patterns). Although many outcomes from climate change will likely reduce recreation opportunities (e.g., loss of natural snow in areas popular for snowmobiling or skiing), climate change may increase the availability of some recreation resources. For example, less snow and warmer springs may increase the length of time that some warm-weather recreation resources are snow-free and accessible. In this case, climate change has made snow-based activities less opportune while potentially favoring day hiking or horseback riding on trails.

Natural disturbances, such as wildfires, floods, and wind events, are ecological processes that have shaped the natural resources we see today. Present-day natural disturbance events can influence the availability of recreation resources by changing resource conditions or by creating hazardous conditions that result in managers or landowners reducing or restricting access to recreation resources. High-severity disturbances (e.g., severe wildfire) can dramatically alter vegetation conditions very rapidly. In general, the research conducted onsite in post-fire landscapes has found that recreation levels drop modestly immediately post-fire but trend back to pre-fire levels in relatively short order (e.g., Brown et al. 2008, McCaffrey et al. 2013, White et al. 2020). Onsite studies have found indications that burned landscapes do not dramatically change visitor satisfaction or reduce opportunities (e.g., White et al. 2020), but they do influence decisions about specific trail and campsite use (e.g., Love and Watson 1992, Schroeder and Schneider 2010). Other studies have examined how recreationists state they would respond to hypothetical burned landscapes, generally finding that burned landscapes reduce the value of recreation for recreationists and that post-fire landscapes can have different effects on recreation depending on fire severity and recreation activity (Bawa 2017). Less is known about the effects of high-severity flooding events on recreation-resource desirability. Over the last decade, public and private landowners have enacted temporary closures of their lands to recreation use in response to active wildfire, weather and forest conditions that yield a high risk of wildfire, and post-disturbance conditions (e.g., unstable slopes or dead trees) that may threaten visitor safety. In addition, there is now preliminary evidence that existing or potential smoke from wildfire is beginning to influence where and when visitors take outdoor recreation trips (e.g., Gellman et al. 2021, White et al. 2020). Continued increases in the frequency of natural disturbances over the coming decades may lead to more periods when natural resources are unavailable for recreation use. This has the potential to compress outdoor recreation to shorter periods during the year, to change the locations where people recreate, and to reduce the number of people engaging in outdoor recreation.

Engagement in Outdoor Recreation

- ❖ Participation rates have been steady in recent years with about 50 percent of the population engaging in outdoor recreation.
- ❖ The relative popularities of individual nature-based outdoor recreation activities have been generally stable over the last decade or longer with hiking, fishing, and camping being the most-popular activities.
- ❖ Outdoor recreation participation rates among minority groups and women have been increasing, albeit slowly.
- ❖ Public lands visitation has been increasing modestly at the Federal level and more rapidly at the State level.
- ❖ For those who have access, private lands are important providers of recreation opportunity for hunting, day hiking, fishing, and motorized off-road use.

Participation in Outdoor Recreation

About half of the U.S. population age 6 and older participates in some type of outdoor recreation (Outdoor Foundation 2019). That level of engagement in recreation has held relatively steady since 2007 (Outdoor Foundation 2018). In 2018, camping/backpacking, fishing, and day hiking were the nature-based outdoor recreation activities with the greatest numbers of participants (Outdoor Foundation 2019), with about 13 to 16 percent of the population participating in each of those activities. Beyond those three activities, participation rates for nature-based outdoor recreation activities range between about 1 to 10 percent of the population (Outdoor Foundation 2019). The motivations most cited for engaging in recreation were improvement of health, spending time with family and friends, experiencing nature, and getting away from other demands (Outdoor Foundation 2018).

Outdoor recreation participants are disproportionately male relative to the U.S. population, although participation rates among women have been increasing in recent years (Outdoor Foundation 2019). People under 24 typically have the highest rates of participation in outdoor recreation, but those over 25 account for most recreation participants (Outdoor Foundation 2018). The majority (74 percent) of outdoor recreation participants are White and about a third have annual household incomes over $100,000 (Outdoor Foundation 2019)—both disproportionately high relative to the U.S. population. Within their respective ethnicities, Asians have the highest rates of participation in

Table 11-5. Most-popular outdoor recreation activities by racial and ethnic group, 2018.

	White		Black		Hispanic		Asian	
Rank	Activity	Percent participating	Activity	Percent participating	Activity	Percent participating	Activity	Percent participating
1	Hiking	20.0	Running	17.3	Running	20.6	Running	26.1
2	Fishing	18.2	Biking	10.4	Biking	14.7	Hiking	21.2
3	Running	16.9	Fishing	9.9	Hiking	14.6	Biking	16.4
4	Camping	16.3	Camping	5.9	Camping	14.2	Camping	11.3
5	Biking	15.5	Hiking	5.5	Fishing	13.2	Fishing	9.9

Source: Adapted from Outdoor Foundation 2019.

outdoor recreation (nearly 70 percent engaging in outdoor recreation), followed by Whites (nearly 53 percent) and Hispanics (more than 40 percent). Participation among Asian and Pacific Islanders and Hispanics has been increasing since the 2010s (Outdoor Foundation 2019). Participation by Blacks in outdoor recreation is less than 40 percent and generally unchanged from observations in the early 2010s. Across all racial/ethnic groups, there was consistency in the set of most-popular outdoor recreation activities, but the popularity rankings of specific activities within the set differed across groups (table 11-5).

For most nature-based outdoor recreation activities, the share of the population participating was stable between 2007 and 2018 (Outdoor Foundation 2018, 2019) (table 11-6). With some exceptions, the share of the population participating in a specific activity in 2018 was within 1 to 2 percentage points of what was observed in 2007. The share of the population participating in day hiking did increase by about 5 percentage points over the timeframe, and the share of the population that engaged in freshwater fishing decreased by 3 percentage points. Camping (driven by losses in car camping and camping outside a home) and wildlife viewing both experienced declines in shares of the population participating that approached 2 percentage points. Trail running and recreational kayaking both saw gains in participation of 1 to 2 percentage points, although less than 4 percent of the population participated in those activities.

Although the share of the population that engaged in outdoor recreation remained relatively stable at around 50 percent between 2008 and 2018, the number of participants in outdoor recreation increased by about 15 million individuals because of continued U.S. population growth (Outdoor Foundation 2019). The increasing number of overall outdoor recreation participants was mirrored by growth in the number of participants engaging in many individual outdoor recreation activities. For those activities gaining participants, increases typically ranged between about 1 and 4 million new participants (table 11-7). However, day hiking experienced a gain of about 18 million additional participants between 2007 and 2018. Recreational kayaking and trail running each experienced about 6 million new participants over that period (Outdoor Foundation 2019).

Freshwater fishing saw the largest decline in number of participants during the period: a loss of about 5 million. The other largest declines in participant numbers were associated with wildlife viewing (2 million) and birdwatching away from home (1 million).

The average number of outings by those engaging in outdoor recreation has been declining year over year over the last decade or more (Outdoor Foundation 2019). Between 2017 and 2018, the average number of outings annually per participant declined by 7.4—a 10-percent decline (Outdoor Foundation 2018, 2019). However, those averages are

Table 11-6. Percent of U.S. population age 6 and older engaging in outdoor recreation activities, 2007, 2010, 2015, 2018.

Activity	2007	2010	2015	2018
Hiking (day)	10.8	11.5	12.7	15.9
Camping (car, backyard, backpacking, & RV)	15.1	14.9	13.6	13.9
Fishing (freshwater/other)	15.8	13.7	12.8	13
Wildlife viewing[a]	8.3	7.4	7	6.8
Hunting (rifle/shotgun/handgun/bow)	5.1	4.9	5.3	5.2
Birdwatching[a]	4.9	4.7	4.5	4.1
Kayaking (recreational)	1.8	2.3	3.2	3.7
Backpacking[a]	2.4	2.9	3.4	3.5
Skiing (Alpine/downhill)[b]	3.7	3.8	3.2	
Trail running	1.5	1.8	2.8	3.3
Canoeing	3.5	3.7	3.5	3
Bicycling (mountain/non-paved surface)	2.5	2.5	2.8	2.9
Snowboarding	2.5	2.6	2.6	2.4
Skiing (cross-country)	1.3	1.5	1.4	1.7
Sailing	1.4	1.4	1.4	1.2
Snowshoeing	0.9	1.2	1.3	1.2
Rafting	1.6	1.6	1.3	1.1
Kayaking (sea/touring)	0.5	0.8	1	0.9
Kayaking (white water)	0.4	0.6	0.9	0.9
Climbing (traditional/ice/mountaineering)	0.8	0.8	0.9	0.8

[a] *More than 1/4 mile from vehicle/home.*

[b] *No data available for 2018 due to redefinition of skiing aggregate from Alpine/Downhill to Alpine/Downhill/Freeski/Telemark (Outdoor Foundation 2019).*

Source: Outdoor Foundation 2019.

Table 11-7. Number of individuals age 6 and older engaging in outdoor recreation activities (millions), 2007, 2010, 2015, 2018.

Activity	2007	2010	2015	2018
Hiking (day)	30	32.5	37.2	47.9
Camping (car, backyard, backpacking, & RV)	41.7	42.3	40	41.7
Fishing (freshwater/other)	43.9	38.9	37.7	39
Wildlife viewing[a]	23	21	20.7	20.6
Hunting (rifle/shotgun/ handgun/bow)	14.1	14	15.5	15.7
Birdwatching[a]	13.5	13.3	13.1	12.3
Kayaking (recreational)	5.1	6.5	9.5	11
Backpacking[a]	6.6	8.3	10.1	10.5
Skiing (Alpine/downhill)[b]	10.4	10.9	9.4	
Trail running	4.2	5.1	8.1	10
Canoeing	9.8	10.6	10.2	9.1
Bicycling (mountain/non-paved surface)	6.9	7.2	8.3	8.7
Snowboarding	6.8	7.4	7.7	7.1
Skiing (cross-country)	3.5	4.2	4.1	5.1
Sailing	3.8	3.9	4.1	3.8
Snowshoeing	2.4	3.4	3.9	3.5
Rafting	4.3	4.5	3.9	3.4
Kayaking (sea/touring)	1.5	2.1	3.1	2.8
Kayaking (white water)	1.2	1.8	2.5	2.6
Climbing (traditional/ice/ mountaineering)	2.1	2.2	2.6	2.5

[a] *More than 1/4 mile from vehicle/home.*

[b] *No data available for 2018 due to redefinition of skiing aggregate from Alpine/Downhill to Alpine/ Downhill/Freeski/Telemark (Outdoor Foundation 2019).*

Source: Outdoor Foundation 2019.

driven, since 2014, by a reduction in engagement by the participants who recreate very frequently. In 2014, those participating in more than 100 outdoor recreation outings per year—the most avid recreationists—accounted for about 22.3 percent of all annual outings. By 2017, that most-avid group accounted for about 20.7 percent of all outings. Over that same period, those recreating 12 to 51 times per year accounted for a nearly constant share of outings and the share of outings from those engaging less than monthly increased slightly (Outdoor Foundation 2019). Ultimately, the share of outdoor recreationists with the greatest avidity levels has declined. In 2018, for those nature-based outdoor recreation activities for which values are reported, participants reported an average of 18 outings per year for fishing, 14 for day hiking, and 13 for camping (Outdoor Foundation 2019) (see the sidebar How COVID-19 Infection Rates and Location Characteristics Have Impacted USDA Forest Service Campground Reservations).

Youth between the ages of 6 and 17 had greater rates of participation in outdoor recreation than their adult counterparts (Outdoor Foundation 2018, 2019). The pattern of greater youth participation rates, relative to adults, has held since the mid-2000s (Outdoor Foundation 2018).

Despite their greater participation relative to adults, youth participation rates in outdoor recreation have declined slightly in recent years (Outdoor Foundation 2019). Among nature-based outdoor recreation activities, youth were most likely to participate in camping, fishing, and day hiking (table 11-8). Youth had higher rates of participation than adults for all activities except wildlife viewing and birdwatching, snowshoeing, and trail running. Participation rates by youth in specific outdoor recreation activities have been relatively stable over the last decade or more. However, there were marginal increases in participation rates for day hiking, kayaking, and hunting, and small declines for camping and fishing.

In addition to having greater participation in outdoor recreation than adults, youth also had more frequent engagement in recreation. Youth participants in outdoor recreation averaged more than 76 outings a year in recreational pursuits. On average, youth engaged in running (including trail running) and biking nearly weekly (45 and 40 outings per year, respectively). Outings for nature-based outdoor recreation occurred less often, with between 15 and 16 outings a year for day hiking and fishing, respectively, and 11 outings a year for camping.

Table 11-8. Percent of U.S. population ages 6 to 18 engaging in outdoor recreation activities, 2007, 2010, 2015, 2018.

Activity	2007	2010	2015	2018
Camping (car, backyard, backpacking, & RV)	24.3	23	21.1	20.5
Fishing (freshwater/other)	21.7	17.8	18.6	17.5
Hiking (day)	11.5	11.9	15	16.1
Wildlife viewing[a]	5.9	6	6.4	7.1
Hunting (rifle/shotgun/ handgun/bow)	4.2	4.4	6.7	6
Snowboarding	4.8	5.1	4	6
Kayaking (recreational)	2.1	2.3	4	4.9
Trail running	1.3	1.3	3.1	4.7
Backpacking[a]	3.6	4.4	5.8	4.6
Bicycling (mountain/non-paved surface)	3.5	3.8	3.8	3.8
Canoeing	5.1	5.6	4.8	3.8
Skiing (Alpine/downhill)[b]	4.4	4.8	4.2	
Birdwatching[a]	2.4	3.2	3.1	2.9
Skiing (cross-country)	1.1	1.5	2.1	2.7
Kayaking (sea/touring)	0.5	0.7	1.7	1.6
Kayaking (white water)	0.4	0.5	1.6	1.6
Sailing	1	1.2	1.8	1.6
Snowshoeing	0.8	1.2	1.4	1.4
Climbing (traditional/ice/ mountaineering)	1	0.7	1.5	1.3
Rafting	2	1.9	2.1	1.2

[a] *More than 1/4 mile from vehicle/home.*

[b] *No data available for 2018 due to redefinition of skiing aggregate from Alpine/Downhill to Alpine/ Downhill/Freeski/Telemark (Outdoor Foundation 2019).*

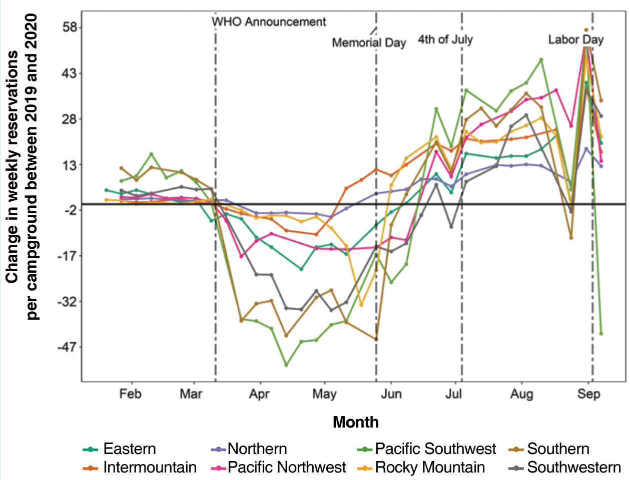
Source: Outdoor Foundation 2019.

How COVID-19 Infection Rates and Location Characteristics Have Impacted USDA Forest Service Campground Reservations

During the COVID-19 pandemic, U.S. public land managers were faced with the unique challenge of maintaining social distancing requirements while experiencing increased visitation. Shartaj et al. (2022) investigated the sizeable increase in reservations that occurred during the summer of 2020 by analyzing final reservations to National Forest System (NFS) campgrounds in the conterminous United States (figure 11-5). The authors highlight the local infection rates, public policies, and proximity to national parks, metropolitan areas, and wildfire on NFS camping demand.

Camping has typically been perceived as a safer form of leisure activity during periods of high virus transmission risk. During the summer of 2020, campgrounds saw a nearly 40-percent increase in average nightly reservations. The mean weekly nights reserved per campground stood at 50.35 during the year. This analysis revealed a positive correlation between the number of reservations at a campground and COVID infection rates in the surrounding county. Public policies were also shown to affect campground reservations: stay-at-home advisory orders significantly reduced campground reservations in both the spring and the summer of 2020. The study showed that being near a national park or a metropolitan area also resulted in considerable increases in summertime NFS campground nights reserved. The magnitude of the increases due to proximity to national parks and metropolitan areas represent 13 and 27 of mean camping nights reserved in 2020, respectively. USDA Forest Service campgrounds near national parks saw particularly large increases when individuals visiting national parks for other recreation activities camped at NFS campgrounds due either to preference or because of national park campground unavailability. NFS campgrounds located near populated metropolitan areas faced increased visitation due to travel restrictions and general lack of COVID-safe recreation activities. Finally, campgrounds located near wildfire boundaries experienced declines in nights reserved in the weeks that the fires were active.

Figure 11-5. Changes in weekly nights reserved per campground between 2019 and 2020 by week for USDA Forest Service regions.



See https://www.fs.usda.gov/about-agency/contact-us/regional-offices for region locations. The World Health Organization (WHO) characterized COVID-19 as a pandemic on March 11, 2020.

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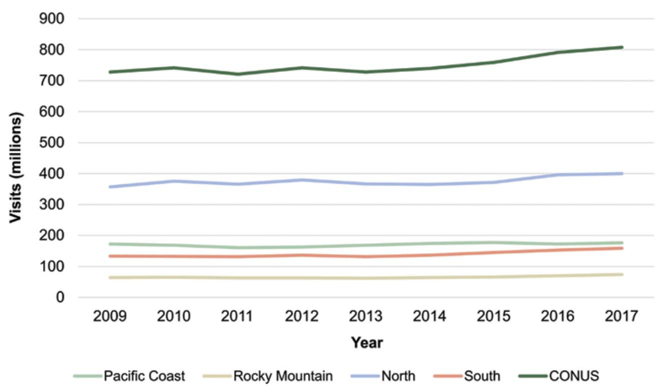
Use of Recreation Resources

Local and State Governments—Local government public lands provide ready access for those living in cities, towns, and residential areas. Although the amount of recreation use at these places in aggregate is likely substantial because of the sheer number of resources and proximity to potential users, there is no reliable estimate of total recreation use at lands managed by local governments. Despite some local governments monitoring the amount of recreation use, there is no comprehensive system to compile those estimates. Partial accounting by The Trust for Public Land's City Park Facts indicates there are more than 240 million visits each year to the most-visited units within the local park systems of the 100 most-populated cities (The Trust for Public Land 2020). Ultimately, many local governments simply lack the funding, capacity, and tools to quantify recreation use at their parks and open spaces (see the sidebar Using Crowd-Sourced and Social Media Data to Understand Recreation Use).

Visitation to State park systems in the United States has increased in recent years after a slowdown in the mid-2000s. In 2018, visitation to State park agencies (813 million visits) was greater than any year since consistent national-level accounting began (Smith et al. 2020). State park systems in the RPA North Region account for nearly half of all visits in the conterminous United States (figure 11-6). The RPA Pacific Coast and South Regions account for nearly equal shares of visits; the RPA Rocky Mountain Region has the lowest total visitation to State park system lands. Since 2009, the RPA South Region has experienced the greatest increase in State park visitation: an 18-percent increase over the period. Over the same timeframe, State park visitation in the RPA Pacific Coast Region increased by only 2 percent.

Figure 11-6. Annual visitation to State park systems by RPA region and conterminous United States (CONUS), 2009 to 2017. Most State park visitation regionally occurs in the North Region, comprising approximately half of the visits for the conterminous United States.



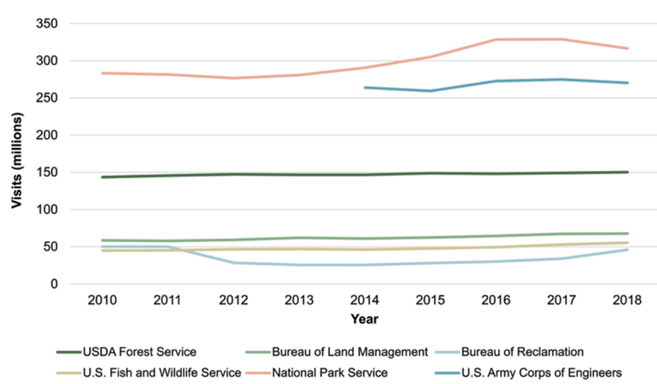
Source: Smith and Leung 2019.

Federal Agencies—Recreation is the primary way that most people engage with federally owned natural resource lands. There are more than 900 million visits each year to federally managed recreation lands. The NPS leads the Federal agencies in the number of recreation visits with more than 316 million visits each year (figure 11-7). The USDA Forest Service receives about 150 million visits to NFS lands each year. The number of visits annually to Federal lands (excluding the ACOE) has increased slightly since 2010. The FWS and the BLM had the greatest percentage increases (by 23 and 16 percent, respectively) over the period, while the NPS experienced the greatest nominal visit increase (about 33 million additional visits).

The USDA Forest Service National Visitor Use Monitoring (NVUM) Program provides the most comprehensive and consistent data about recreationists using Federal lands (Leggett et al. 2017). Results from the NVUM Program can provide insight into how recreation patterns on federally managed lands compare to national recreation patterns. The most-popular outdoor recreation activities across the United States (see prior section) are also common on NFS land (USDA Forest Service 2020). For example, both nationally and on NFS lands, hiking is the most common recreation activity. However, the types of recreation opportunities available on NFS land do lead to some key differences. For example, downhill skiing/snowboarding is the second-most common primary activity on NFS land but a less common activity when considering recreation on all lands. That difference results because public lands, particularly NFS lands, provide much more downhill skiing opportunity than private lands. The relative popularity of different recreation activities on NFS lands has been stable over the last decade or more. The most common recreation activities (hiking, viewing nature, and skiing/snowboarding) have maintained their prominence and the number of visits for less-common activities have generally held steady.

More than 60 percent of visits to NFS lands are made by men—generally consistent with the demographic patterns of outdoor recreation participants nationally (USDA Forest Service 2020). Whites account for the vast majority of visits to the NFS. On average, NFS recreation visits come from users with above-average incomes and users between ages 30 and 60 (USDA Forest Service 2020). The demographic patterns of visits to the NFS have been relatively stable over time. On average, more than half of visits come from those who have traveled less than 50 miles from home (USDA Forest Service 2020). That pattern is consistent with the distance people commonly travel to engage in outdoor recreation on all lands (Outdoor Foundation 2019); however, visitors often travel much greater distances to visit unique NFS recreation resources and many NPS destinations. Most outdoor recreation visits on NFS lands are short: nearly 40 percent last less than 3 hours (USDA Forest Service 2020). An additional 30 percent of visits last between 3 and 6 hours.

Figure 11-7. Annual visitation to federally managed outdoor recreation resources.



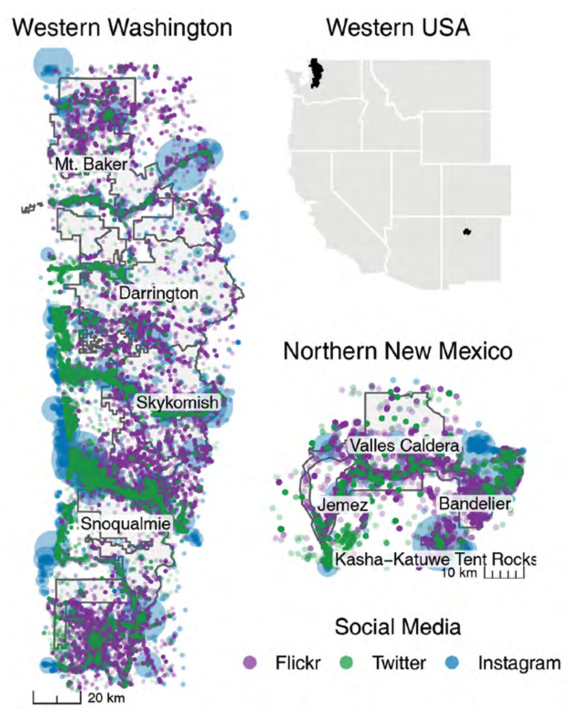
Note: The Army Corps of Engineers (ACOE) visit estimation procedure was revised beginning in 2014; prior year data is not comparable to the current approach used by ACOE. Day visits to the ACOE are measured in units equivalent to the visits of other agencies. However, overnight visits to the ACOE are measured in person nights, which would yield a higher recreation use estimate than the visits measure used by the other agencies.

Sources: Chang 2020 (ACOE); English 2020 (USDA Forest Service); Miller 2020 (NPS, BLM, FWS, and BOR).

Using Crowd-Sourced and Social Media Data To Understand Recreation Use

Common approaches to recreation monitoring, such as traffic counters and visitor surveys, are useful for gathering consistent, long-term data about recreation on public lands. Traditional approaches can be time-consuming, relatively costly, and challenging to use. A growing body of peer-reviewed research shows that volunteered geographic data from social media can complement existing information about visitor distributions, behaviors, and preferences (Fisher et al. 2018, Sessions et al. 2018, Wood et al. 2013). Visitors to public lands often share digital information about their experience in the form of photos, posts, or trip logs, some of which are geographically specific. One recent study examining the promise and potential pitfalls of using social media to estimate recreational use in the United States (Wood et al. 2020) found that the number of social media posts shared in a location can substantially improve visitor estimates at unmonitored sites. Visitation estimates are further improved when models are parameterized with onsite counts, showing that although social media posts do not fully substitute for onsite data, they can be a powerful component of recreation research and visitor management.

Figure 11-8. Spatial coverage of geotagged posts from multiple social media platforms (Flickr, Twitter, and Instagram) across areas in western Washington and northern New Mexico. Points represent the latitude and longitude where a Flickr photograph (purple) or tweet (green) was created. For Instagram, points represent places to which images were assigned by users (blue). Larger points represent a greater number of Instagram posts from the location.



Studies have concluded that there are potential advantages, but also limitations, to monitoring recreation with volunteered geographic information. The spatial and temporal coverage of social media makes the information widely available year-round and independent of land ownership (figure 11-8). Nonetheless, social media users are a self-selected population. Individuals use a variety of social media platforms, and the cost of data access can vary by source. Social media data may be most beneficial for filling in spatial and temporal gaps in traditional recreation monitoring programs, to capture unique events or other situations that might cause visitation to deviate from the long-term trend (Wood et al. 2020). Future research is necessary to understand how volunteered data can be fully leveraged to improve the accuracy and efficiency of recreation monitoring efforts.

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Private Lands—Understanding the amount of recreation use involving recreation resources helps managers, policymakers, and researchers assess the relative contribution of different types of recreation resources in meeting recreation demand. Unfortunately, recreation use of private lands has not been quantified. Although there is no comprehensive estimate of the amount of outdoor recreation use on private lands, surveys of outdoor recreationists and landowners indicate that outdoor recreationists are indeed using private lands to recreate (USDA Forest Service 2012). For example, more than half of the forest land owned by individuals and families is used for recreation by the owners (Butler et al. 2020). Further, about 5 percent of the forest land area owned by individuals and families is available to the public for recreation (Butler et al. 2020). The most common recreational use of forest lands owned by individuals and families is hunting, followed by fishing, hiking/walking, and off-highway vehicle recreation. Private lands are a key recreation provider for some activities and in some regions. For example, across the United States, and particularly in the RPA South Region, private land recreation resources are important places for hunting (USDA Forest Service 2012). Private land recreation may be informal, such as individuals recreating on lands owned by family or friends, or more formal such as individuals purchasing permits to recreate on lands owned by forest industry (e.g., Mingie et al. 2017).

COVID-19 Pandemic—The pandemic, the associated reduction in other leisure opportunities, and the desire to engage in activities that seemingly posed limited COVID exposure risk led to increased participation and engagement in outdoor recreation in 2020. In 2020, the share of the U.S. population participating in recreation increased by 2 percentage points (to 53 percent) and about 7.1 million people (Outdoor Foundation 2021a). Those 2020 participants renewing their participation in outdoor recreation or engaging for the first time were most likely to participate in walking/hiking (47 percent) followed by outdoor running/jogging (28 percent) and outdoor bicycling (26 percent) (Outdoor Foundation 2021b). About half of the newly engaging participants in 2020 reported that they had previously engaged in their recreation activity and were returning (Outdoor Foundation 2021b). Although the number of participants in outdoor recreation increased in 2020, it appeared that participants did not change the number of times

COVID-19 and Recreation Visitation to NFS Units

The COVID-19 pandemic had wide-ranging and substantial effects on the amount of recreation visitation to National Forest System (NFS) lands during most of 2020. National Visitor Use Monitoring (NVUM) sampling occurred on 24 NFS reporting units spread across the country during fiscal year 2020 (October 2019 to October 2020). These same units were previously sampled in 2015, as part of the 5-year NVUM cycle. The observed differences in visitation between the 2015 and 2020 samples were similar across the sampled units.

We observed a general loss in visitation at developed sites, primarily owing to shortened seasons due to COVID-19 closures. A number of downhill ski areas closed for their spring season, and many saw large reductions in summer use. Visitor centers, picnic areas, and other types of day use facilities that normally support concentrated visitation had closures and/or use limitations from April 2020 onwards. In many parts of the country, larger campgrounds opened later in the year, and group campsites had very little usage. Use of smaller day-use sites and campgrounds, however, rebounded substantially starting in mid-summer.

In comparison, visitation to dispersed settings boomed as people sought outdoor experiences in uncrowded spaces. Visitation rates to undeveloped general forest settings rose by more than 50 percent in April to October 2020, compared to observed visitation in 2015. Access points that normally see lower levels of use saw the greatest increases in visitation. In contrast, the most-popular locations had only moderate levels of increased visitation. Visitation rates to Wilderness access points were more than double the rates observed in 2015. The greatest proportional increases in visitation occurred at less popular locations.

To develop an accurate national visit estimate for 2020, we needed to account for the likely increased visitation at units not sampled in 2020. We calculated the percent change in visitation between the 2015 and 2020 observed on the 2020 sample forests in the last half of the fiscal year, adjusted for a normal growth rate over time, and applied that percentage change to the NFS units that were not sampled in 2020. In total, the NFS saw about 18 million more visits (a 12-percent increase) in 2020 than in 2019. The increase in use is well above the year-to-year increases observed in recent years (table 11-9).

Table 11-9. NVUM-based estimates of recreation visits (millions) on NFS lands across four site types for FY2019 and FY2020, with computed differences (millions) between the two time periods.

	FY2019 (millions)	FY2020 (millions)	Change from 2019 (millions)
Day use developed sites	77.4	74.9	-2.5
Overnight use developed sites	14.2	12.9	-1.3
General forest areas	93.2	115.9	+22.7
Wilderness	9.0	16.0	+7.0
Total site visits	193.9	219.7	+25.8
National Forest visits	150.0	168.2	+18.2

FY = fiscal year; NFS = National Forest System; NVUM = National Visitor Use Monitoring.

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they engaged in recreation in 2020 (Outdoor Foundation 2020a). There were inconsistent patterns in the change in visitation to Federal lands in 2020. Combined visitation to all NPS units in 2020 declined by 26 percent, but visitation at 15 units set records in 2020 (NPS 2021). For the USDA Forest Service, visitation increased by about 12 percent, but those increases were confined to dispersed recreation opportunities, such as trails (see the sidebar COVID-19 and Recreation Visitation to NFS Units). Although it is unknown what will happen, there is little to suggest that COVID-induced recreation patterns will influence long-term (decades hence) patterns in recreation participation. About 25 percent of the new or renewing participants in 2020 reported their intention to discontinue recreating in future years (Outdoor Foundation 2021b). Further, although the significant events of the first decades of the 21st century (e.g., the September 11th terrorist attacks, the Great Financial Crisis, and spikes in gasoline prices) did yield observable changes in recreation patterns, those changes were ultimately transitory, and patterns returned to baseline trends. However, one important unknown is whether an overly long COVID pandemic, driven by vaccine reluctance, or a cycle of recurring pandemics over the coming decades could yield sustained, long-term changes in recreation patterns.

Projection of Future Recreation Demand

- ❖ Modest changes in per capita participation are projected for almost all activities, with a slight majority of activities projected to experience decreased per capita participation rates in the coming decades.
- ❖ Downhill skiing and snowboarding, motorized water use, equestrian riding on trails, and mountain biking are projected to see moderate increases in per capita participation levels in most scenarios, while hunting and motorized snow use are projected to have the largest declines in per capita participation in future decades.
- ❖ The numbers of participants and days of engagement are projected to increase under most scenarios for most recreation activities, primarily attributable to projected population growth.
- ❖ Developed site use, swimming, and day hiking are projected to have the greatest numbers of participants.
- ❖ Lower levels of atmospheric warming generally lead to greater participant numbers.
- ❖ Projected declines in participants and consumption are generally confined to the low population growth and economic development scenario and the RPA North Region.

To be successful, recreation managers and policymakers plan and manage for both current and anticipated future recreation demand. Understanding how recreation demand might change can provide insight into how people will interact with natural resources in the future and inform short- and long-term planning about recreation resource investment. As in prior RPA Assessments, we project recreation demand 50 years into the future. In this assessment, we use a base year of 2012 and project demand for each decade to 2070. We develop estimates of how many people are projected to engage in outdoor recreation in the future, along with the frequency of their engagement.

Projection Methods

As in prior RPA Assessments, we develop projections of future recreation participation and consumption for a set of outdoor recreation activities and activity aggregates (hereafter activity(ies)) (table 11-10). Aside from nature viewing, which includes birding, all other activities are mutually exclusive, and recreationists may engage in one or more at least once within the year. The activity set used here differs slightly from those used in prior RPA Assessments (e.g., Bowker et al. 2012). The set of activities we use in this assessment aligns better with those considered by the Outdoor Foundation in their studies of U.S. outdoor recreation engagement (e.g., Outdoor Foundation 2019) and the activity set used by the USDA Forest Service in their recreation monitoring program, National Visitor Use Monitoring. In this RPA Assessment, we treat camping in developed campgrounds as a unique individual activity. Conversely, we merge the previously used developed site use aggregate (minus developed site camping) and the previously used visiting interpretative sites aggregate into a single developed site use aggregate. Finally, after treating mountain biking as an individual activity, we removed from analysis the remaining “challenge activities” considered in prior assessments, an aggregate of mountain climbing, rock climbing, and caving.

We followed the approach used in the 2010 RPA Assessment and the Update to the 2010 RPA Assessment to project future recreation demand (Askew and Bowker 2018, Bowker et al. 2012). For each outdoor recreation activity, we project both future participation and consumption. Participation is a measure of how many people are engaged in each recreation activity; consumption is a measure of the magnitude of recreation occurrences for that activity. The former provides insight into how popular or common a recreation activity is among the population, and the latter can provide information on the number of recreation occurrences that managers and policymakers might expect.

To project future participation in outdoor recreation, we developed statistical models of anticipated per capita

Table 11-10. Recreation activities and assumed initial outdoor recreation engagement in 2012.

Activity or activity grouping	**Population participating** (percent of the U.S. population, 16 and over)	**Days of participation each year**
Developed site recreation		
Developed site use—family gatherings, picnicking, etc.	37.6	12.0
Camping in developed campgrounds	10.2	7.7
Viewing/photographing nature		
Viewing nature—related to fauna, flora, or natural settings	7.7	15.5
Birding—viewing or photographing birds[a]	4.9	14.2
Non-motorized, undeveloped activities		
Day hiking	12.5	15.3
Primitive area activities—undeveloped area camping, backpacking, visiting Wilderness	2.8	1.5
Mountain biking	2.5	19.8
Equestrian riding on trails	1.4	12.7
Motorized activities		
Motorized water use	11.1	13.3
Motorized off-road use	8.6	16.4
Motorized snow use—snowmobiling	2.5	6.7
Hunting and fishing		
Fishing—anadromous, cold-water, saltwater, warm-water	12.5	16.0
Hunting—small game, big game, migratory bird, other	5.1	18.9
Non-motorized winter activities		
Downhill skiing and snowboarding	6.8	6.4
Cross-country skiing and snowshoeing	3.8	5.3
Non-motorized water activities		
Swimming—swimming, snorkeling, and scuba diving	19.6	12.0
Floating—canoeing, kayaking, or rafting	4.1	6.0

[a] *Birding participation rates and days of participation are also incorporated in the values for viewing nature.*

Source: Initial values were based on the Outdoor Industry Association (Outdoor Foundation 2018), in conjunction with the National Survey on Recreation and the Environment (NSRE). These were obtained either directly, by activity matching between the Outdoor Foundation and NSRE, or indirectly, by formulating Outdoor Foundation-based scalars for adjustments of NSRE estimates (for more conservative estimation).

participation for each activity. The per capita participation rates identify the share of the respective adult populations engaging in each activity. We combined those per capita participation rates with projections of future population to arrive at the projected number of future participants. To project future consumption of outdoor recreation, we developed statistical models to project how many days per year those participating in a specific activity will engage in that activity. We combined those average days per participant with the projections of number of future participants to arrive at an estimate of total projected consumption (measured in total participant days per year).

Models of per capita participation and consumption are estimated for each activity and for all adults (16 and older), within each RPA region. The national-level figures reported here are developed from aggregating the regional-level results, after accounting for differences in regional populations. Our projections of future demand do not include individuals living in Alaska, Hawaii, or the U.S. territories because we lack data to characterize recreation use of those populations. Models include variables to describe anticipated socio-demographic characteristics of future populations as well as variables related to regional recreation resource supply and climatic conditions. Model variables used to describe climatic conditions include seasonal maximum or minimum temperature, seasonal precipitation, and potential evapotranspiration (a water loss measure that combines information about temperature, humidity, sunlight, and wind). Following Askew and Bowker (2018), each activity model incorporates one, best statistically performing, climate variable. More detailed regional-level results and model specifications will be provided in future RPA Assessment supporting documents.

We project recreation demand for the four future scenarios recognized in this RPA Assessment (see the sidebar RPA Scenarios). Taken individually, the scenarios provide information on the potential outcomes in recreation demand under a specific set of future conditions. Collectively, our recreation projections under the four scenarios provide insight into the potential range of demand for outdoor recreation in the future. Pairwise comparisons between scenarios offer the opportunity to isolate the influences of changing climatic and socioeconomic conditions. Because the assumed socioeconomic trajectories in the Low Moderate (LM) and High Moderate (HM) scenarios are very similar (Langner et al. 2020), differences in recreation outcomes between those scenarios primarily trace to different projections of future climatic change as influenced by different levels of atmospheric warming (see the sidebar RPA Scenarios). Thus, we compare the projections of future recreation demand under the LM and HM scenarios to assess the influence of atmospheric warming on recreation demand. Likewise, because the assumed future atmospheric warming conditions are identical in the High Low (HL) and High High (HH) scenarios (Langner et al. 2020), any differences in recreation outcomes reflect the influence of socioeconomic change on recreation demand. Thus, we compare the projections of future demand under the HL and HH scenarios to assess the influence of socioeconomic change on recreation demand.

Activity Participation Rates and the Influence of Future Climate and Socioeconomic Pathways

Our projections of future participation rates represent the share of the U.S. population age 16 and older expected to participate in an activity at least once a year under each of the RPA scenarios. In this analysis, we focus on projections for 2070 to consider the relative effects of climate and socioeconomic change on per capita participation (results for 2040 are available in the next section of this chapter). For each activity and scenario, we calculated the mean indexed participation (2070 relative to 2012) across the five climate projections. We then compared those mean indexed participation values between paired RPA scenarios (i.e., LM versus HM, HL versus HH) to classify each activity as exhibiting relative sensitivity primarily to future climate, future socioeconomic conditions, both, or neither. Across the 17 activities considered here, we project that between 2012 and 2070, six activities will experience an increase in per capita participation, nine will experience a decline, and two will see little change (table 11-11). Projected participation in six of our activities exhibited sensitivity to differences in the socioeconomic change in our scenarios and six were sensitive to both socioeconomic change and climatic change. Five activities exhibited little sensitivity to either socioeconomic or climatic change. Aside from assumed level of atmospheric warming associated with the RPA scenario, projected per capita participation for several of our activities was sensitive to one or more climate projections. When projected participation rates were sensitive to climate projection, higher rates of participation were frequently associated with the least warm climate projection and lower rates of participation were frequently associated with the hot climate projection.

We use two graphs for each activity to explore the sensitivities of the activity to the influence of changing climate (LM versus HM) and socioeconomic conditions (HL versus HH). In graphing future outlooks for a given activity, the vertical and horizontal axes correspond to paired RPA scenarios (S_1 and S_2, respectively); each graph depicts a comparison of indexed per capita participation rate in 2070 under the scenarios jointly (figure 11-9). The indexed participation rates are computed relative to the participation rate observed in the base year 2012, and values reflect a percentage change from the 2012 estimate. A value greater than 1.0 indicates a higher projected participation rate than that observed in 2012. For example, if the projected participation rate in 2070 was 20 percent and the observed participation rate in 2012 was 15 percent, the resulting indexed participation rate would be 1.33. Conversely, a value less than 1.0 indicates a lower projected participation rate in 2070 relative to 2012. For example, if the projected participation rate in 2070 was 5 percent and the observed participation rate in 2012 was 10 percent, the resulting indexed participation rate would be 0.50. The markers on the graph represent the pairwise values of projected participation for 2070 between Scenarios S_1 and S_2. The star marker represents the comparison between scenarios of the mean indexed participation rate across the five climate projections; the other shapes represent comparisons for the individual climate projections (see the sidebar RPA Scenarios). A marker located above the solid diagonal line (area A of the graph) indicates that projected participation rates in 2070 are greater in Scenario S_1 compared to Scenario S_2 for that climate model. A marker located below the solid diagonal line (area B of the graph) indicates the opposite. The distance the marker is located from the solid line depicts the magnitude of the difference in projected participation rates between the two scenarios: markers nearest the diagonal line indicate smaller differences between the scenarios. Markers above the smaller dashed horizontal line (area C of the graph) indicate the projected participation rate in 2070 is greater than the rate observed in 2012 under Scenario S_1. Markers located below the smaller dashed horizontal line (area D in the graph) indicate the projected participation rate in 2070 is lower than the rate observed in 2012 under Scenario S_1. Areas on either side of the longer dashed vertical line (E and F in the graph) have the same meanings, but for Scenario S_2. It is possible that results under both scenarios S_1 and S_2 may jointly yield projections of future participation that are higher (or lower) than that observed in 2012.

Atmospheric Warming as Primary Driver: LM versus HM—No activities exhibited responsiveness primarily to changing climate conditions alone, represented by the differences in atmospheric warming between our LM and

Figure 11-9. Example comparison of relative per capita participation indices in example scenarios S_1 and S_2. See text for descriptions of letters A through F.

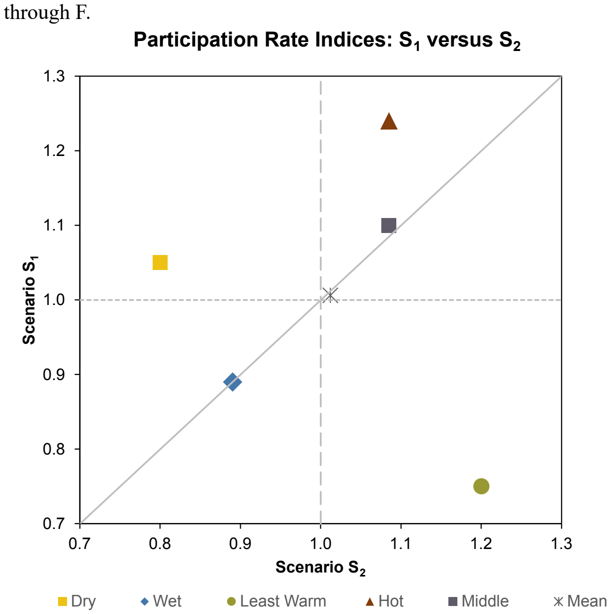


Table 11-11. Projected changes in per capita participation between 2012 and 2070 and the relationship of influencing factors to participation rate.

Activity or activity grouping	Projected change in per capita participation between 2012 and 2070	Responsiveness to socioeconomic change or climactic change	Influence of higher levels of socioeconomic growth on per capita participation	Influence of higher levels of atmospheric warming on per capita participation	Climate projection(s) leading to highest projected per capita participation	Climate projection(s) leading to lowest projected per capita participation
Developed site recreation						
Developed site use—family gatherings, picnicking, etc.	⇔	Neither	⇔	⇔	⇔	⇔
Camping in developed campgrounds	⬇	Socioeconomic change	⬇	⇔	Dry	Least warm
Viewing/photographing nature						
Viewing nature—related to fauna, flora, or natural settings	⇔	Neither	⇔	⇔	⇔	⇔
Birding—viewing or photographing birds[a]	↓	Neither	⇔	⇔	Least warm	Hot
Non-motorized, undeveloped activities						
Day hiking	↑	Both	⬆	⬇	Least warm, Wet	Hot
Primitive area activities—undeveloped area camping, backpacking, visiting Wilderness	⬇	None	⇔	⇔	Least warm	Hot, Middle
Mountain biking	↑	Both	⬆	⬇	⇔	⇔
Equestrian riding on trails	⬆	Socioeconomic change	⬆	⇔	Hot, Middle	⇔
Motorized activities						
Motorized water use	⬆	Socioeconomic change	⬆	⇔	Hot, Middle	Least warm
Motorized off-road use	⬇	Socioeconomic change	⬇	⇔	⇔	⇔
Motorized snow use—snowmobiling	⬇	Both	⬆	⬇	Least warm	Hot, Dry
Hunting and fishing						
Fishing—anadromous, cold-water, saltwater, warm-water	↓	None	⇔	⇔	Middle	Hot
Hunting—small game, big game, migratory bird, other	⬇	Socioeconomic change	⬇	⇔	⇔	⇔
Non-motorized winter activities						
Downhill skiing and snowboarding	⬆	Socioeconomic change	⬆	⇔	⇔	⇔
Cross-country skiing and snowshoeing	↓	Both	⬆	⬇	Least warm	⇔
Non-motorized water activities						
Swimming—swimming, snorkeling, and scuba diving	↑	Both	⬆	⬇	Wet, Least warm	Hot
Floating—canoeing, kayaking, or rafting	⬇	Both	⬆	⬇	Wet, Least warm	⇔

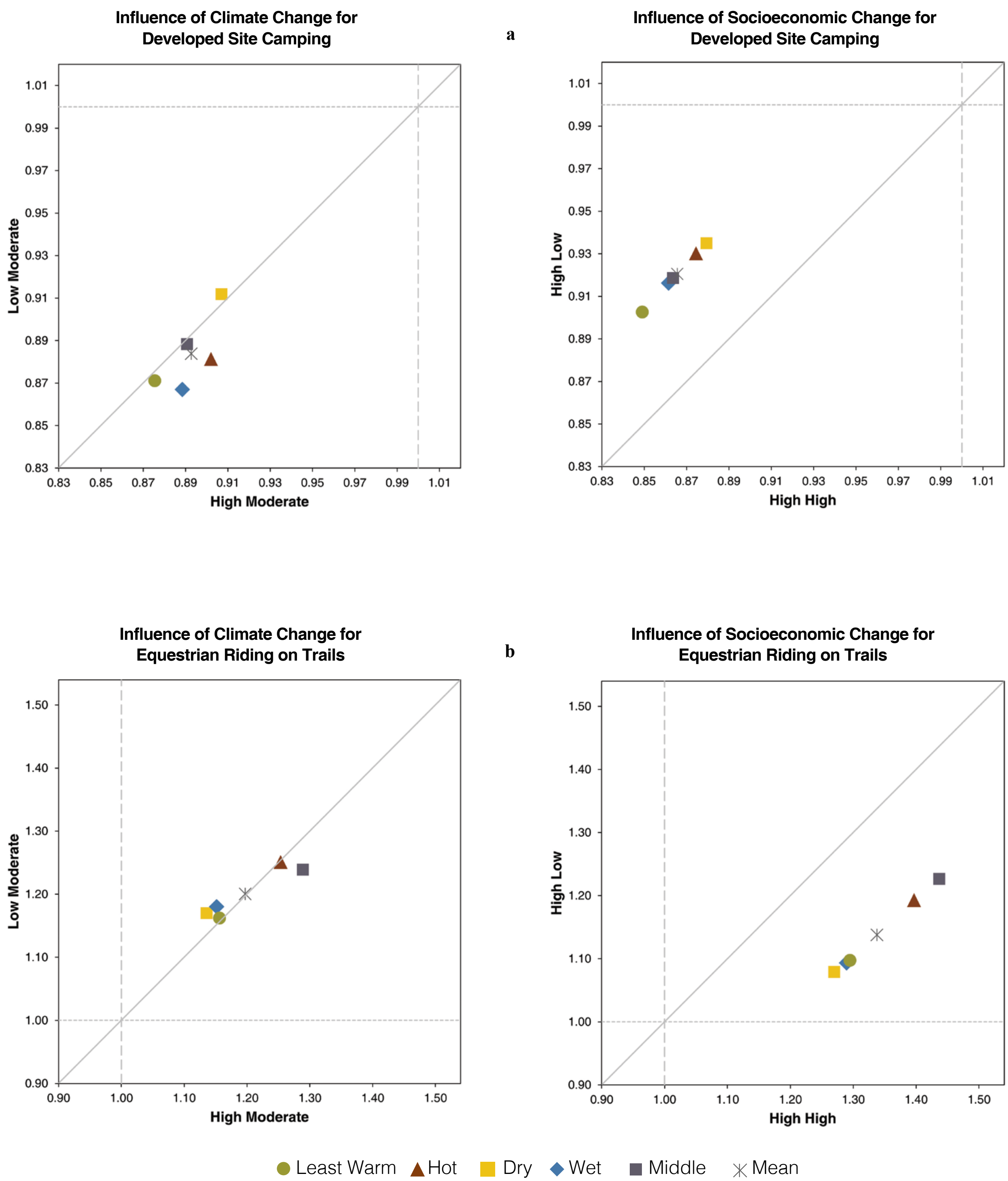
[a] *Birding participation rates and days of participation are also incorporated in the values for viewing nature.*

⬆⬇ *= unambiguous increase or decrease in projected per capita participation,* ↑↓ *= increase or decrease in per capita participation in most projection cases,* ⇔ *= no clear outcome or relationship.*

HM scenarios. Six activities (discussed in a later section) exhibited responsiveness to both atmospheric warming and changing socioeconomic conditions. Further, many activities (discussed in subsequent sections) exhibited responsiveness to different climate futures (e.g., wet, least warm, hot) within the individual RPA scenarios.

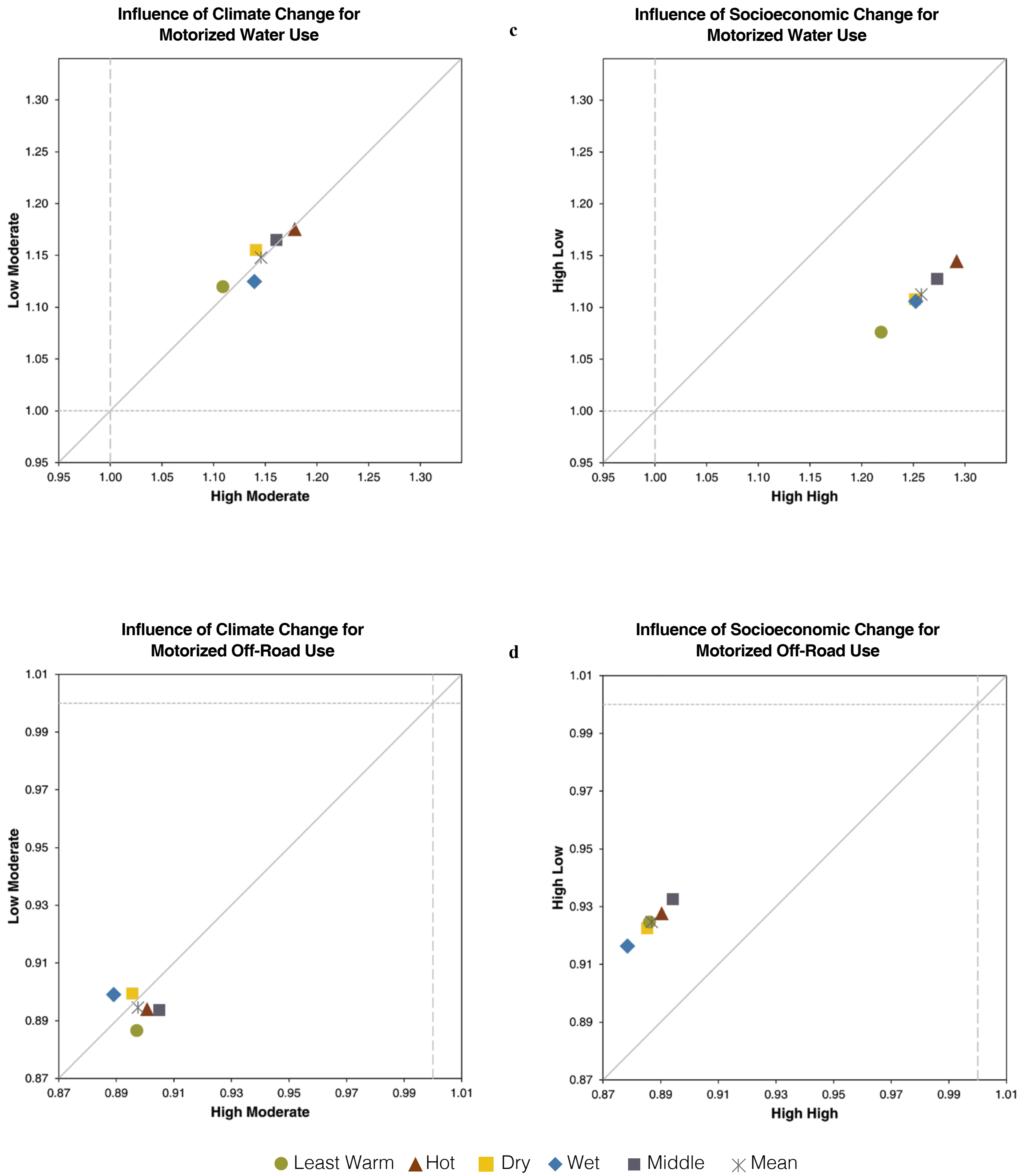
Economic Development and Population Growth as Primary Driver: HL versus HH—Participation rates in developed site camping, equestrian riding on trails, motorized water use, motorized off-road use, hunting, and downhill skiing and snowboarding exhibit responsiveness to the levels of population and economic growth but are relatively unchanged by differing levels of future atmospheric warming (demonstrated by increased distance from markers to diagonal line for the HL/HH figure relative to the LM/HM figure; figure 11-10). Projected participation rates in 2070 for developed site camping, motorized off-road use, and hunting are all greater under the HL scenario than

Figure 11-10. Projected per capita participation in 2070 indexed to 2012, comparing RPA scenarios LM with HM (climate change, left) and HL with HH (socioeconomic change, right) for (a) developed site camping, (b) equestrian riding on trails, (c) motorized water use, (d) motorized off-road use, (e) hunting, and (f) downhill skiing and snowboarding.



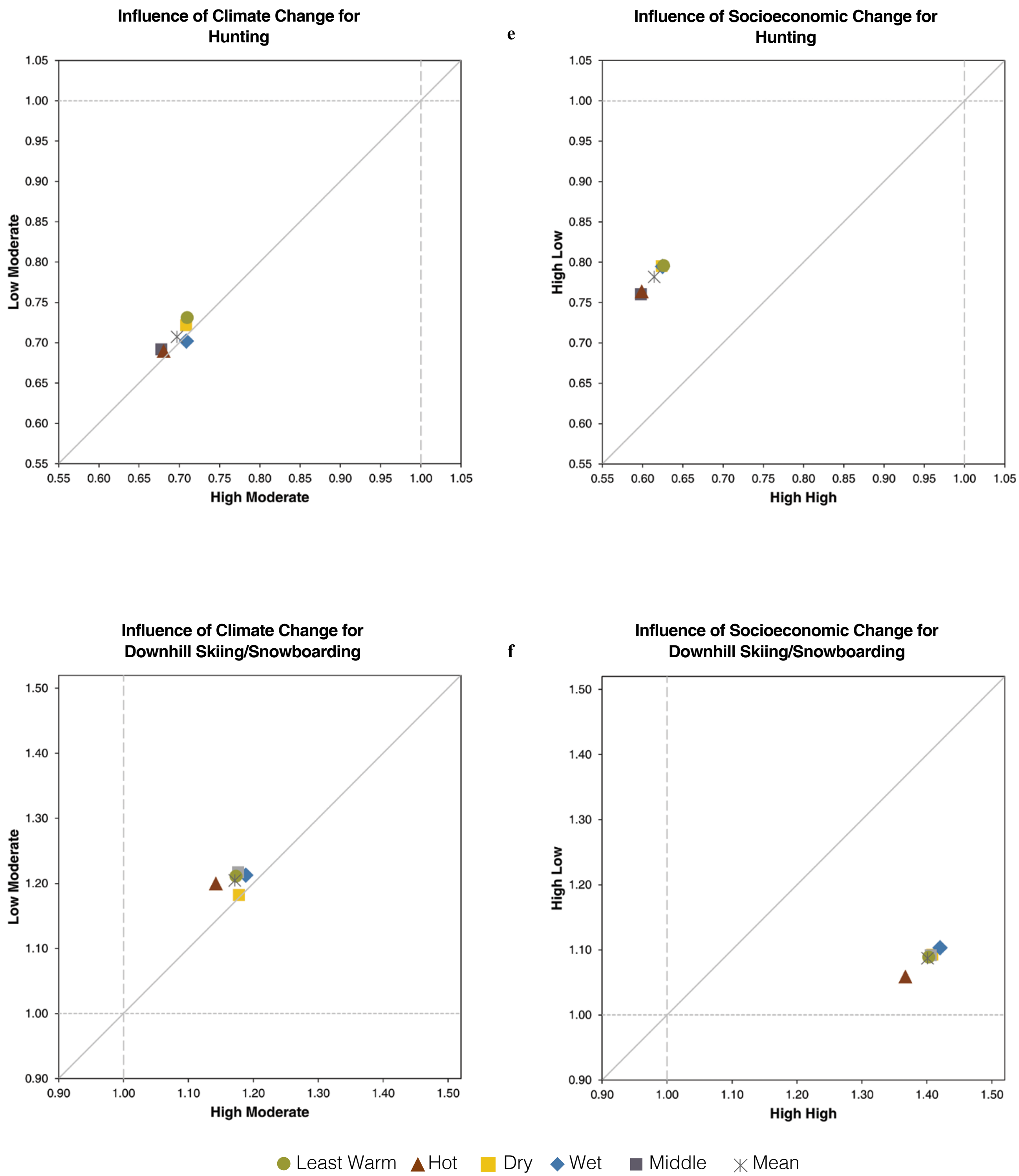
LM = lower warming-moderate U.S. growth; HL = high warming-low U.S. growth; HM = high warming-moderate U.S. growth; HH = high warming-high U.S. growth.

Figure 11-10 continued. Projected per capita participation in 2070 indexed to 2012, comparing RPA scenarios LM with HM (climate change, left) and HL with HH (socioeconomic change, right) for (a) developed site camping, (b) equestrian riding on trails, (c) motorized water use, (d) motorized off-road use, (e) hunting, and (f) downhill skiing and snowboarding.



LM = lower warming-moderate U.S. growth; HL = high warming-low U.S. growth; HM = high warming-moderate U.S. growth; HH = high warming-high U.S. growth.

Figure 11-10 continued. Projected per capita participation in 2070 indexed to 2012, comparing RPA scenarios LM with HM (climate change, left) and HL with HH (socioeconomic change, right) for (a) developed site camping, (b) equestrian riding on trails, (c) motorized water use, (d) motorized off-road use, (e) hunting, and (f) downhill skiing and snowboarding.



LM = lower warming-moderate U.S. growth; HL = high warming-low U.S. growth; HM = high warming-moderate U.S. growth; HH = high warming-high U.S. growth.

HH because the improved economic well-being and greater population growth of the HH scenario result in lower future rates of per capita participation in those activities. This relationship is most pronounced for hunting. In contrast, improved economic well-being and increased population growth lead to higher rates of participation in equestrian riding on trails, motorized water use, and downhill skiing and snowboarding.

Although the projections of per capita participation for these activities do not exhibit much responsiveness to changes in the levels of future atmospheric warming (LM versus. HM scenarios), projected per capita participation rates for developed site camping, equestrian riding on trails, and motorized water use exhibit responsiveness to individual climate projections (depicted by the more dispersed participation projections for those activities). For developed site camping, projected participation rates are highest when using the dry projection and lowest under the least warm projection. For equestrian riding and motorized water use, the hot and middle projections result in per capita participation rates that are meaningfully higher than the other climate projections across all RPA scenarios. For motorized water use, the least warm projection yields a per capita participation rate that is meaningfully lower than other climate projections across all RPA scenarios.

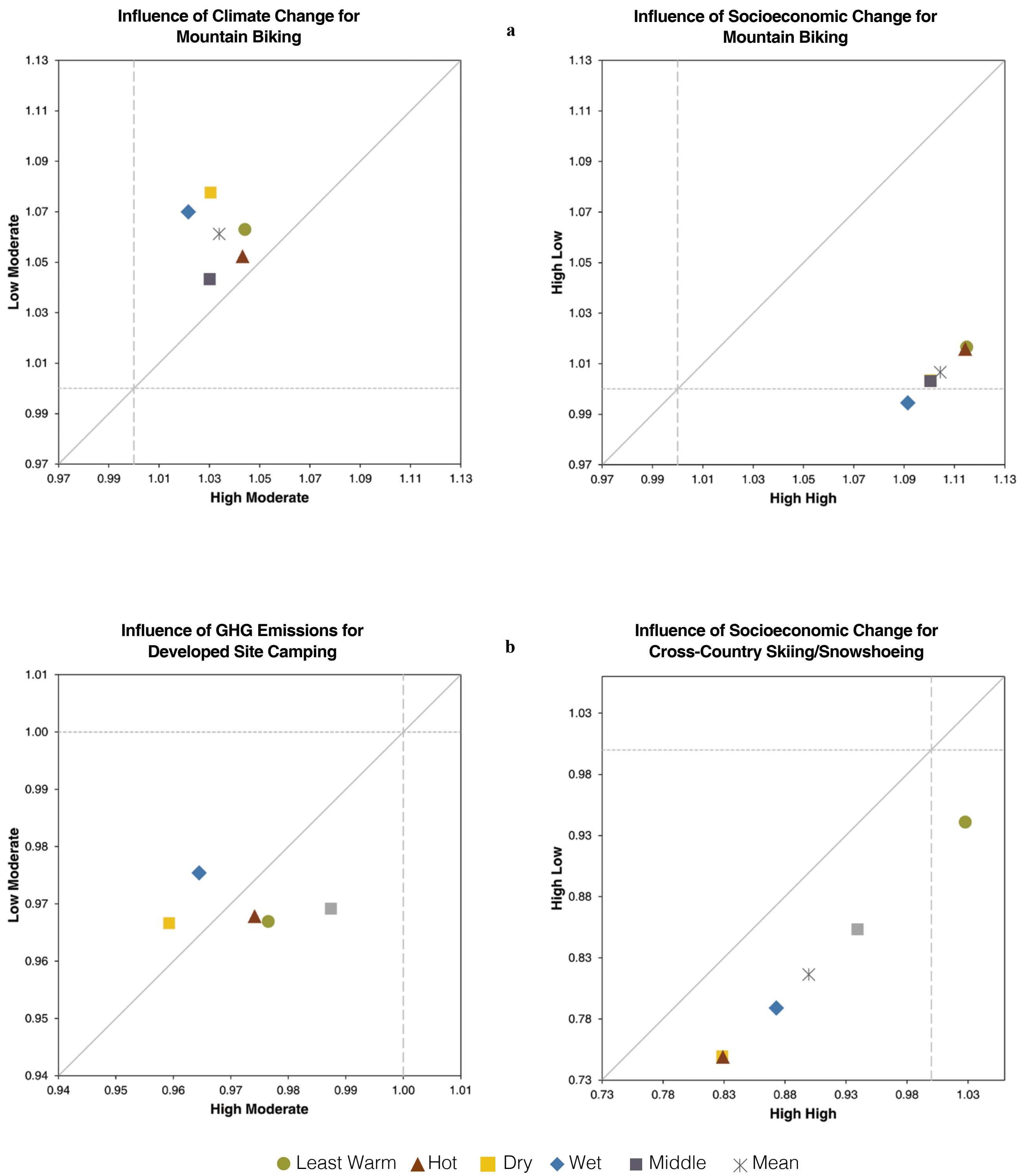
***Per Capita Participation Relative to 2012*—**Projected per capita participation in equestrian riding on trails, motorized water use, and downhill skiing and snowboarding is projected to be greater in 2070 than in 2012 across all scenarios (depicted by projections greater than 1.0). The greatest increases in per capita participation are projected for downhill skiing and snowboarding under the HH scenario, with participation rates potentially up to around 140 percent of observed 2012 participation. Projected per capita participation in developed site camping, motorized off-road use, and hunting are projected to be lower in 2070 than 2012 across all scenarios and all projections. Hunting is projected to experience the greatest per capita participation declines, with projected relative 2070 per capita participation as low as 60 percent (under HH-middle and HH-hot) and as high as 80 percent (under HL-dry and HL-least warm) of observed 2012 participation rates.

Responsive to Both Drivers—Projections of per capita participation in mountain biking, cross-country skiing and snowshoeing, motorized snow use, floating, swimming, and day hiking are responsive to both levels of atmospheric warming and population growth and economic development (figure 11-11) (depicted by projections off the diagonal line in both the LM/HM and HL/HH graphs). For all of these activities, per capita participation is projected to be greater under lower atmospheric warming (the LM scenario compared to the HM scenario). In addition, each activity has higher levels of projected per capita participation in the high-growth HH scenario compared to the low-growth HL scenario.

Although the lower atmospheric warming in the LM scenario leads to higher projected per capita participation relative to the HM scenario for each activity, the potential range in future climate alters the degree to which there is a positive influence on per capita participation (i.e., the distance from the diagonal line). For day hiking, the most pronounced differences between the lower and high climatic change scenarios are found when using the wet and the hot climate projections; for mountain biking, the wet and dry climate projections yield the greatest differences. Finally, the dry climate projection produces the greatest differences in projected participation in cross-country skiing and snowshoeing and motorized snow use.

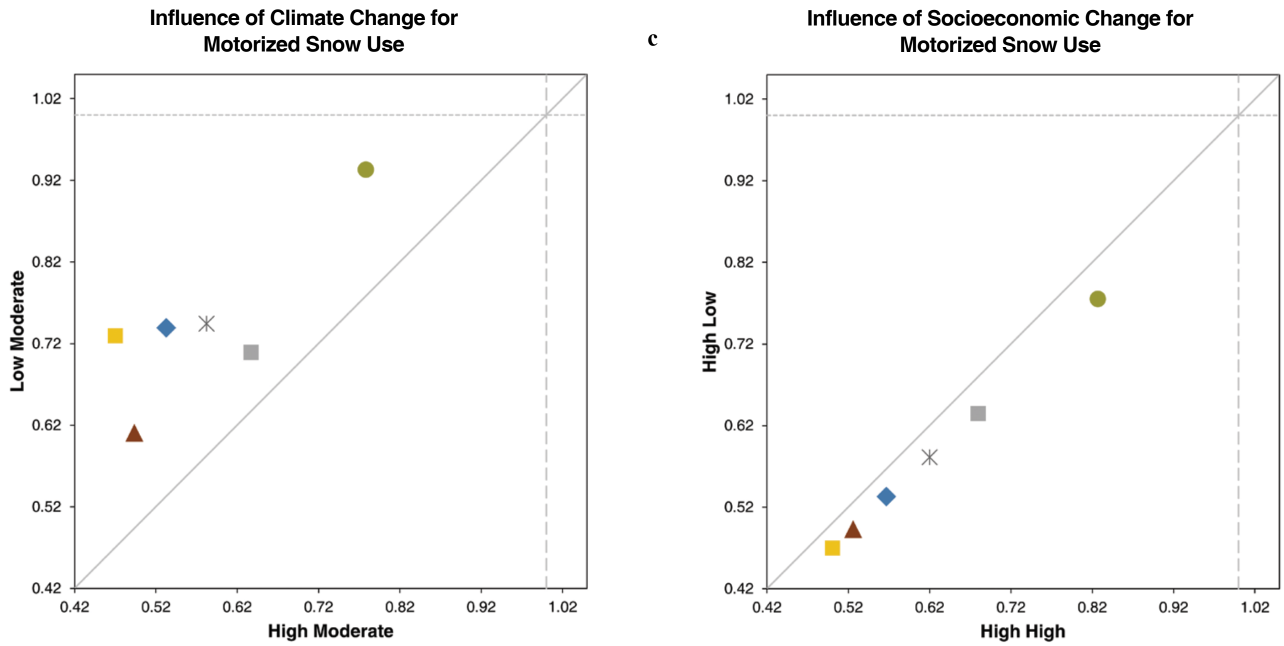
***Per Capita Participation Relative to 2012*—**For this set of activities, there is high variation across the 20 RPA scenario-climate futures in how projected per capita participation in 2070 compares to 2012. For every activity except motorized snow use, at least two scenario-climate futures project growth in per capita participation between 2012 and 2070 (i.e., participation values greater than 1.0). For mountain biking, an increase in per capita participation is projected in all combinations except HL-wet. Cross-country skiing and snowshoeing aggregate exhibits pathways to growth in per capita participation, relative to 2012, under LM-least warm and HH-least warm. For floating and swimming, the greatest participation rates correspond to the wet and least warm climate projections (across all scenarios), either by greatest increase or slowest decline from 2012. Finally, projected per capita participation in day hiking exhibits increases in all scenario-climate futures except HH-hot, LM-least warm, and LM-wet. The smallest reduction in participation in motorized snow use (93 percent of 2012 participation) is projected for LM-least warm; the least warm climate projection yields the highest motorized snow use participation rates across all four scenarios.

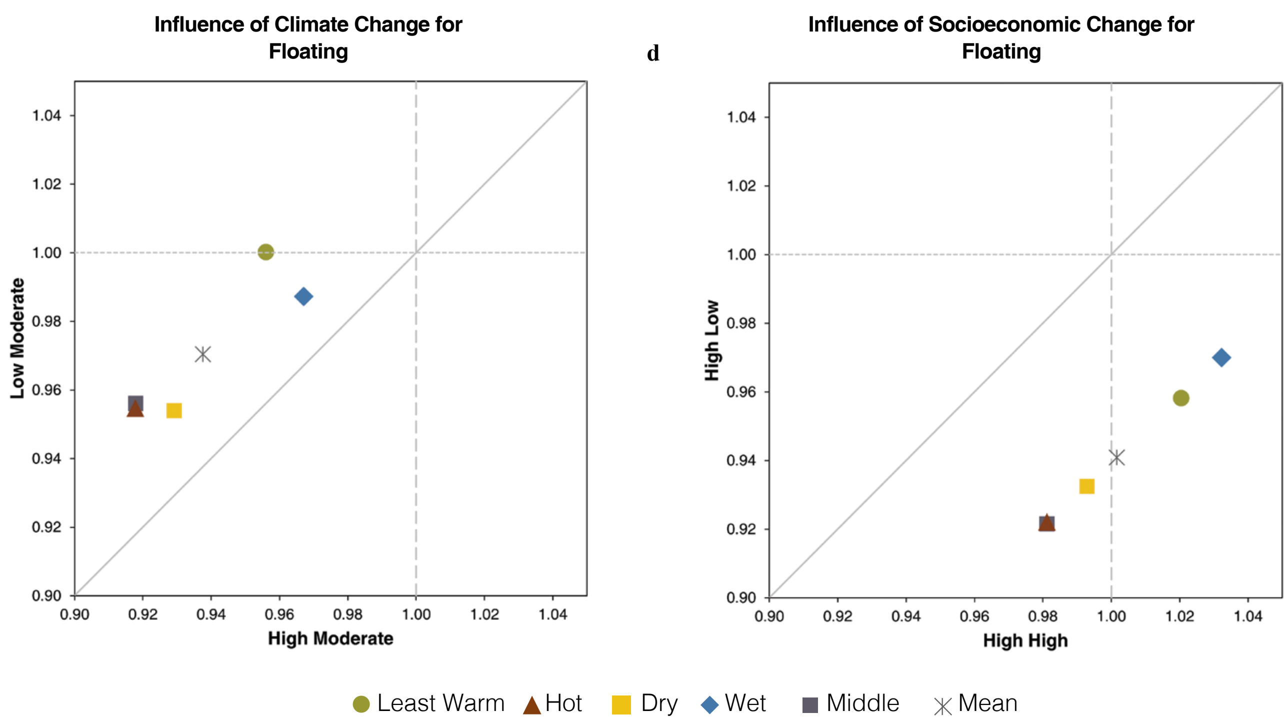
Figure 11-11. Projected per capita participation in 2070 indexed to 2012 comparing RPA scenarios LM with HM (climate change, left) and HL with HH (socioeconomic change, right) for (a) mountain biking, (b) cross-country skiing and snowshoeing, (c) motorized snow use, (d) floating, (e) swimming, and (f) day hiking.



LM = lower warming-moderate U.S. growth; HL = high warming-low U.S. growth; HM = high warming-moderate U.S. growth; HH = high warming-high U.S. growth.

Figure 11-11 continued. Projected per capita participation in 2070 indexed to 2012 comparing RPA scenarios LM with HM (climate change, left) and HL with HH (socioeconomic change, right) for (a) mountain biking, (b) cross-country skiing and snowshoeing, (c) motorized snow use, (d) floating, (e) swimming, and (f) day hiking.

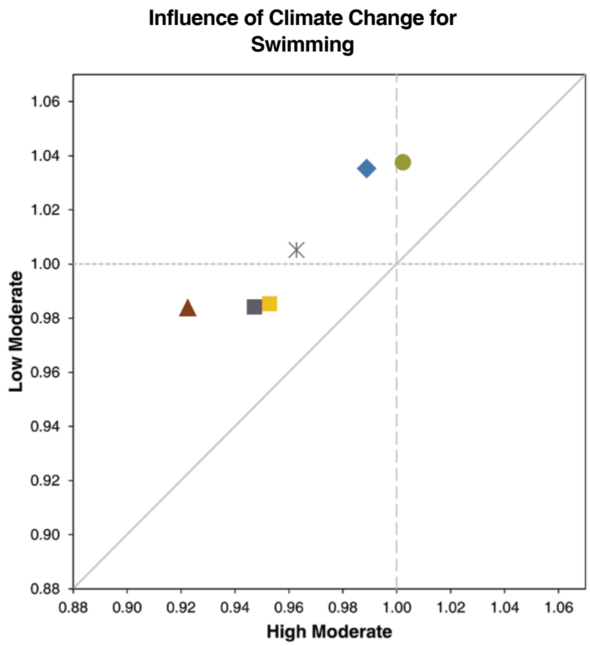


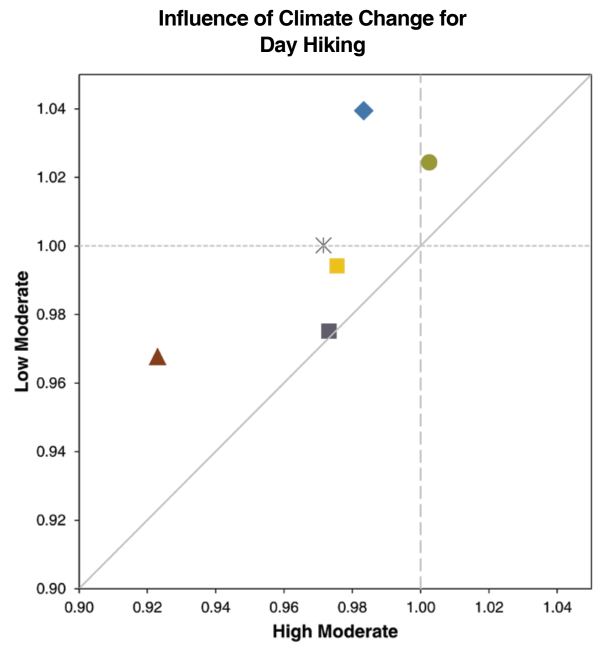


LM = lower warming-moderate U.S. growth; HL = high warming-low U.S. growth; HM = high warming-moderate U.S. growth; HH = high warming-high U.S. growth.

Figure 11-11 continued. Projected per capita participation in 2070 indexed to 2012 comparing RPA scenarios LM with HM (climate change, left) and HL with HH (socioeconomic change, right) for (a) mountain biking, (b) cross-country skiing and snowshoeing, (c) motorized snow use, (d) floating, (e) swimming, and (f) day hiking.

e





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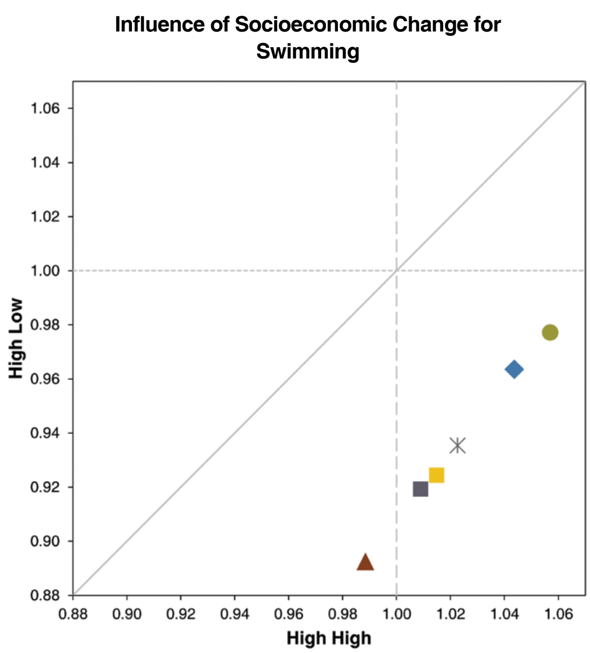
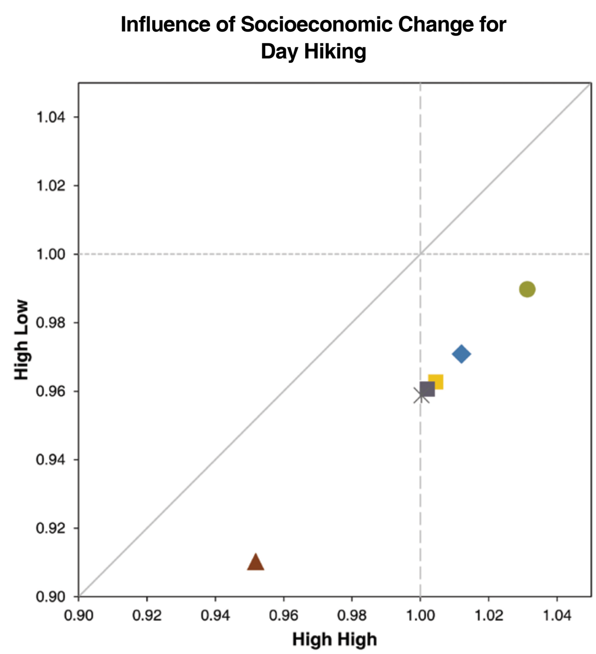


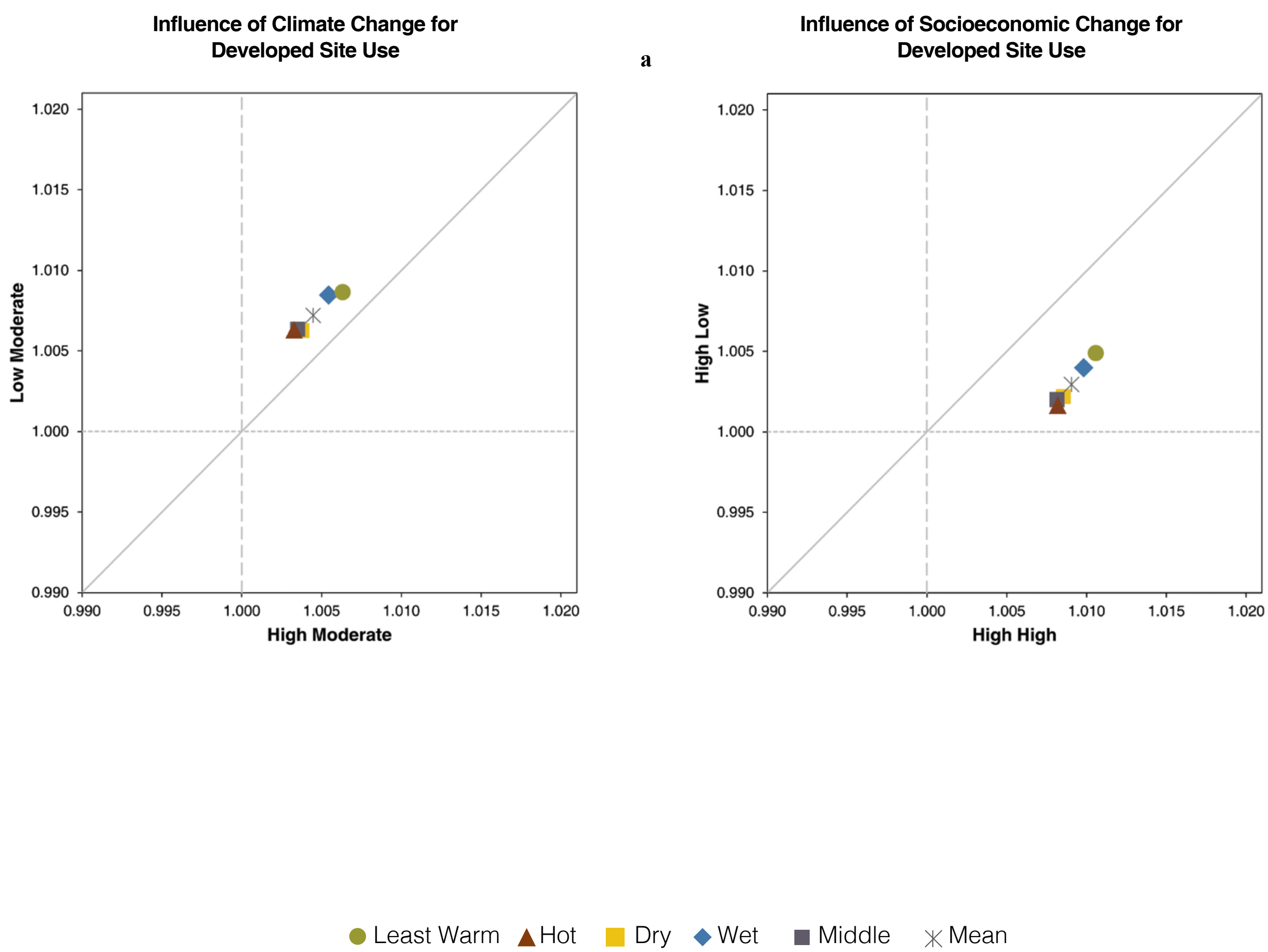


LM = lower warming-moderate U.S. growth; HL = high warming-low U.S. growth; HM = high warming-moderate U.S. growth; HH = high warming-high U.S. growth.

No Evidence of Clear Driver—Developed site use, viewing nature, fishing, primitive area recreation, and birding exhibit minimal response to alternate levels of atmospheric warming or economic development and population growth (figure 11-12). However, for fishing and birding there are some larger differences in indexed participation rates between the LM and HM scenarios for a few individual climate projections. Under the hot and wet climate projections, participation in birding is projected to be distinctly higher in the LM compared to the HM scenario. Conversely, under the middle climate projection, birding participation is highest under the HM scenario, counter to the pattern for that activity in any other climate projection. For fishing, the HM scenario produces slightly higher participation over the LM scenario in all climate projections, but this difference is more pronounced under the middle climate projection.

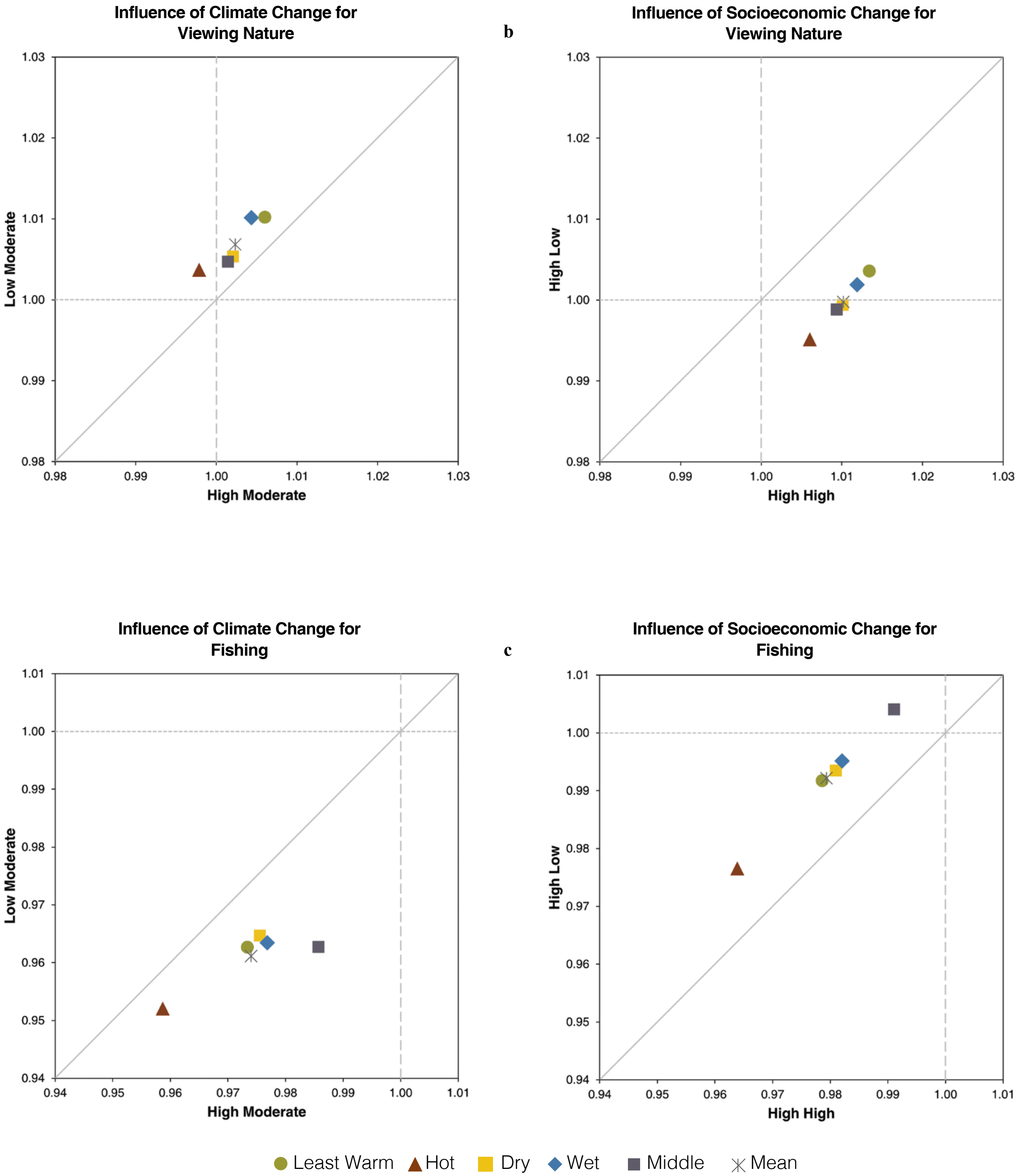
Per Capita Participation Relative to 2012—Projected participation in 2070 in developed site use and viewing nature are largely unchanged from observed 2012 participation. Slight declines in fishing participation are projected for all scenario-climate futures except HL-middle. Fishing participation declines are projected to be greatest under the hot climate projection. Similarly, the hot and middle climate projections lead to the largest declines in participation in primitive area recreation. Projected declines for that activity are smallest under the least warm climate projection. Participation in birding is projected to range from largely unchanged from 2012 in LM-wet to up to a 9-point loss under the hot climate projection.

Figure 11-12. Projected per capita participation in 2070 indexed to 2012 comparing RPA scenarios LM with HM (climate change, left) and HL with HH (socioeconomic change, right) for (a) developed site use, (b) viewing nature, and (c) fishing, (d) primitive area use, and (e) birding.



LM = lower warming-moderate U.S. growth; HL = high warming-low U.S. growth; HM = high warming-moderate U.S. growth; HH = high warming-high U.S. growth.

Figure 11-12 continued. Projected per capita participation in 2070 indexed to 2012 comparing RPA scenarios LM with HM (climate change, left) and HL with HH (socioeconomic change, right) for (a) developed site use, (b) viewing nature, and (c) fishing, (d) primitive area use, and (e) birding.



LM = lower warming-moderate U.S. growth; HL = high warming-low U.S. growth; HM = high warming-moderate U.S. growth; HH = high warming-high U.S. growth.

Figure 11-12 continued. Projected per capita participation in 2070 indexed to 2012 comparing RPA scenarios LM with HM (climate change, left) and HL with HH (socioeconomic change, right) for (a) developed site use, (b) viewing nature, and (c) fishing, (d) primitive area use, and (e) birding.

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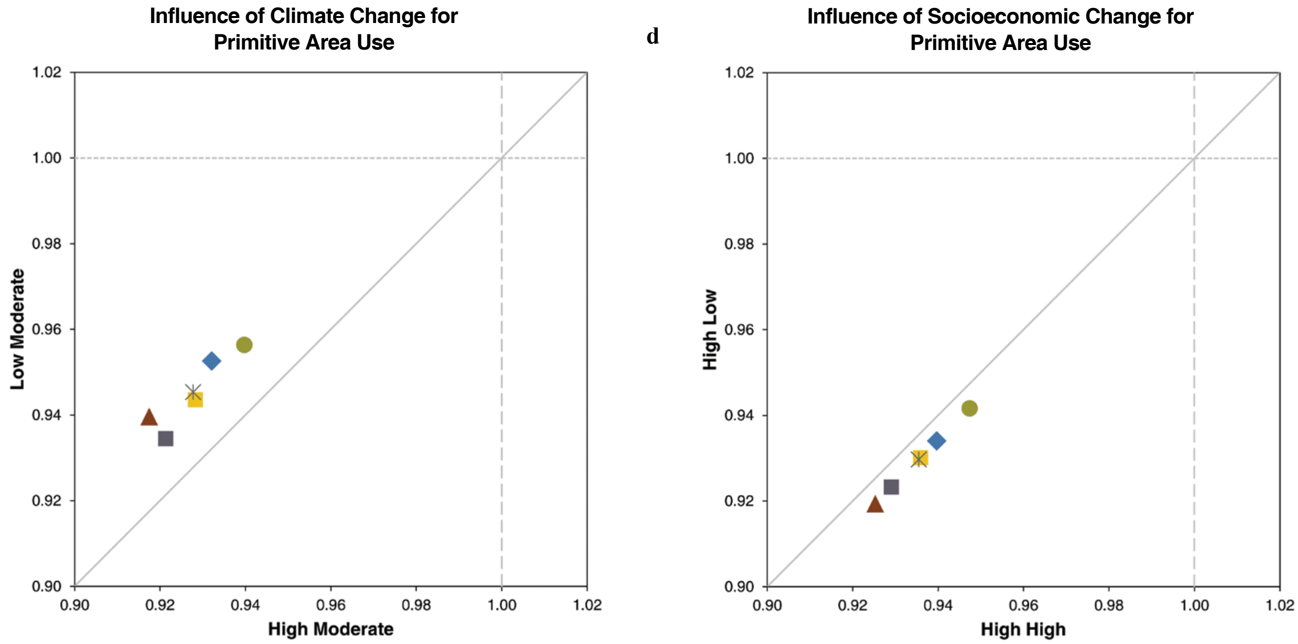

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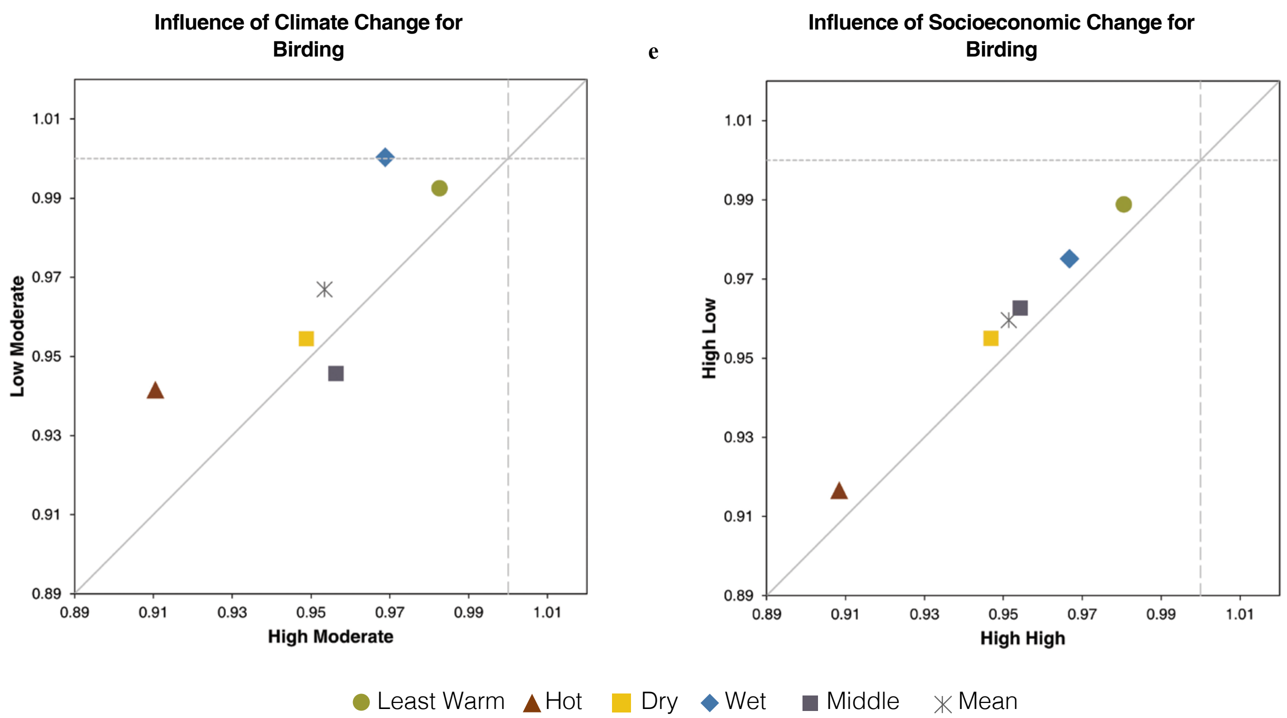

LM = lower warming-moderate U.S. growth; HL = high warming-low U.S. growth; HM = high warming-moderate U.S. growth; HH = high warming-high U.S. growth.

Participants and Consumption

Population growth, because of its magnitude, is often the determining factor in long-term trends in the number of recreation participants and the collective total days of recreation. The number of participants engaging in a recreation activity in the future reflects both changes in per capita participation over time and the size of the future population. Similarly, the total days of recreation (consumption) in the future is a combination of the number of people participating in the activity and the mean days annually that participants engage in the activity. Although there may be meaningful changes (increases or decreases) in per capita participation and average number of days of engagement for individual activities (the per capita consumption measure), population growth typically magnifies (for increases) or offsets (for decreases) those changes.

Participants—The large gross domestic product (GDP) growth and substantial population increases of the HH scenario result in the greatest projected numbers of recreation participants for almost all activities (table 11-12). Three exceptions to this pattern are motorized snow use, cross-country skiing and snowshoeing, and hunting. For motorized snow use, there is overlap between the HH and HM scenarios in the projected numbers of participants nationally and in the North Region for 2040 and 2070. This overlap reflects the substantial projected decline in per capita participation in motorized snow use—to an extent that even high population growth under the HH scenario cannot offset—for some future climates, particularly the hot climate projection. Additionally, the absence of motorized snow use engagement in the South Region translates to a reduced national total, especially since large population increases are projected for that region in 2040 and 2070.

Table 11-12. Projected numbers of outdoor recreation participants (millions) for conterminous United States and RPA regions in 2040 and 2070, averaged across five climate projections within each RPA scenario.

		Baseline	LM		HL		HM		HH	
Activity	**Geography**	**2012**	**2040**	**2070**	**2040**	**2070**	**2040**	**2070**	**2040**	**2070**
Developed site use (visiting natural prehistoric, and/or historic sites; family gatherings; picnicking)										
	Conterminous United States	93.0	122.4	141.6	104.6	98.6	119.4	134.9	137.4	186.8
	North	38.0	45.1	49.0	38.6	34.2	44.0	46.7	50.6	64.5
	South	31.8	44.8	54.2	38.3	37.5	43.8	51.5	50.4	71.6
	Rocky Mountain	8.7	12.7	15.7	10.9	10.9	12.4	14.9	14.3	20.8
	Pacific Coast	14.5	19.7	22.8	16.9	16.0	19.2	21.7	22.1	29.9
Developed camping										
	Conterminous United States	25.3	30.7	33.8	26.8	24.6	30.2	32.6	34.3	43.6
	North	9.1	10.0	10.3	8.8	7.6	9.9	10.1	11.2	13.3
	South	7.3	9.2	10.3	8.1	7.6	9.1	10.0	10.3	13.2
	Rocky Mountain	3.5	4.8	5.7	4.1	4.0	4.7	5.4	5.3	7.4
	Pacific Coast	5.3	6.7	7.5	5.8	5.4	6.6	7.1	7.5	9.6
Nature viewing (viewing or photographing birds, other wildlife, natural scenery, gathering, other)										
	Conterminous United States	19.1	25.2	29.1	21.5	20.2	24.5	27.6	28.3	38.4
	North	7.8	9.3	10.0	7.9	7.0	9.1	9.6	10.4	13.3
	South	6.5	9.2	11.2	7.9	7.7	9.0	10.6	10.4	14.8
	Rocky Mountain	1.8	2.6	3.2	2.2	2.2	2.6	3.1	3.0	4.3
	Pacific Coast	3.0	4.0	4.6	3.4	3.2	3.9	4.4	4.5	6.0
Birding (viewing or photographing)										
	Conterminous United States	12.0	15.9	17.6	13.6	12.2	15.5	16.6	17.8	22.8
	North	5.1	6.2	6.4	5.3	4.5	6.1	6.1	7.0	8.4
	South	4.0	5.8	6.7	4.9	4.5	5.6	6.2	6.4	8.6
	Rocky Mountain	1.0	1.6	1.8	1.3	1.3	1.5	1.7	1.7	2.4
	Pacific Coast	1.8	2.4	2.7	2.1	1.9	2.4	2.5	2.7	3.4
Day hiking										
	Conterminous United States	31.0	40.3	46.9	34.2	31.4	39.2	43.5	45.3	61.7
	North	12.3	14.2	15.0	12.2	10.5	14.0	14.4	16.1	20.1
	South	8.4	11.8	14.6	9.8	9.1	11.3	12.9	13.2	18.7
	Rocky Mountain	3.9	5.8	7.6	5.0	5.1	5.7	7.1	6.7	10.3
	Pacific Coast	6.3	8.4	9.7	7.2	6.7	8.2	9.0	9.4	12.5
Primitive-area use (visiting wilderness, primitive camping, backpacking)										
	Conterminous United States	6.8	8.6	9.8	7.3	6.7	8.4	9.2	9.6	12.7
	North	2.7	3.0	3.2	2.6	2.2	2.9	3.0	3.3	4.1
	South	2.1	2.8	3.4	2.4	2.2	2.7	3.1	3.2	4.3
	Rocky Mountain	0.8	1.2	1.5	1.0	1.0	1.2	1.4	1.3	1.9
	Pacific Coast	1.2	1.6	1.8	1.4	1.3	1.6	1.7	1.8	2.4

Continued ...

Table 11-12 continued. Projected numbers of outdoor recreation participants (millions) for conterminous United States and RPA regions in 2040 and 2070, averaged across five climate projections within each RPA scenario.

... Continued		Baseline	LM		HL		HM		HH	
Activity	**Geography**	**2012**	**2040**	**2070**	**2040**	**2070**	**2040**	**2070**	**2040**	**2070**
Mountain biking										
	Conterminous United States	6.2	7.9	9.9	6.7	6.6	7.7	9.3	9.0	13.6
	North	2.8	3.3	4.0	2.8	2.7	3.3	3.8	3.8	5.5
	South	1.7	2.2	2.8	1.8	1.8	2.1	2.5	2.5	3.7
	Rocky Mountain	0.7	1.1	1.5	0.9	1.0	1.0	1.4	1.2	2.2
	Pacific Coast	1.0	1.3	1.6	1.1	1.1	1.3	1.5	1.5	2.1
Equestrian (horseback riding on trails)										
	Conterminous United States	3.4	4.7	6.2	3.9	4.1	4.6	5.9	5.4	9.0
	North	1.2	1.6	2.0	1.4	1.5	1.6	2.1	1.9	3.2
	South	1.2	1.7	2.3	1.4	1.4	1.6	2.1	1.9	3.4
	Rocky Mountain	0.4	0.6	0.9	0.5	0.5	0.6	0.7	0.7	1.2
	Pacific Coast	0.6	0.8	1.0	0.6	0.6	0.7	0.9	0.9	1.3
Motorized water (motor boating, water skiing, personal watercraft use)										
	Conterminous United States	27.5	37.4	47.7	31.2	32.3	36.2	45.5	42.1	68.8
	North	11.4	14.1	16.8	12.0	11.8	13.8	16.4	16.0	24.2
	South	9.5	13.8	18.6	11.4	12.4	13.2	17.5	15.4	26.9
	Rocky Mountain	2.7	4.1	5.6	3.4	3.6	4.0	5.3	4.7	8.3
	Pacific Coast	3.9	5.4	6.7	4.5	4.5	5.2	6.3	6.0	9.4
Off-road driving										
	Conterminous United States	21.3	25.3	28.8	21.9	20.8	24.7	27.6	28.0	37.6
	North	8.0	8.9	9.6	7.7	7.1	8.7	9.6	9.9	13.3
	South	7.2	8.6	9.7	7.5	7.0	8.4	9.1	9.4	12.0
	Rocky Mountain	2.7	3.8	5.0	3.3	3.4	3.8	4.7	4.4	6.8
	Pacific Coast	3.4	4.0	4.5	3.5	3.2	3.9	4.2	4.4	5.5
Motorized snow (snowmobiling)										
	Conterminous United States	4.1	4.2	4.3	3.3	2.4	3.8	3.2	4.4	4.7
	North	2.9	2.6	2.3	2.1	1.2	2.4	1.6	2.8	2.4
	Rocky Mountain	0.7	1.0	1.2	0.7	0.6	0.8	0.8	0.9	1.3
	Pacific Coast	0.5	0.6	0.8	0.5	0.6	0.6	0.7	0.7	1.0
Fishing (warm water, cold water, saltwater, anadromous)										
	Conterminous United States	31.0	39.3	45.1	33.9	32.5	38.5	43.6	43.9	60.4
	North	12.2	13.9	14.9	11.9	10.4	13.6	14.2	15.6	20.0
	South	12.0	16.2	19.3	14.2	14.5	16.0	19.2	18.1	26.1
	Rocky Mountain	3.0	4.2	5.1	3.6	3.6	4.1	4.8	4.7	6.7
	Pacific Coast	3.8	5.0	5.8	4.2	4.1	4.8	5.4	5.5	7.7
Hunting (all types of legal hunting)										
	Conterminous United States	12.7	13.6	13.6	12.2	10.5	13.3	12.8	14.5	15.5
	North	5.0	4.5	3.7	4.0	2.8	4.3	3.3	4.6	3.8
	South	5.0	5.8	6.2	5.3	5.1	5.7	6.1	6.2	7.3
	Rocky Mountain	1.7	2.2	2.5	1.8	1.7	2.0	2.2	2.3	2.9
	Pacific Coast	1.0	1.2	1.2	1.1	1.0	1.2	1.2	1.4	1.6
Developed skiing (downhill skiing, snowboarding)										
	Conterminous United States	11.0	14.4	20.0	11.7	12.6	13.8	18.5	16.4	30.5
	North	6.6	8.0	10.7	6.5	6.9	7.7	10.1	9.1	16.5
	Rocky Mountain	1.6	2.5	3.9	2.0	2.4	2.4	3.6	2.9	6.1
	Pacific Coast	2.8	3.9	5.4	3.1	3.3	3.7	4.8	4.4	8.0
Undeveloped skiing (cross-country skiing, snowshoeing)										
	Conterminous United States	6.2	7.1	8.0	6.0	5.0	6.8	7.0	7.9	10.3
	North	4.1	4.3	4.4	3.5	2.6	4.0	3.5	4.6	5.1
	Rocky Mountain	1.0	1.4	1.7	1.2	1.2	1.3	1.6	1.5	2.4
	Pacific Coast	1.1	1.5	1.9	1.3	1.3	1.5	1.8	1.8	2.8
Swimming (swimming in streams, lakes, ponds, or ocean; snorkeling; scuba diving)										
	Conterminous United States	48.4	61.7	73.6	51.6	47.8	59.7	67.3	69.4	98.5
	North	20.2	22.9	25.1	19.2	16.1	22.1	22.5	25.7	32.8
	South	16.1	22.3	28.2	18.6	18.0	21.6	25.7	25.2	38.2
	Rocky Mountain	3.8	5.3	6.7	4.5	4.5	5.1	6.2	6.0	9.0
	Pacific Coast	8.3	11.2	13.6	9.4	9.3	10.9	12.9	12.6	18.5
Floating (canoeing, kayaking, rafting)										
	Conterminous United States	10.0	12.1	14.7	10.2	10.0	11.6	13.6	13.4	20.0
	North	4.4	4.6	5.0	3.9	3.2	4.4	4.4	5.2	6.5
	South	3.2	4.2	5.5	3.6	4.0	4.0	5.2	4.6	7.7
	Rocky Mountain	1.0	1.4	1.9	1.2	1.3	1.3	1.8	1.5	2.7
	Pacific Coast	1.5	1.9	2.3	1.6	1.5	1.8	2.1	2.1	3.1

Activities are individual or activity composites derived from the NSRE. Initial participants are determined from the scenario adult (16 years or older) population estimates for the conterminous United States during 2012 and initial estimates by activity based on Outdoor Foundation estimates and/or NSRE responses from 2006 to 2012.

NSRE = National Survey on Recreation and the Environment; LM = lower warming-moderate U.S. growth; HL = high warming-low U.S. growth; HM = high warming-moderate U.S. growth; HH = high warming-high U.S. growth.

For hunting, the projected number of participants in the RPA North Region under the HH scenario overlaps with projections for the HM scenario in 2040 and 2070, reflecting the large decline in per capita participation in hunting under the HH scenario and the relatively low population increase projected in the North Region, even under the HH scenario. The cross-country skiing and snowshoeing aggregate exhibits a similar response, with overlap between the HH and HM scenario in the North Region in 2070.

Comparing projections under the LM and HM scenarios, with their relatively equivalent population and GDP trends, lower atmospheric warming (LM) tends to favor increased numbers of participants and recreation consumption. For most activities, the projected number of participants in 2040 and 2070 is slightly greater under the LM scenario compared to the HM scenario. These general differences between the LM and HM scenarios are more pronounced in some regions. Meaningful regional differences tend to occur for the RPA North Region (for many activities) and, beyond the North Region, for activities where future climatic change more strongly influenced per capita participation (e.g., motorized snow use, day hiking, and floating). The LM scenario has slightly higher GDP and population projections by 2070 than the HM scenario. Those slightly higher trends also promote slightly greater participant projections for many activities.

Projected losses in the numbers of participants engaging in activities in 2040 and 2070 relative to 2012 were primarily confined to the HL scenario, nationally and regionally. Relatively small projected population growth and economic development gains in the HL scenario are insufficient to overcome the declines in per capita participation projected for many activities. Potential declines in the numbers of participants in 2040 and 2070 extend into the HM scenario for several regions and nationally for hunting, motorized snow use, cross-country skiing and snowshoeing, and floating. Projected declines in participation for hunting extend into the HH scenario in the RPA North Region. The hunting results reflect the steep projected decline in per capita hunting participation in the face of both high atmospheric warming and strong population and economic growth. Although most activities have projected declines in at least one scenario-climate future, downhill skiing and snowboarding, equestrian riding on trails, and motorized water use activities have increasing numbers of projected participants across all regions, scenarios, and climate projections.

The presently most-popular activities remain the most-popular in projections of future recreation for 2040 and 2070. Developed site use (i.e., visiting natural, historic, or prehistoric sites, picnicking, outdoor family gatherings) is projected to have the greatest number of participants of the activity aggregates by far, with between 104 and 137 million participants in 2040. Swimming is projected to be the next most-popular activity—with about half the participants of developed site use—followed by day hiking, fishing, and motorized water use. Developed site camping rounds out the greatest-participant activity aggregates with projections of between 27 and 34 million participants by 2040. Each of the most-popular activities has projected percentage increases in participants that are around 30 percent by 2040 and 45 percent or more by 2070, relative to 2012. Downhill skiing and snowboarding, floating, mountain biking, and equestrian riding on trails—activities that currently have moderate numbers of participants—exhibit some of the largest percentage increases in participants between 2012 and 2070. Despite the large percentage increases, the numbers of participants in floating, mountain biking, and equestrian riding on trails remain modest in 2040 and 2070 relative to those seen in more general and broadly accessible activities such as day hiking and viewing nature.

Days of Engagement—In general, our projections show continued modest declines in the average number of days each year that participants engage in a recreation activity. This pattern is consistent with recent trends over the last decade or more. Ultimately, those engaging in outdoor recreation are doing so with less frequency, and that trend is projected to continue. Projected declines in the average number of days of engagement are common across activities, regions, scenarios, and climate projections. Three activities are exceptions to this general pattern—motorized water use, mountain biking, and hunting—although each activity still has projected engagement declines in at least one region/scenario combination. For hunting, the lack of a uniform decline across regions and scenarios in projected average days of engagement is noteworthy given the projected marked declines in per capita participation in hunting.

Despite general declines in the mean days of recreation per participant, the total days of recreation in each activity is typically projected to increase (table 11-13). This pattern results because the total number of participants in each activity is typically projected to increase in the future. When present, projected declines in the total days of recreation for individual activities are most common under the HL scenario. In some cases, those projected declines are substantial, as they reflect both projected declines in participant numbers and engagement frequency. For example, national-level days of recreation in 2070 are projected to decline by 40 percent for cross-country skiing and snowshoeing, 50 percent for snowmobile use, and 9 percent for primitive area activities under the HL scenario. When projected declines occur, they are often especially pronounced in the RPA North Region, with its low projected population growth in the future. As with projected participation, projected declines in total days of recreation extend through the HH scenario in some regions for snowmobile use, cross-country skiing and snowshoeing, and hunting. Declines in snowmobile use and cross-country skiing and snowshoeing in the North Region result from the compounded influence of atmospheric warming and declining population. Per capita consumption in hunting for the North Region is projected to be mostly stable except for under the hot climate projection. Factoring in substantially declining per capita participation alongside population outlooks, the number of days of hunting in the North Region is projected to decline substantially by 2070.

Projected patterns of increase (or decrease) in engagement generally continue in linear fashion over the projection period. Discrepancies between 2040 and 2070 projections are most common under the HL scenario. For example, the projected number of birding days in 2040 under the HL scenario is 7 percent higher than 2012 observations, but the 2070 projection is a reduction of 13 percent from 2012 levels. Similarly, projections of day hiking under the HL scenario show a slight gain in total days for 2040 (6 percent), which turns into a slight loss of 5 percent from

Table 11-13. Projected numbers of days (millions) of recreation engagement for conterminous United States and RPA regions in 2040 and 2070, averaged across five climate projections within each RPA scenario.

		Baseline	LM		HL		HM		HH	
Activity	**Geography**	**2012**	**2040**	**2070**	**2040**	**2070**	**2040**	**2070**	**2040**	**2070**
Developed site use (visiting natural prehistoric, and/or historic sites; family gatherings; picnicking)										
	Conterminous United States	1,119	1,474	1,746	1,247	1,197	1,422	1,630	1,635	2,284
	North	446	522	572	441	378	506	524	586	750
	South	366	520	655	445	472	501	626	569	846
	Rocky Mountain	120	173	211	145	143	166	196	191	273
	Pacific Coast	187	259	308	216	204	249	284	289	415
Developed camping										
	Conterminous United States	198	237	257	206	189	232	249	262	330
	North	65	72	72	63	55	71	73	80	97
	South	58	68	76	59	54	66	72	75	94
	Rocky Mountain	31	42	50	37	38	42	49	47	66
	Pacific Coast	44	55	59	47	42	53	55	60	73
Nature viewing (viewing or photographing birds, other wildlife, natural scenery, gathering, other)										
	Conterminous United States	296	372	407	319	282	361	375	410	504
	North	125	140	140	120	96	136	128	155	173
	South	103	142	170	122	116	138	157	157	210
	Rocky Mountain	26	36	41	31	28	35	38	39	50
	Pacific Coast	43	54	57	47	41	52	53	59	70
Birding (viewing or photographing)										
	Conterminous United States	172	217	221	185	149	209	198	237	263
	North	74	82	75	71	51	80	68	91	91
	South	63	86	97	73	63	83	85	94	113
	Rocky Mountain	12	18	18	15	13	17	17	19	20
	Pacific Coast	22	30	31	26	21	29	28	33	38
Day hiking										
	Conterminous United States	473	581	650	500	451	563	597	638	806
	North	182	194	188	169	133	190	176	216	230
	South	130	165	199	141	132	158	173	179	236
	Rocky Mountain	53	76	96	67	69	76	94	88	134
	Pacific Coast	110	146	167	122	117	138	154	156	206
Primitive-area use (visiting wilderness, primitive camping, backpacking)										
	Conterminous United States	11	13	15	11	10	13	13	14	19
	North	4	4	4	3	3	4	4	4	5
	South	3	4	5	4	3	4	5	5	6
	Rocky Mountain	1	2	2	2	2	2	2	2	3
	Pacific Coast	2	3	3	2	2	3	3	3	4
Mountain biking										
	Conterminous United States	125	161	206	136	138	157	193	182	281
	North	54	62	73	53	48	61	67	70	97
	South	29	40	54	33	34	38	49	45	72
	Rocky Mountain	22	33	46	28	31	32	43	37	64
	Pacific Coast	20	26	33	23	24	26	34	30	48
Equestrian (horseback riding on trails)										
	Conterminous United States	46	61	83	50	49	58	69	67	110
	North	11	18	28	16	17	18	24	21	36
	South	17	24	36	18	19	22	29	27	53
	Rocky Mountain	14	14	13	12	9	14	12	15	15
	Pacific Coast	4	5	5	4	3	4	4	5	6

Continued ...

Table 11-13 continued. Projected numbers of days (millions) of recreation engagement for conterminous United States and RPA regions in 2040 and 2070, averaged across five climate projections within each RPA scenario.

		Baseline	LM		HL		HM		HH	
Activity	**Geography**	**2012**	**2040**	**2070**	**2040**	**2070**	**2040**	**2070**	**2040**	**2070**
... Continued		**Baseline**	**LM**		**HL**		**HM**		**HH**	
Activity	**Geography**	**2012**	**2040**	**2070**	**2040**	**2070**	**2040**	**2070**	**2040**	**2070**
Motorized water (motor boating, water skiing, personal watercraft use)										
	Conterminous United States	366	518	715	429	470	503	678	592	1,109
	North	126	162	197	139	145	160	200	185	304
	South	169	254	380	208	241	246	355	292	606
	Rocky Mountain	28	41	56	34	37	40	53	47	83
	Pacific Coast	43	61	82	48	48	57	69	68	116
Off-road driving										
	Conterminous United States	350	414	467	360	355	402	457	450	600
	North	109	121	128	102	96	116	129	132	177
	South	152	181	209	163	171	180	211	196	258
	Rocky Mountain	45	63	79	52	52	60	71	69	104
	Pacific Coast	44	49	51	42	36	47	46	52	61
Motorized snow (snowmobiling)										
	Conterminous United States	28	26	24	20	12	23	16	26	24
	North	23	18	15	14	7	16	10	19	14
	Rocky Mountain	3	4	5	3	2	4	4	4	5
	Pacific Coast	3	3	4	3	2	3	3	3	4
Fishing (warm water, cold water, saltwater, anadromous)										
	Conterminous United States	501	614	694	537	518	603	676	679	902
	North	188	204	209	175	143	199	193	227	269
	South	217	288	345	258	279	287	355	319	458
	Rocky Mountain	37	49	57	41	39	47	52	53	72
	Pacific Coast	58	74	83	63	57	71	75	80	103
Hunting (all types of legal hunting)										
	Conterminous United States	238	257	259	235	217	255	260	275	308
	North	90	80	65	71	49	77	58	83	67
	South	106	129	145	120	130	130	154	140	184
	Rocky Mountain	23	26	27	22	18	24	23	27	30
	Pacific Coast	19	22	22	22	21	24	24	25	27
Developed skiing (downhill skiing, snowboarding)										
	Conterminous United States	70	92	132	72	73	87	113	106	208
	North	37	40	50	32	26	38	40	46	70
	Rocky Mountain	10	17	31	13	16	16	26	20	52
	Pacific Coast	23	34	51	27	31	33	47	40	85
Undeveloped skiing (cross-country skiing, snowshoeing)										
	Conterminous United States	33	36	37	29	20	33	29	39	44
	North	22	20	18	16	8	18	12	21	17
	Rocky Mountain	5	7	9	6	5	7	8	8	11
	Pacific Coast	6	8	10	7	7	8	10	10	15
Swimming (swimming in streams, lakes, ponds, or ocean; snorkeling; scuba diving)										
	Conterminous United States	582	709	860	585	529	678	747	791	1,125
	North	211	231	257	189	151	219	215	257	328
	South	221	284	368	233	217	271	312	319	482
	Rocky Mountain	37	50	61	42	41	48	57	56	83
	Pacific Coast	113	145	174	121	120	139	163	160	231
Floating (canoeing, kayaking, rafting)										
	Conterminous United States	60	71	86	60	58	68	78	78	115
	North	26	28	30	23	19	27	27	31	39
	South	21	26	35	22	25	25	32	28	47
	Rocky Mountain	5	6	8	5	5	6	7	7	11
	Pacific Coast	9	11	13	9	9	11	12	12	18

Activities are individual or activity composites derived from the NSRE. Initial participants are determined from the scenario adult (16 years and older) population estimates for the conterminous United States during 2012 and initial estimates by activity based on Outdoor Foundation estimates and/or NSRE responses from 2006 to 2012.

NSRE = National Survey on Recreation and the Environment; LM = lower warming-moderate U.S. growth; HL = high warming-low U.S. growth; HM = high warming-moderate U.S. growth; HH = high warming-high U.S. growth.

baseline by 2070. These patterns are likewise projected for participant totals from 2040 to 2070 for both activities, albeit to a less pronounced extent. Furthermore, for both activities, projections under HL diverge from the other scenarios, indicating relatively more meaningful changes in number of annual days of engagement.

Management Implications

Our projections of annual days of recreation activities show increases across most activities and under most scenarios. Projected numbers of recreation days are greatest for general activities, such as day hiking, viewing nature, developed site use, and developed site camping. Our projections of days of engagement are likely the most meaningful for recreation managers because that metric is most closely related to visitation. Recreation-related natural resource management and policy decisions are often made in the context of patterns in current and expected future recreation visitation. For example, changes in occupancy rates at a campground, the number of visits annually to a trail, or the number of permits requested by river kayakers might recommend changes in management of, and policies for, recreation resources.

Developed sites and recreation infrastructure are likely to continue facing pressure to meet recreation demand. Developed site use—a compilation of activities including visiting historic sites and picnicking—and developed site camping continue to be among the leading activities in terms of participants and days of recreation and are also projected to experience some of the greatest expansion in both metrics. Developed facilities providing for these recreation activities will likely continue to see substantial and increasing use in future decades. In addition to developed site recreation, other activities that frequently require developed infrastructure are also projected to see large gains in recreation consumption in future decades, under most scenarios. For example, motorized boating typically requires boat ramps, developed skiing requires ski area infrastructure, and day hiking, one of the most-popular recreation activities, requires trail systems.

Our projections show little indication of significant changes in the types of outdoor recreation activities likely to be desired in the coming decades, especially at the national level. Those activities that are most-popular now are projected to remain most-popular. The activities with the highest projected rates of participation in future decades remain visiting developed sites, swimming, day hiking, fishing, and motorized water use. Those activities that presently have relatively small but enthusiastic participant populations remain popular among a relatively small contingent of outdoor recreationists. We do project steep reductions in per capita participation for several activities under most scenarios: hunting, motorized snow use, and cross-country skiing and snowshoeing.

Our projections of recreation demand include general supply factors (e.g., Federal forest land per capita within 200 miles) but do not consider factors related to how increased or more-severe natural disturbance may influence recreation resource availability. For example, our models do not consider the effects of frequent recreation resource closures because of wildfire or reduced desirability of recreation resources from presence of wildfire smoke. Researchers do not yet have a very rich understanding of how natural disturbance influences recreation behavior. In the short term, if disturbance does not alter recreation demand, it may influence recreationist decisions about where or when to recreate. Recreation managers may see recreationists opting to recreate in different seasons of the year (e.g., to avoid potential wildfire closures) or in different regions (e.g., avoiding places prone to hurricane or wind disturbance). Over the long term, increased frequency or severity of natural disturbance may influence recreation demand in ways not accounted for in our models.

Conclusions

A future that includes continuing population growth and conversion of open space to developed land is projected to result in increasing pressure on the remaining natural resources to provide for nature-based outdoor recreation. Although there have been some increases in areas of State park systems and lands managed by land conservancy organizations, the area of land accessible for recreation has not kept pace with recent population growth. Looking forward, the per capita area of forest and land accessible for recreation is projected to continue to decline if population growth occurs at the pace of our high- or moderate-growth scenarios—HH, LM, and HM. Projected losses in per capita recreation opportunities differ across regions in the United States, with declines being slower in regions with less population growth and less conversion of lands to developed land uses.

Looking ahead to the coming decades, our projections of future recreation demand generally indicate only modest changes (both increases and decreases) in the share of the population participating in specific recreation activities. This is consistent with patterns found in recent decades. Hunting participation is an exception to the otherwise mostly modest changes in projected participation. Moderate to steep declines in hunting participation are projected across all scenarios. The most-popular outdoor recreation activities today (viewing nature, day hiking, and visiting developed recreation areas) are projected to remain the most-popular in the coming decades. Although our projections of participation yield a mix of increases and decreases across activities, our projections of engagement frequency indicate declines across almost all recreation activities. Increases in engagement frequency in the coming decades are projected only for motorized water use, mountain biking, and hunting. Our projected declines in engagement are consistent with patterns observed in recent decades.

Future levels of atmospheric warming and economic development and population growth can have diverse influences on recreation demand. Participation and engagement in individual activities exhibit a range of responsiveness to changes in climate and economic development and population growth. Most activities are responsive to either socioeconomic change only or atmospheric warming and socioeconomic change jointly. Two activities most responsive to climate change are motorized snow use and the cross-country skiing and snowshoeing aggregate, with both exhibiting steep projected declines in participation as atmospheric warming levels increase. In addition, high levels of atmospheric warming have the largest negative impacts on recreation in the RPA North Region. Downhill skiing and snowboarding and hunting are both very responsive to increases in economic development and population growth: the former exhibits steep increases in projected participation rates while the latter exhibits steep declines. Our projections do not include residents of Alaska, Hawaii, or the U.S. territories. It is possible that future climate change will yield different outcomes for recreation participation and engagement in those locales.

In the presence of continued population growth, the number of individuals participating in recreation activities is generally projected to increase in the coming decades. However, if future population growth and economic development are instead more similar to our low-growth scenario (HL), we project some declines in the numbers of participants as the modest population increases under that scenario are insufficient to overcome projected declining per capita participation. Within RPA regions, the North Region is most likely to have projected declines in numbers of participants because of smaller population increases relative to other regions. The greatest numbers of participants are projected under the HH scenario because it projects a higher population than the other scenarios. In scenarios of moderate population growth and economic development (the LM and HM scenarios), participant numbers are frequently greater under lower levels of atmospheric warming. In a world with high levels of atmospheric warming, however, the greatest levels of population growth and economic expansion (the HH scenario) lead to the greatest number of participants.

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Appendix A

List of Abbreviations and Acronyms

ACI	All Conditions Inventory (USDA Forest Service program)
ACOE	U.S. Army Corps of Engineers
AF	adjustment factor
AFGC	annual forb and grass cover
AIM	Assessment, Inventory, and Monitoring (BLM program)
AR5	IPCC Fifth Assessment Report
BBS	American Breeding Bird Survey
BCR	Bird Conservation Regions
BG	bare ground
BLM	U.S. Bureau of Land Management
BMT C	billion metric tons carbon
BOR	U.S. Bureau of Reclamation
C	carbon
CBO	U.S. Congressional Budget Office
CCAFS	Research Program on Climate Change, Agriculture and Food Security
CGIAR	Consultative Group for International Agricultural Research
CO_2	carbon dioxide
CRP	Conservation Reserve Program
CV	coefficients of variability
DBH	diameter at breast height
EOS	end of season (rangeland growing season)
EPA	Environmental Protection Agency
ESA	Endangered Species Act
ESM	Earth System Models
EU	European Union
FAD	forest area density
FAO	Food and Agriculture Organization
FAOSTAT	Food and Agriculture Organization statistical data
FDM	Forest Dynamics Model
FHP	Forest Health Protection
FIA	Forest Inventory and Analysis
FOROM	Forest Resource Outlook Model
FTG	forest type groups
FWS	U.S. Fish and Wildlife Service
G1	critically imperiled species
G2	imperiled species
G3	vulnerable species
GDP	gross domestic product
GFC	Great Financial Crisis
GHG	greenhouse gases
GTR	general technical report
HH	RPA scenario representing high atmospheric warming and high socioeconomic growth (RCP 8.5-SSP5)
HL	RPA scenario representing high atmospheric warming and low socioeconomic growth (RCP 8.5-SSP3)
HM	RPA scenario representing high atmospheric warming and moderate socioeconomic growth (RCP 8.5-SSP2)
HUC	hydrologic unit code
HWP	harvested wood products
IDS	Insect and Disease Survey
IEA	International Energy Agency
IGSM-CAM	Integrated Global System Model-Community Atmosphere Model
IIASA	International Institute for Applied Systems Analysis
IIFT	Integrated Interagency Fuels Treatment Database
ILRI	International Livestock Research Institute
IPCC	Intergovernmental Panel on Climate Change
IUCN	International Union for the Conservation of Nature
LANDFIRE	Landscape Fire and Resource Management Planning Tool
LM	RPA scenario representing lower atmospheric warming and moderate socioeconomic growth (RCP 4.5-SSP1)
LMF	Landscape Monitoring Framework
MACA	Multivariate Adaptive Constructed Analogs (climate modeling)
MC2	dynamic global vegetation model
MIT	Massachusetts Institute of Technology
MMT C	million metric tons carbon
MODIS	Moderate Resolution Imaging Spectroradiometer
MRLC	Multi-Resolution Land Characteristics
MT	metric tons
MTBS	Monitoring Trends in Burn Severity
NARR	North American Regional Reanalysis
NASA	U.S. National Aeronautics and Space Administration
NASS	USDA National Agricultural Statistics Service

NDC	Nationally Determined Contribution
NFS	National Forest System
NIR	National Inventory Report
NLCD	National Land Cover Database
NOAA	U.S. National Oceanic and Atmospheric Administration
NPP	net primary productivity
NPS	U.S. National Park Service
NRI	National Resources Inventory
NSRE	National Survey on Recreation and the Environment
NTFP	nontimber forest products
NVUM	National Visitor Use Monitoring
NWCG	National Wildfire Coordinating Group
NWPS	National Wilderness Preservation System
OECD	Organization for Economic Cooperation and Development
OSB	oriented strand board
PAD-US	Protected Areas Database of the United States
PCA	principal component analysis
PDI	Percent Developed Imperviousness
PET	potential evapotranspiration
PFGC	perennial forb and grass cover
PI	photointerpretation
PRIA	Public Range Improvement Act
PRISM	Parameter-elevation Regressions on Independent Slopes Model (precipitation model)
RAP	Rangeland Analysis Platform
RCP	Representative Concentration Pathway
REIT	real estate investment trusts
RPA	Resources Planning Act
RPMS	Rangeland Production Monitoring Service
SGCN	Species of Greatest Conservation Need
SGS	singing-ground survey
SLR	sea level rise
SOC	soil organic carbon
SOS	start of season (rangeland growing season)
SPEI	Standardized Precipitation Evapotranspiration Index
SSP	Shared Socioeconomic Pathway
SWAP	State Wildlife Action Plan
SWDS	solid waste disposal site
TCC	Tree Canopy Cover
TCSI	Terrestrial Climate Stress Index
Tg	teragram
TIMO	timberland investment management organizations
TPO	Timber Product Output
UNECE	United Nations Economic Commission for Europe
UNFCCC	United Nations Framework Convention on Climate Change
USBLS	U.S. Bureau of Labor Statistics
USCB	U.S. Census Bureau
USDA	U.S. Department of Agriculture
USDA FAS	U.S. Department of Agriculture, Foreign Agricultural Service
USDA NRCS	U.S. Department of Agriculture, Natural Resources Conservation Service
USDC	U.S. Department of Commerce
USGCRP	U.S. Global Change Research Program
USGS	U.S. Geological Survey
USITC	United States International Trade Commission
VIC	Variable Infiltration Capacity
WEAP	Water Evaluation and Planning
WUI	wildland-urban interface

Appendix B

List of Chapter Citations

Chapter 1

U.S. Department of Agriculture, Forest Service. 2023. Key Findings of the 2020 RPA Assessment. In: U.S. Department of Agriculture, Forest Service. 2023. Future of America's Forest and Rangelands: Forest Service 2020 Resources Planning Act Assessment. Gen. Tech. Rep. WO-102. Washington, DC: 1-1–1-11. Chapter 1. https://doi.org/10.2737/WO-GTR-102-Chap1.

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