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.

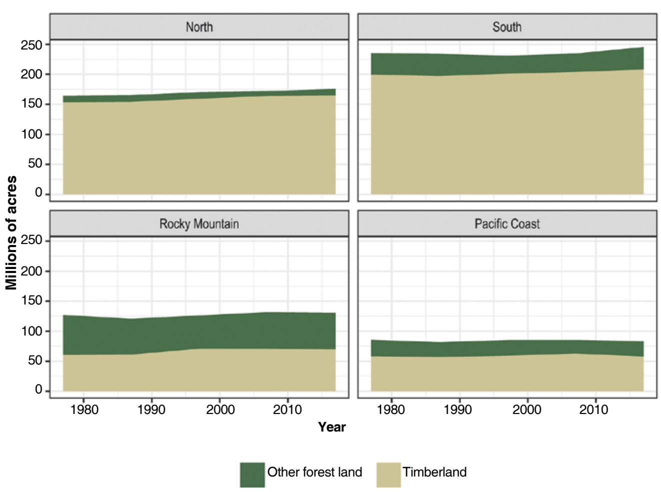
Solid waste disposal site (SWDS): IPCC carbon pool that tracks HWP carbon by product and end use once it has been disposed of.

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).

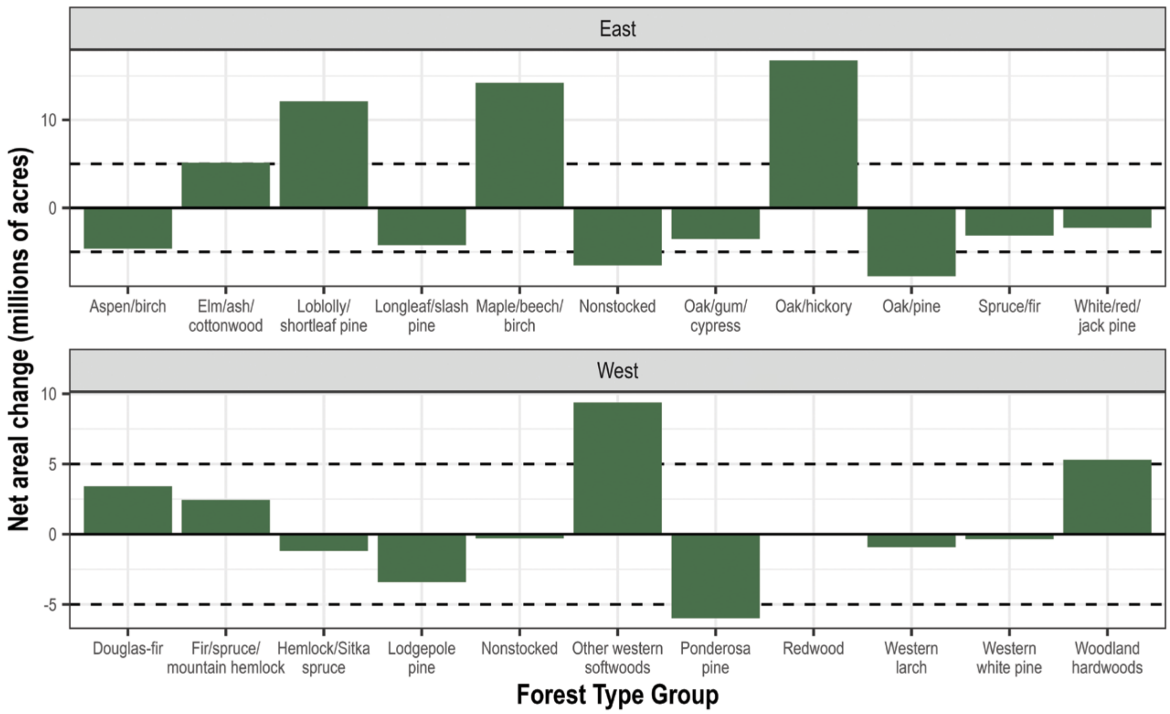
Timberland Area by Forest Type Group

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.

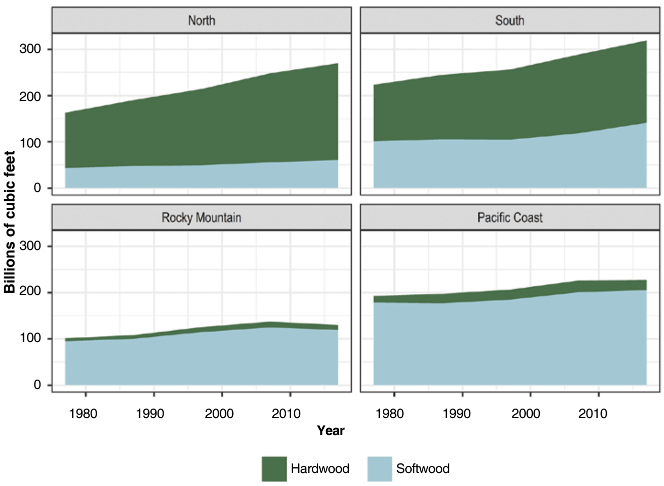
in area over much of the 20th century due to historic fire suppression, land use conversion, and conversion to other forest type groups like loblolly/shortleaf pine (Oswalt et al. 2014). While the area of longleaf pine forests started to increase in the 1990s, it has not reached previous levels (Oswalt 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.



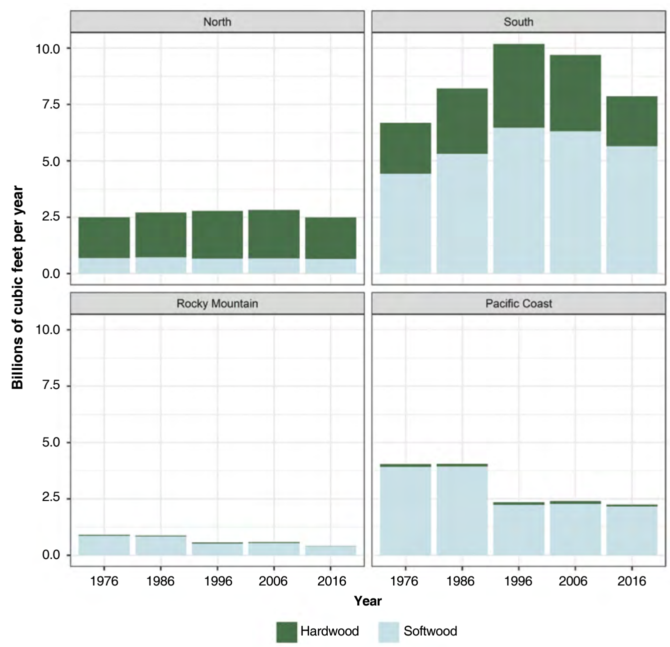
South Regions, hardwood species made up 84.3 percent (90.3 billion cubic feet) and 58.1 percent (55.6 billion cubic feet) of the increased timberland volume, respectively. In contrast, the increased timberland volume in the Rocky Mountain and Pacific Coast Regions was primarily from softwood species: 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.

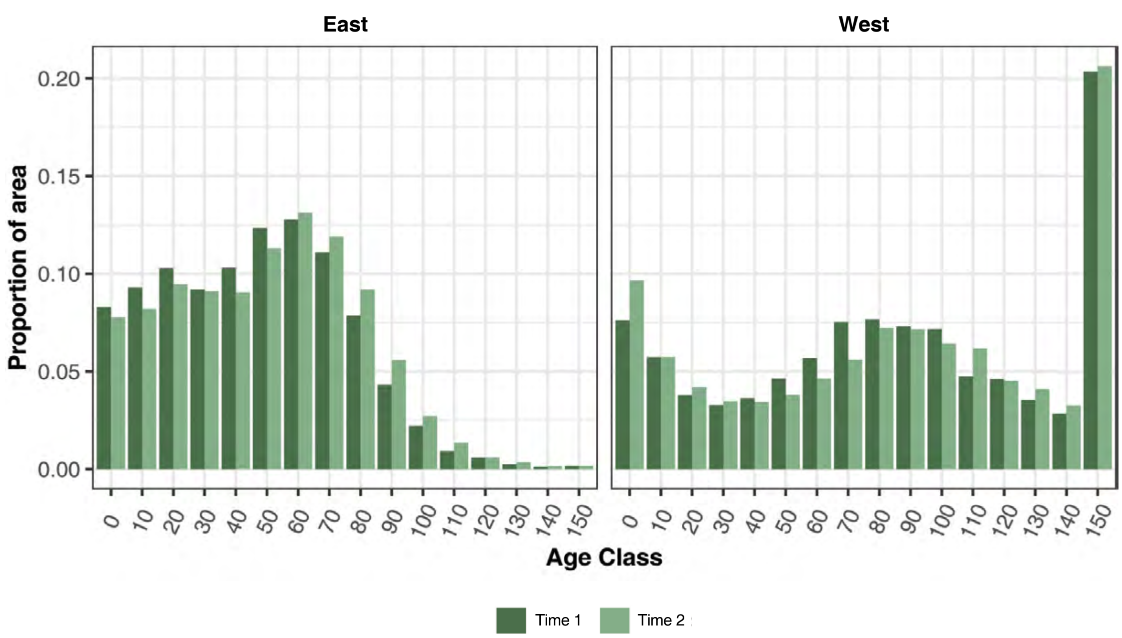
Figure 6-5 shows the forest age distributions based on the two most current measurements of the FIA inventory. In the Eastern United States, the forest area in age classes younger than 60 years decreased between time 1 and time 2 measurements, and there was a corresponding increase in forest greater 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.



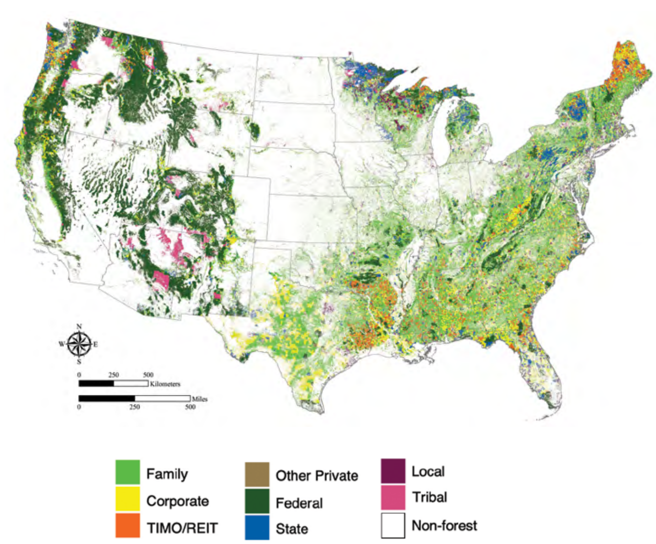
a person or organization can and cannot do with a given piece of land and its associated resources are called land tenure rights. The United States has strong and well-defined land tenure rights that help determine the exclusivity, transferability, alienability, and enforceability associated with the 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.



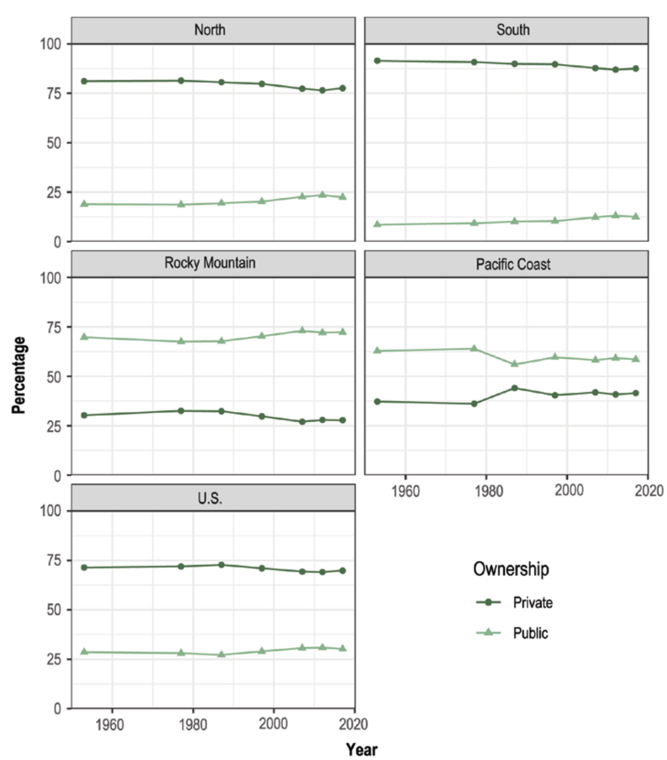
REIT = real estate investment trusts; TIMO = timberland investment management organization.
Source: Sass et al. 2020.

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.

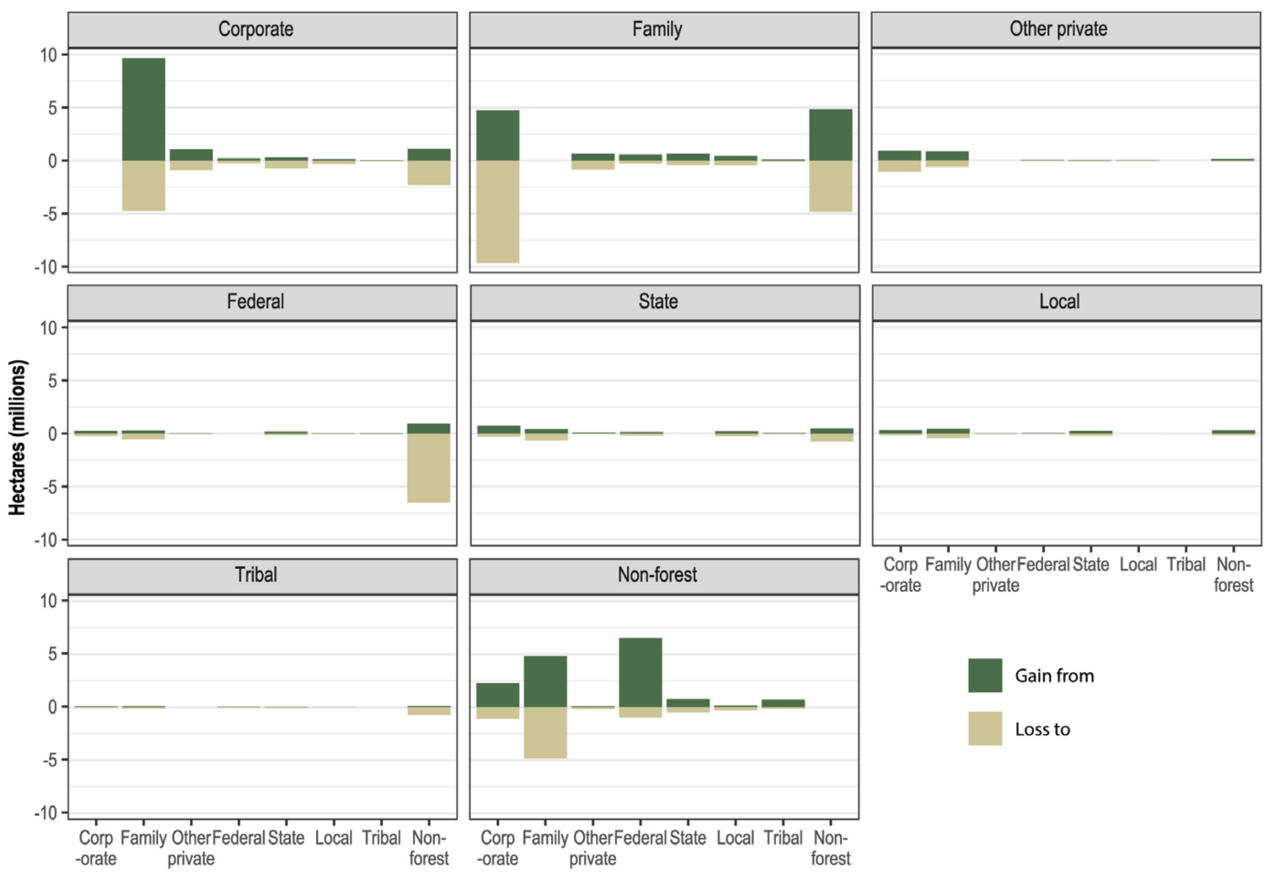
The largest net changes across ownership groups over the past decade have been an increase in corporate forest land and decreases in family and Federal forest land (figure 6-8; Sass et al. 2021). Most of the increase in corporate forest land has come from family forest lands. Although the details are 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.



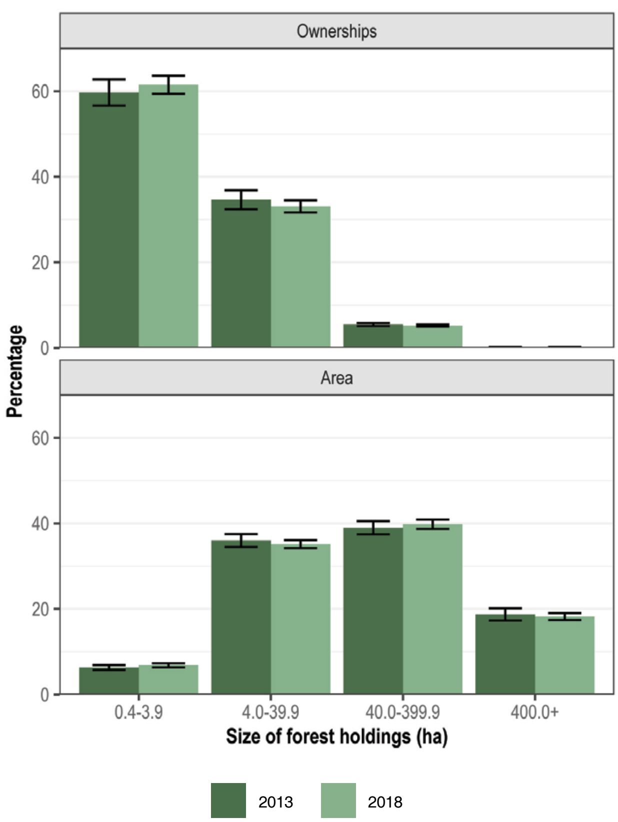
Source: Sass et al. 2021.

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).

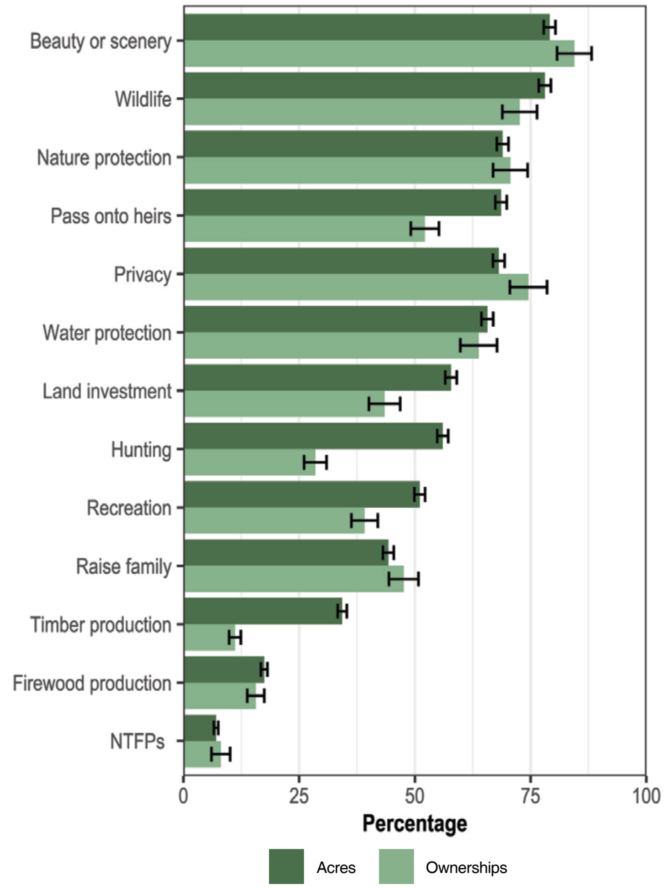
Demographics are important for understanding family forest ownership trends. Given that the age of the primary family forest decisionmaker is 65 or older for 56 percent of the family forest land, intergenerational transfer has the

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.

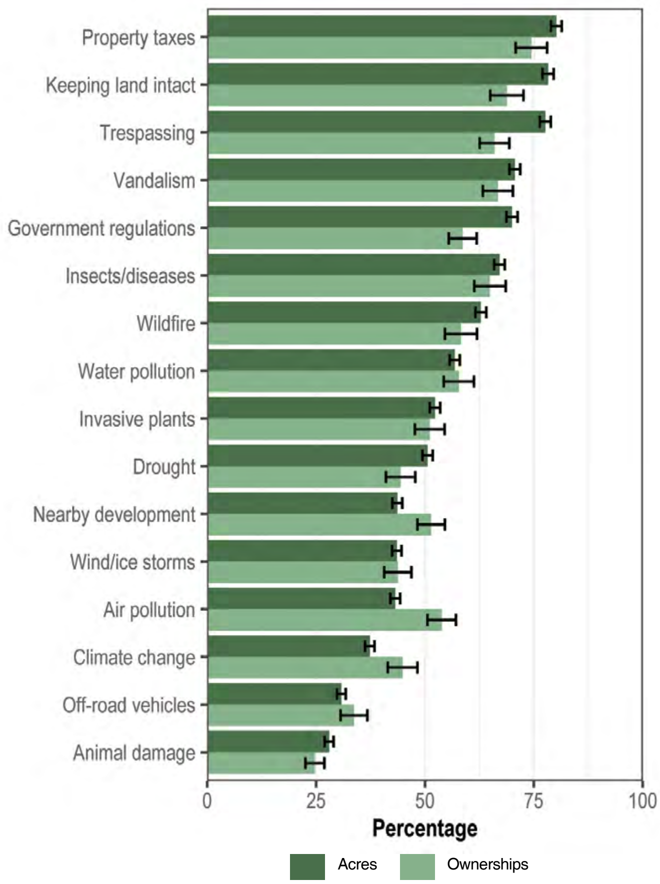


NTFPs = nontimber forest products.

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.

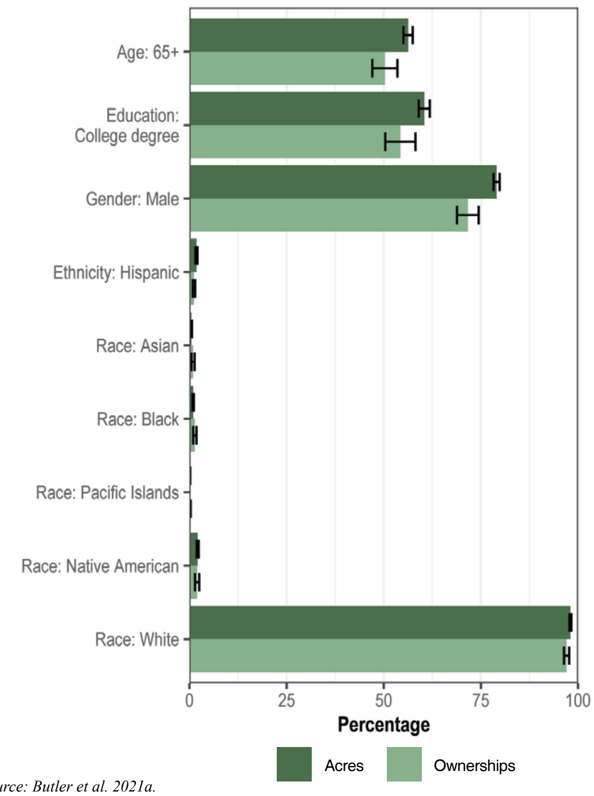
Figure 6-11. Percentage of family forest acreage and family forest ownerships identifying potential ownership concerns in 2018. Error bars are 95 percent confidence intervals.



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.



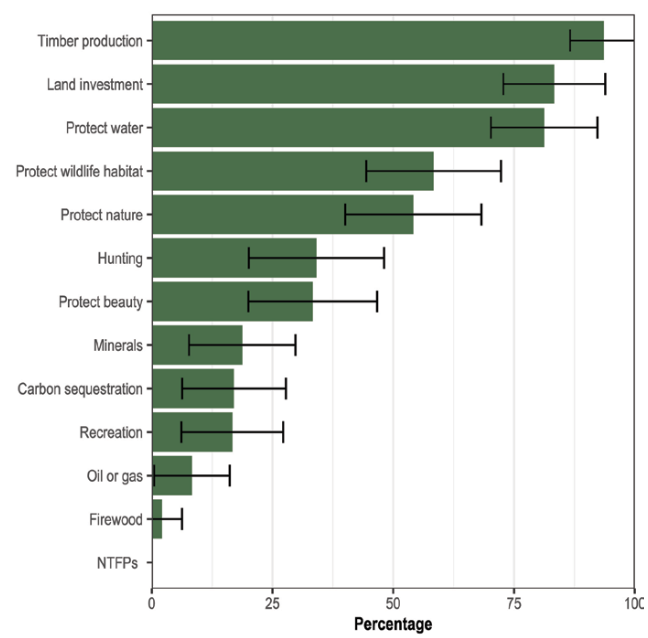
Source: Butler et al. 2021a.

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.



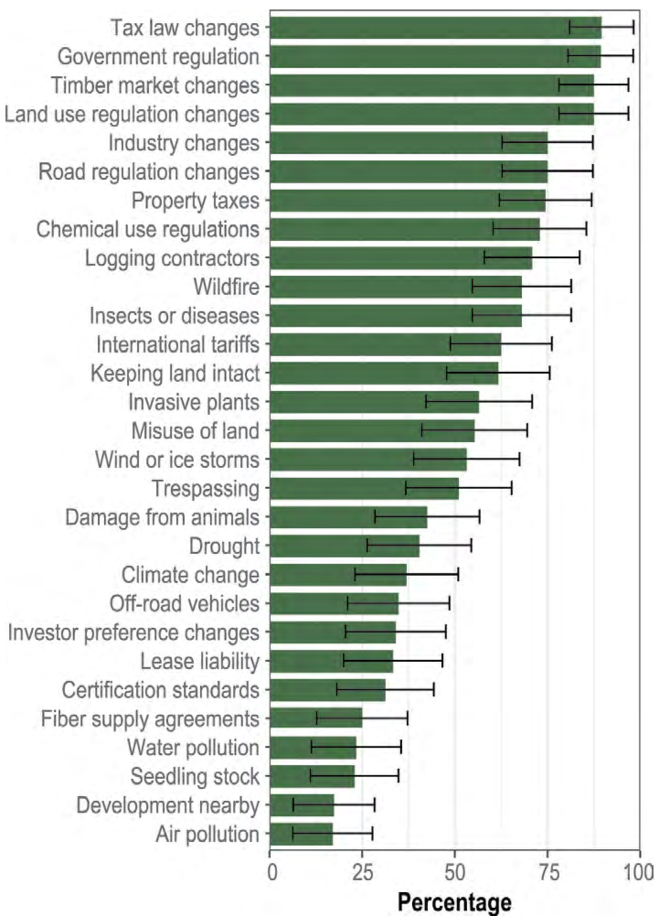
NTFPs = nontimber forest products.

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

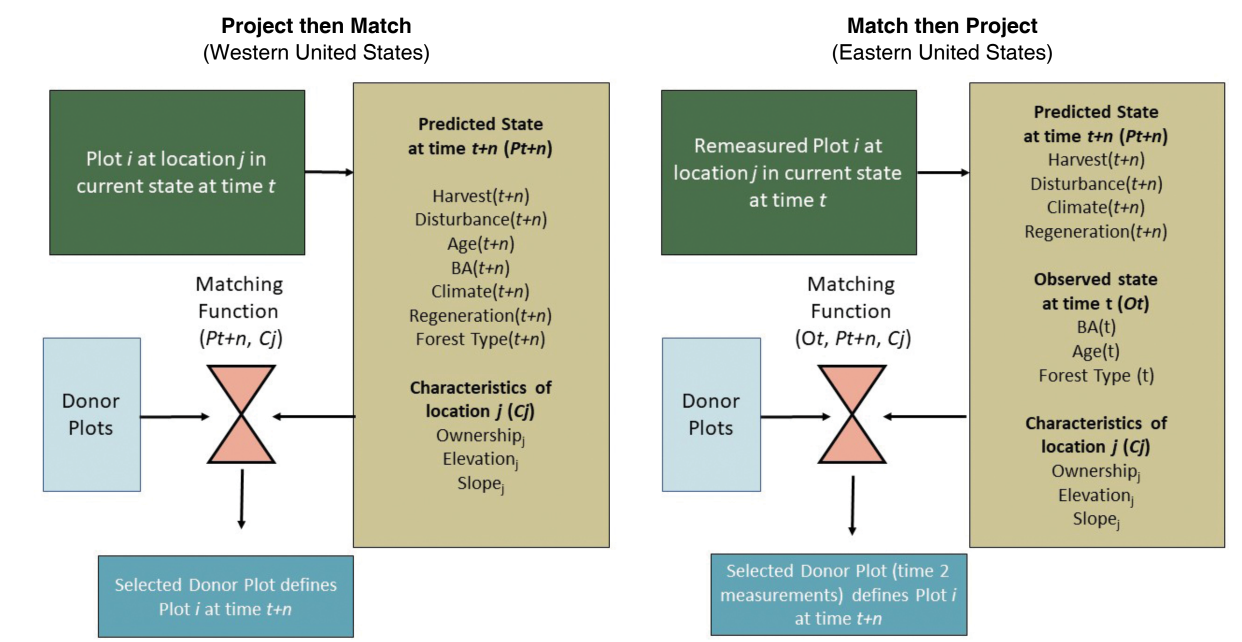
The Forest Dynamics Model is a stochastic modeling system which projects the FIA database at the plot (condition) level using an imputation approach (Coulston et al. in preparation). This approach allows for consistent projections across a range of variables of interest (e.g., volume, age, carbon, forest 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.

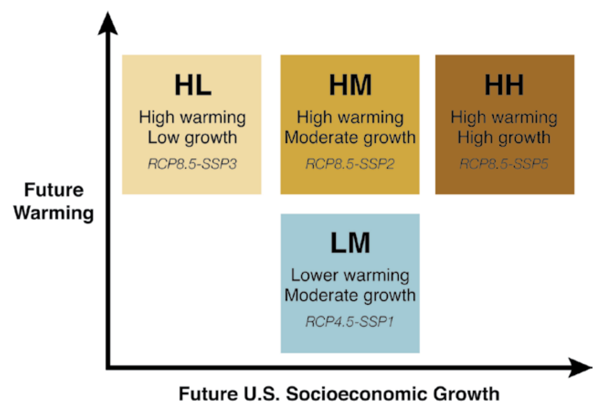
In 2020, 78.5 percent (498 million acres) of the forest land area in the conterminous United States was timberland, and timberland area futures follow the same trends as forest land use futures to a large degree. However, because timberland is partially defined by growth potential, timberland area can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

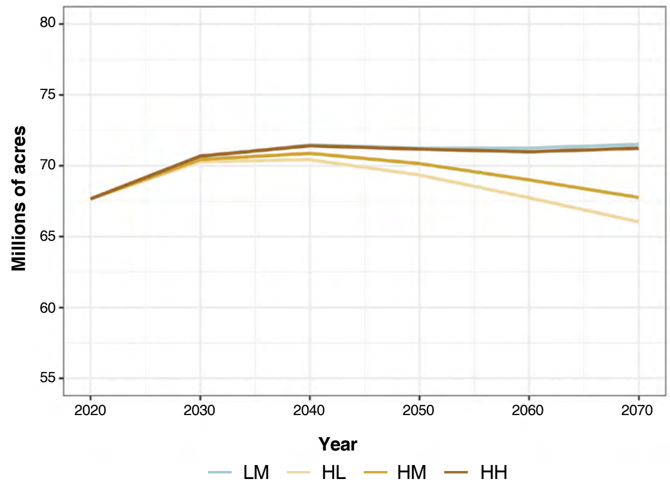
Timberland area projections differ by RPA region (figure 6-18). Most timberland loss is expected in the South, where between 5.7 (HL-hot) and 10.1 (HH-least warm) million acres are expected to be lost primarily to developed uses by 2070. The Pacific Coast Region is expected to lose between 1.6 and 2.5 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.

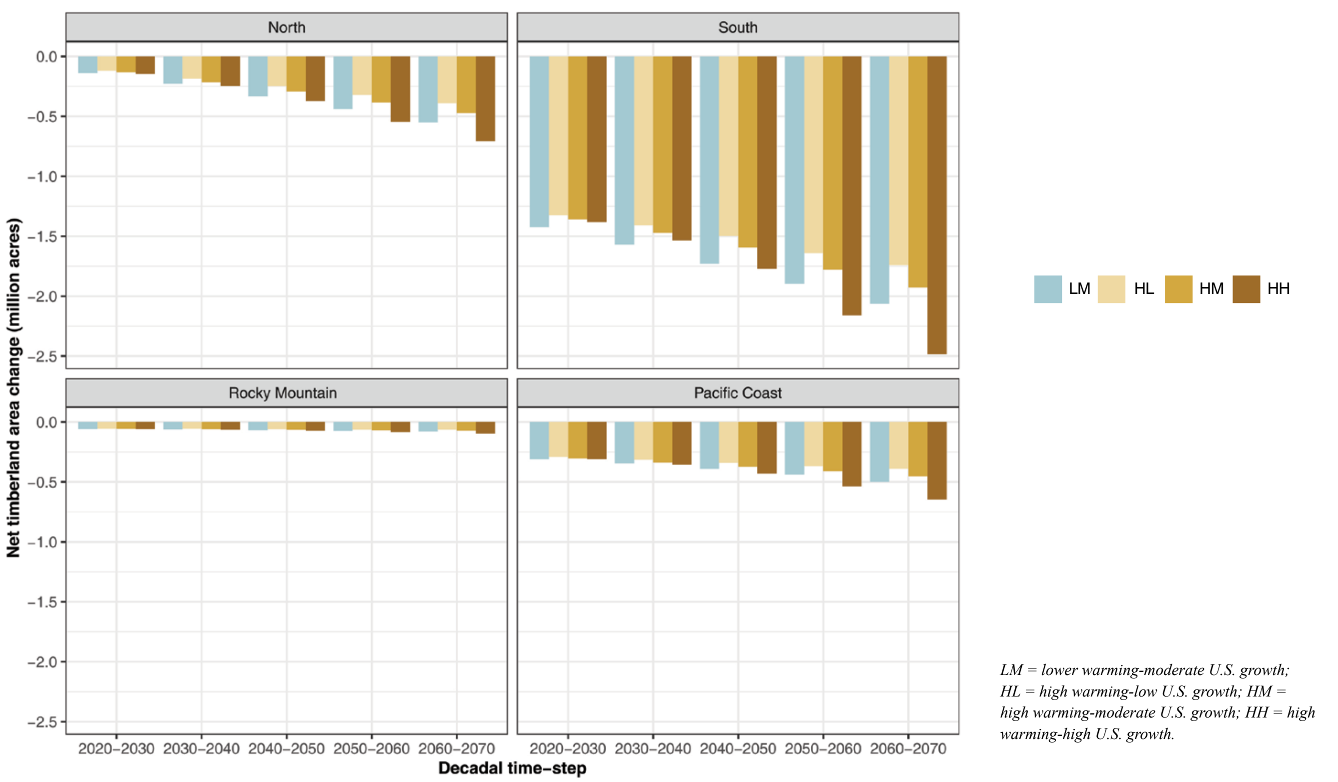
Under all RPA scenarios, planted forest area is projected to increase between 4 percent (HL) and 6 percent (LM) until 2040 (figure 6-19). From 2040 to 2070, planted area

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.

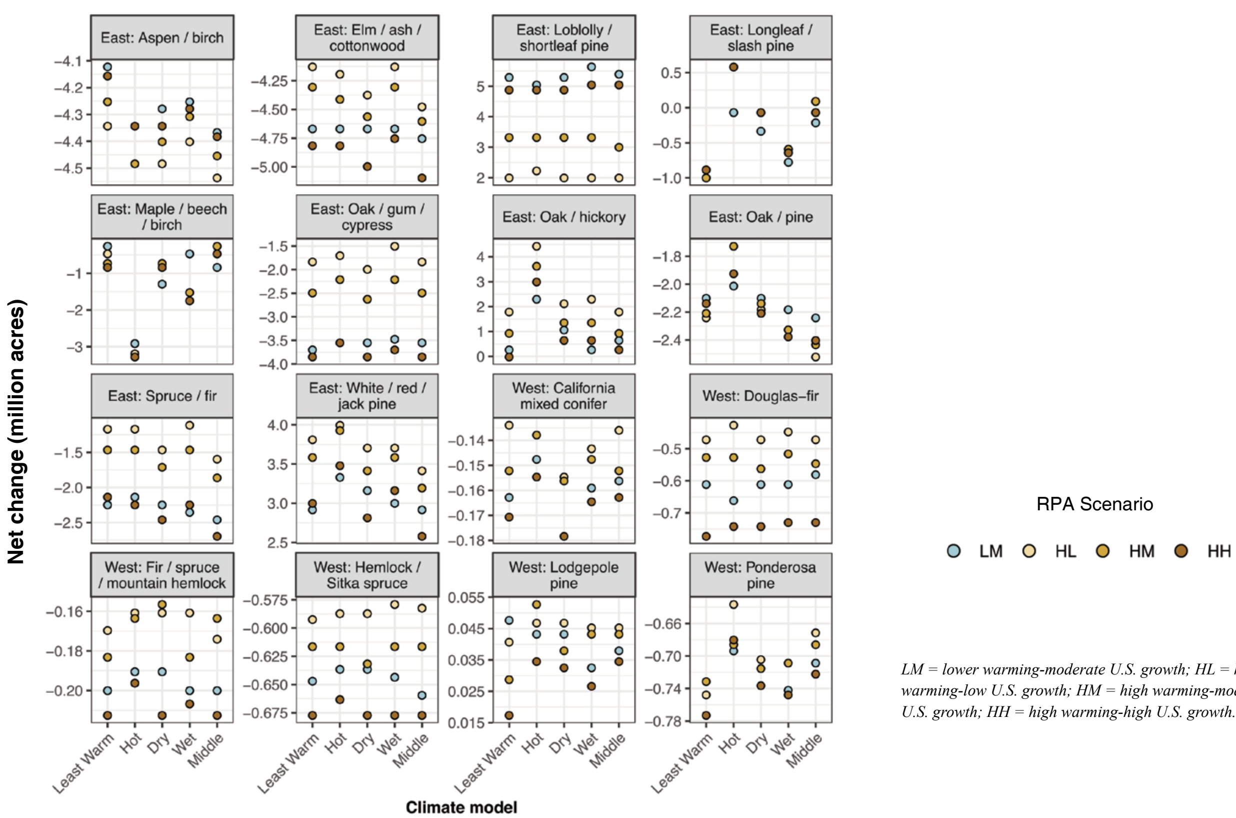
The national planted area projection trends are primarily driven by planting and replanting in the South Region, which contained 71 percent of planted forest in 2020. Planted area trends in the South therefore mirror the national trends. In the North and Rocky Mountain Regions, planted forest area is 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.

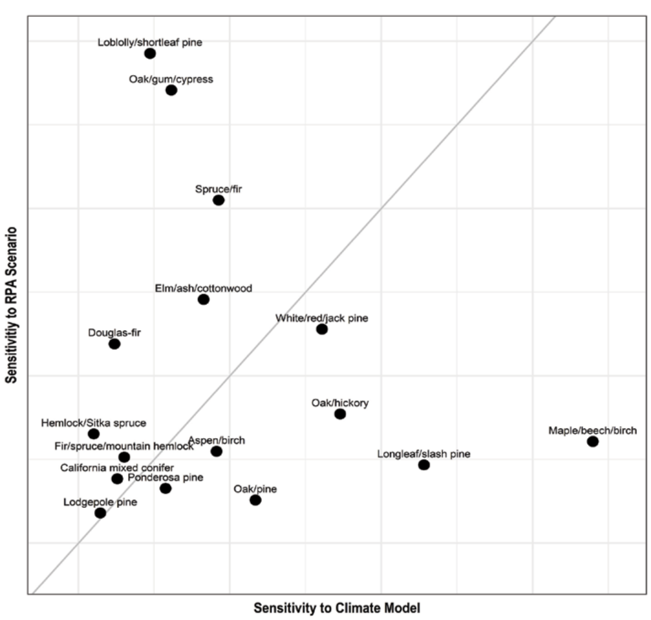


LM = lower warming-moderate U.S. growth; HL = high warming-low U.S. growth; HM = high warming-moderate U.S. growth; HH = high warming-high U.S. growth.

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).

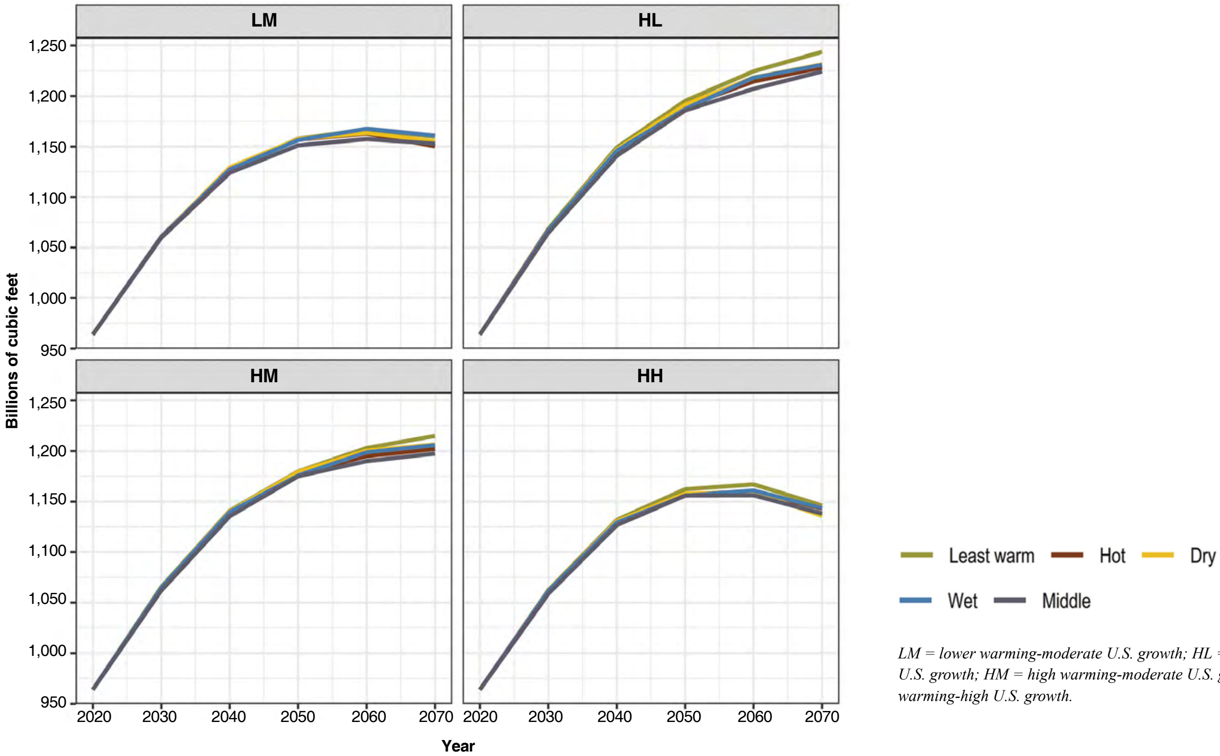
There are distinct regional patterns with respect to growing stock volume futures (figure 6-23). In the North, both hardwood and softwood growing stock inventories are projected to increase across RPA scenarios throughout the projection period. Hardwood inventory is more sensitive to demand because the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

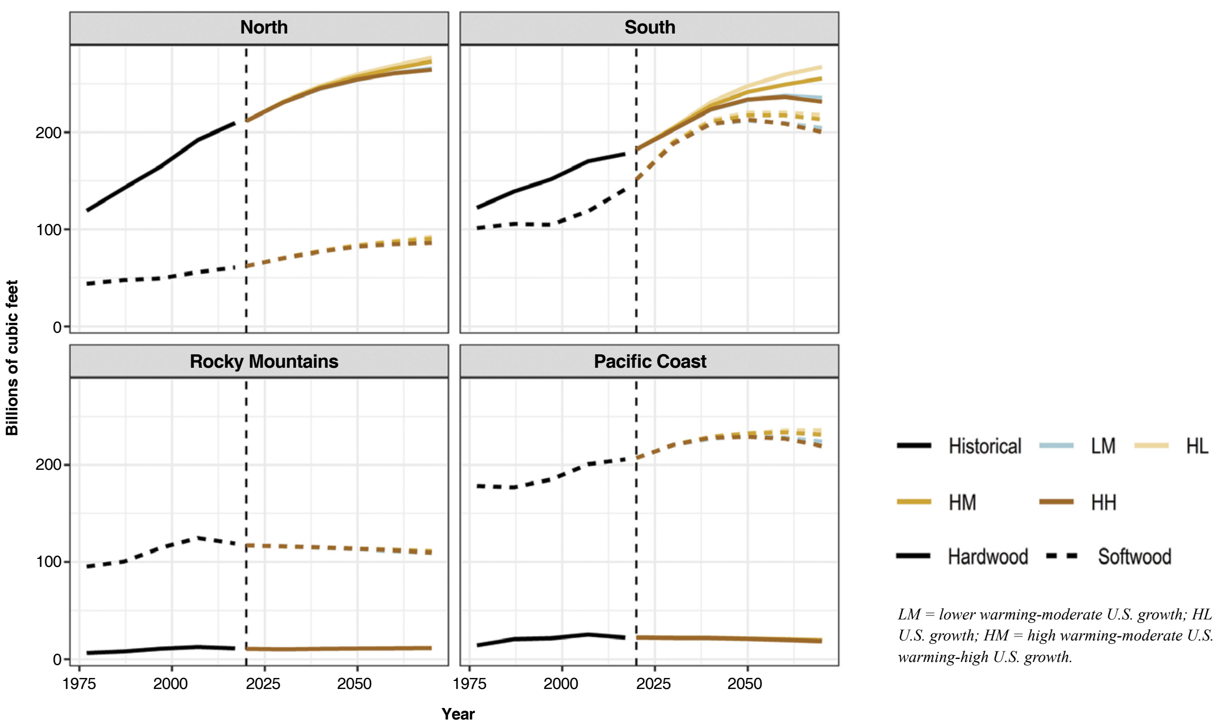
The Pacific Coast is also a softwood-dominated region, and softwood growing stock volume is projected to increase

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.

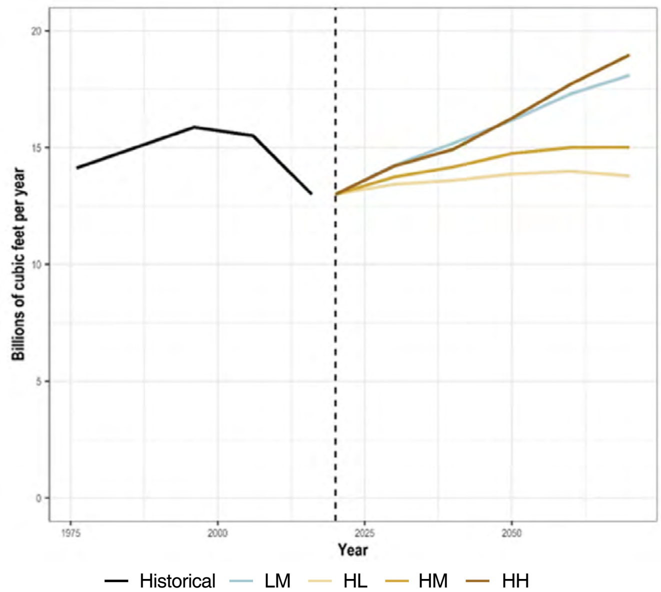
through 2050 across RPA scenarios, while hardwood growing stock volume is projected to decline slightly throughout the projection period. Similar to the South, post-2050 softwood growing stock futures depend on roundwood demand, where softwood growing stock volume are projected to decrease post-2050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

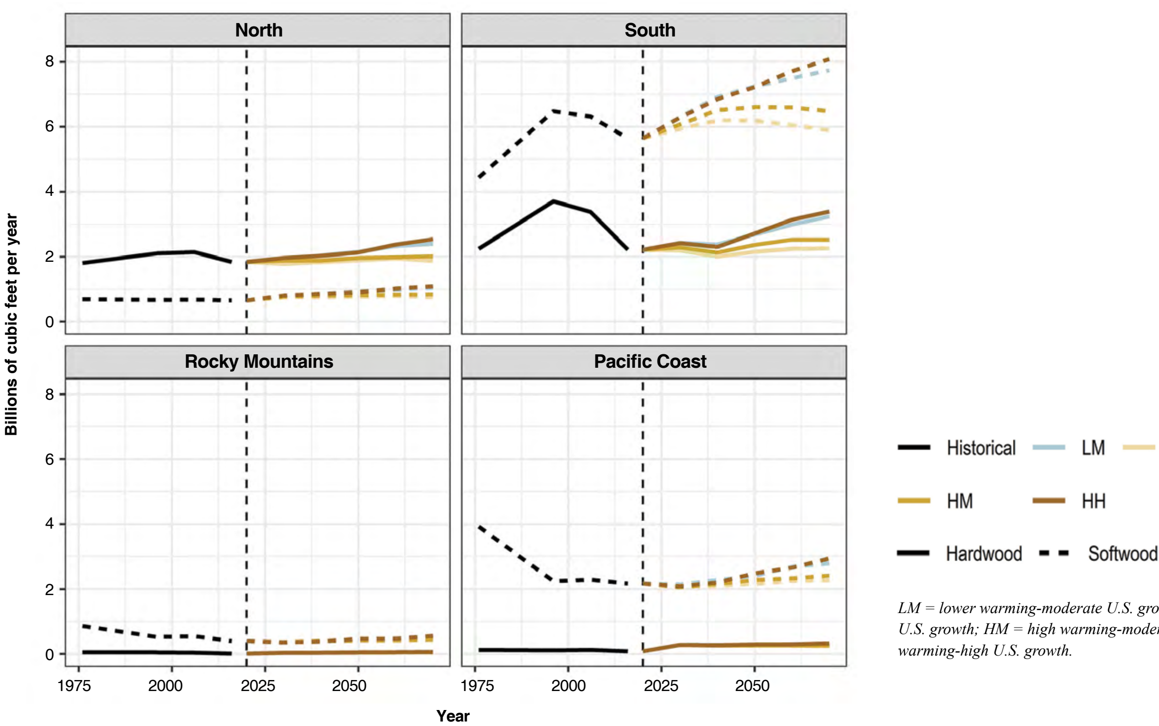
Hardwood and softwood removals are generally projected to recover from the lows that occurred in the 2000s in each region, but the North and South Regions are expected to show substantial increases in all removals by 2070 relative to 2020 removals (figure 6-25). These increases roughly mirror

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.

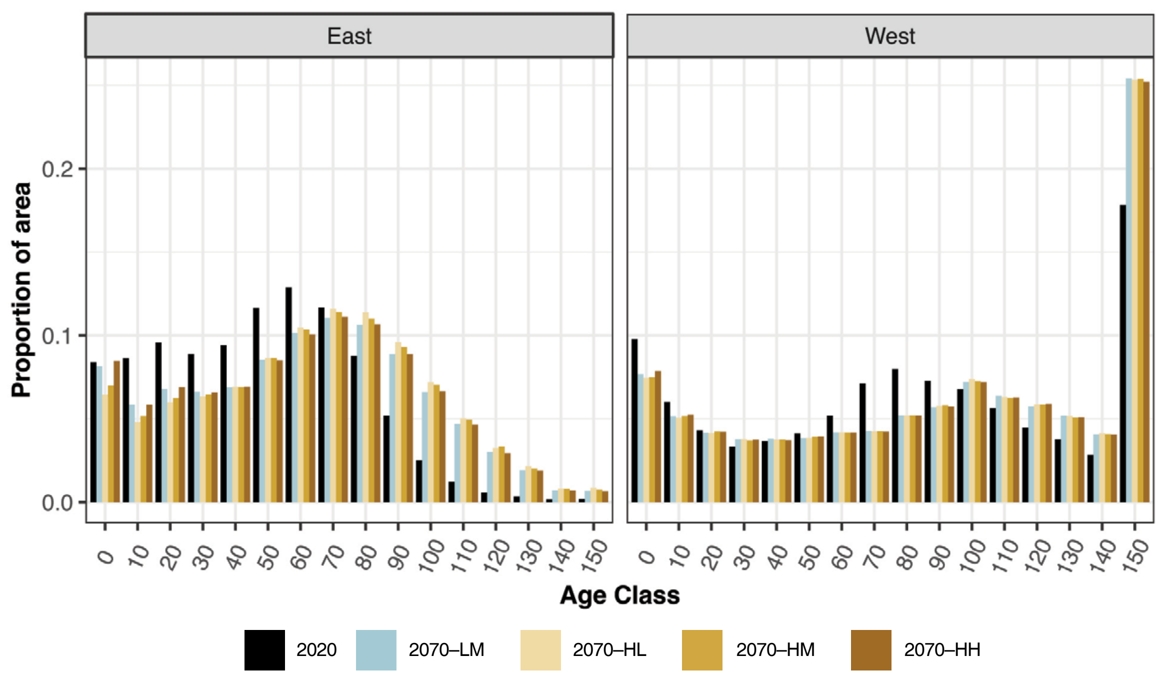
projected wood prices (see the Forest Products Chapter). As with trends across the conterminous United States, RPA scenario impacts the rate of this recovery, and in some cases, whether removals are expected to return to pre-2000s levels (e.g., softwoods in the Rocky Mountain and Pacific Coast Regions 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.

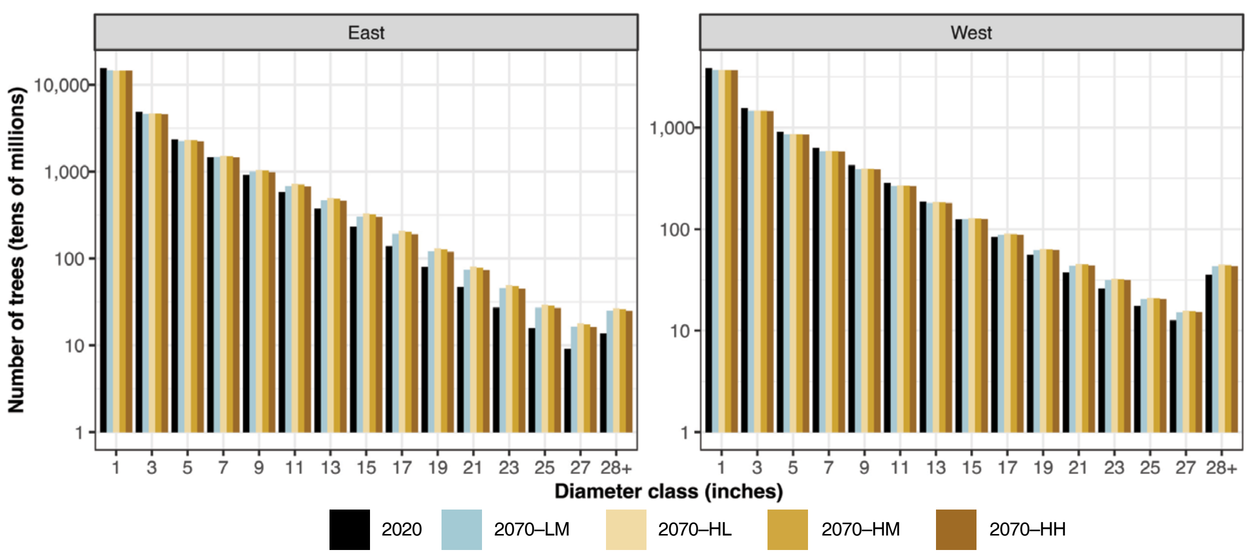
LM = lower warming-moderate U.S. growth; HL = high warming-low U.S. growth; HM = high warming-moderate U.S. growth; HH = high warming-high U.S. growth.

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.

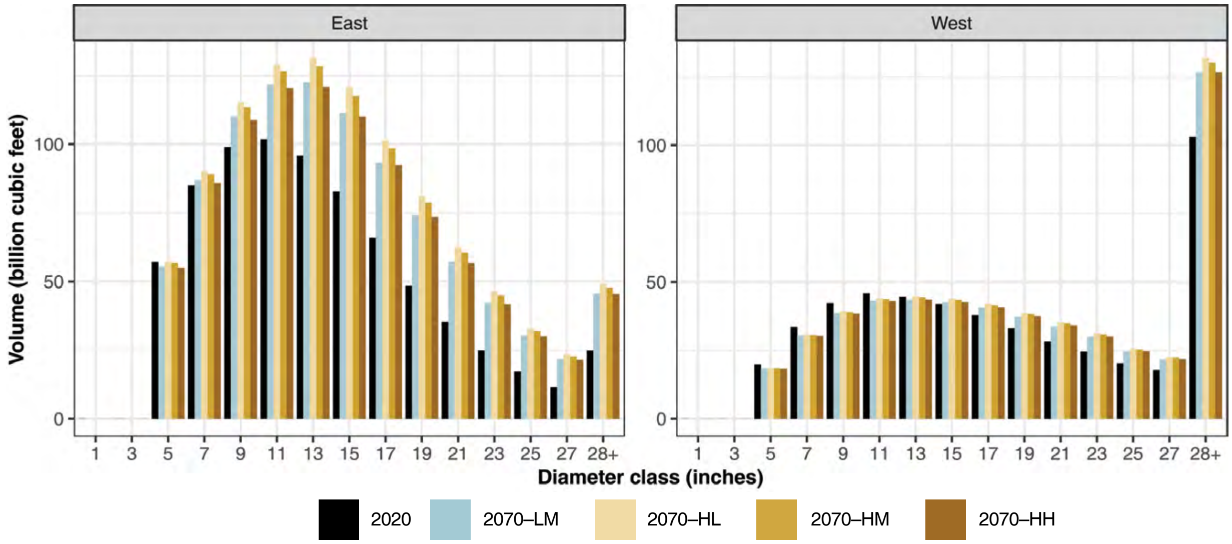
While the projected shifts in the number of trees by diameter class may appear subtle, these shifts have a large effect on the volume distribution by diameter class, particularly for diameter classes larger than 5 inches in the East and larger than 13 inches in the West (figure 6-28). The increase in 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.

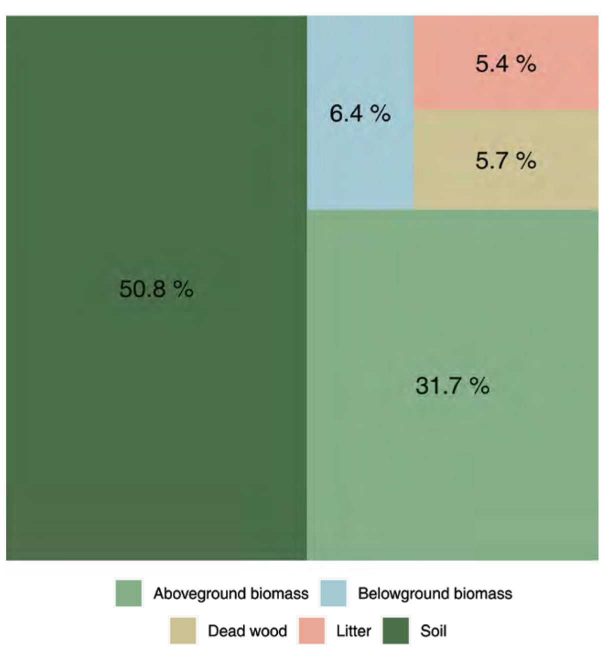
	Year						
Carbon pool	**1990**	**1995**	**2000**	**2010**	**2015**	**2019**	**2020**
	BMT C (MMT C yr^{-1})						
Forest ecosystem total	40.61 (173)	41.46 (168)	42.30 (164)	43.90 (161)	44.70 (166)	45.35 (155)	45.51 (--)
Aboveground biomass	11.08 (120)	11.67 (116)	12.25 (112)	13.35 (109)	13.89 (112)	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.

		RPA scenario			
Climate model	2020 forest remaining forest	LM	HL	HM	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

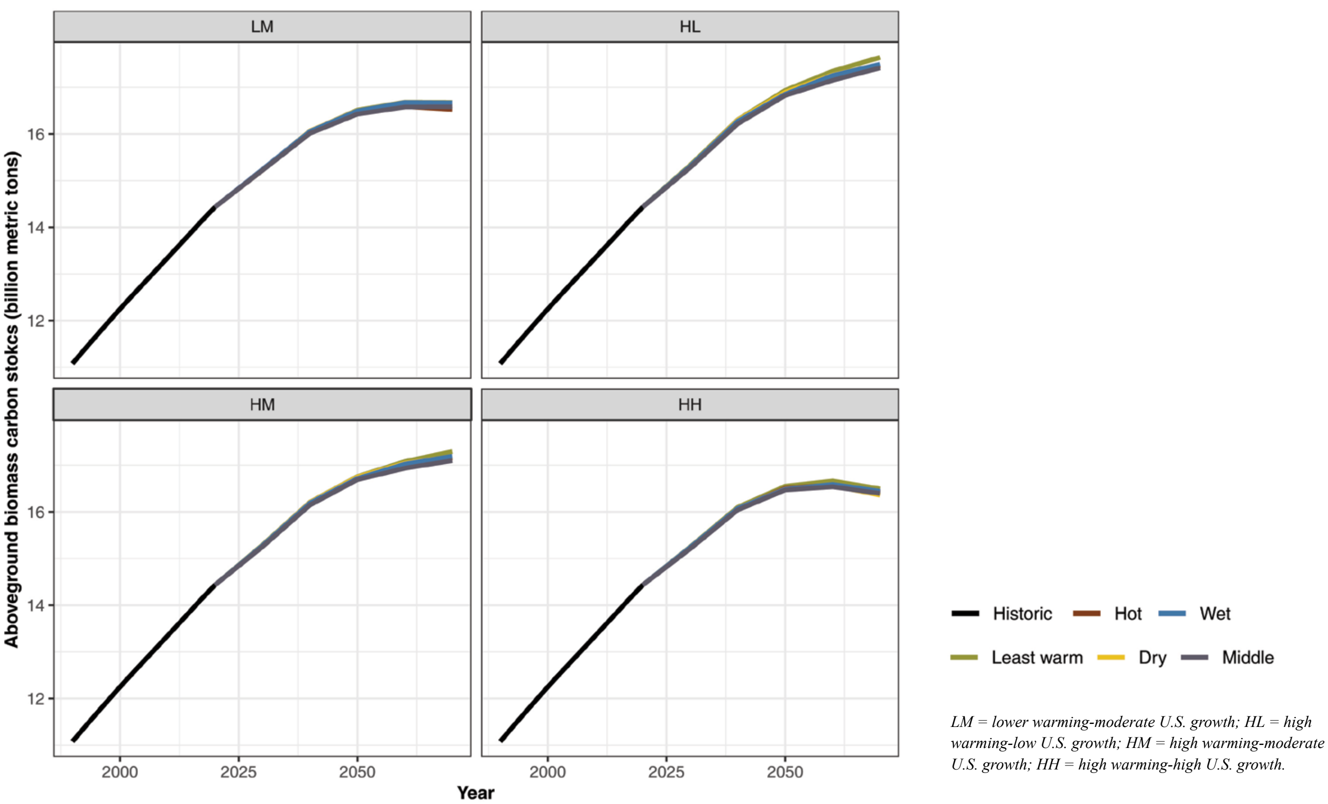
The aboveground biomass C pool is the primary driver of overall C sequestration (Pan et al. 2011). Our results suggest that this pool will increase at a decreasing rate from 2020 to 2070. While land use conversion and future disturbance play a role in reducing future sequestration rates, forest aging 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.

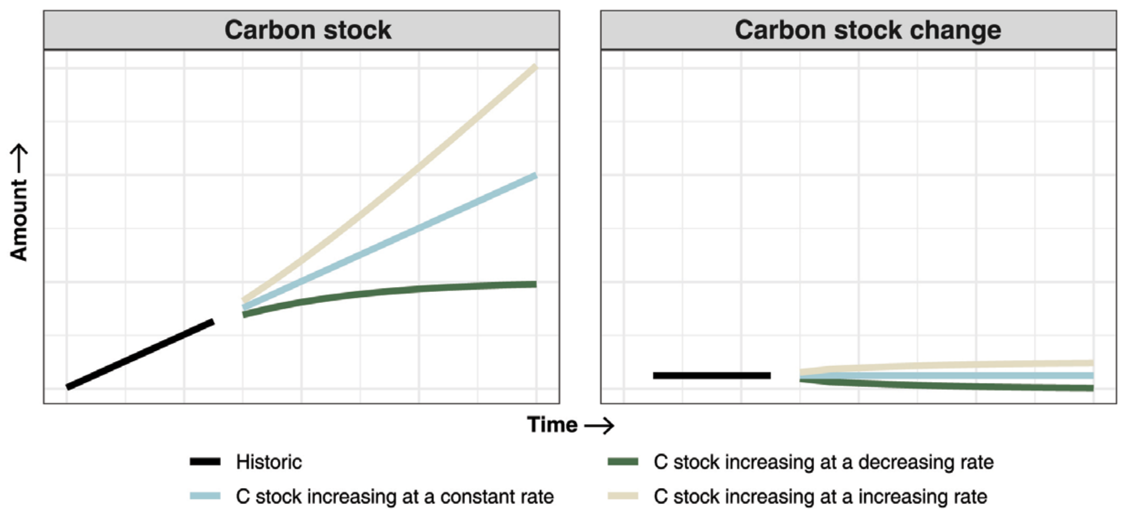


LM = lower warming-moderate U.S. growth; HL = high warming-low U.S. growth; HM = high warming-moderate U.S. growth; HH = high warming-high U.S. growth.

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.



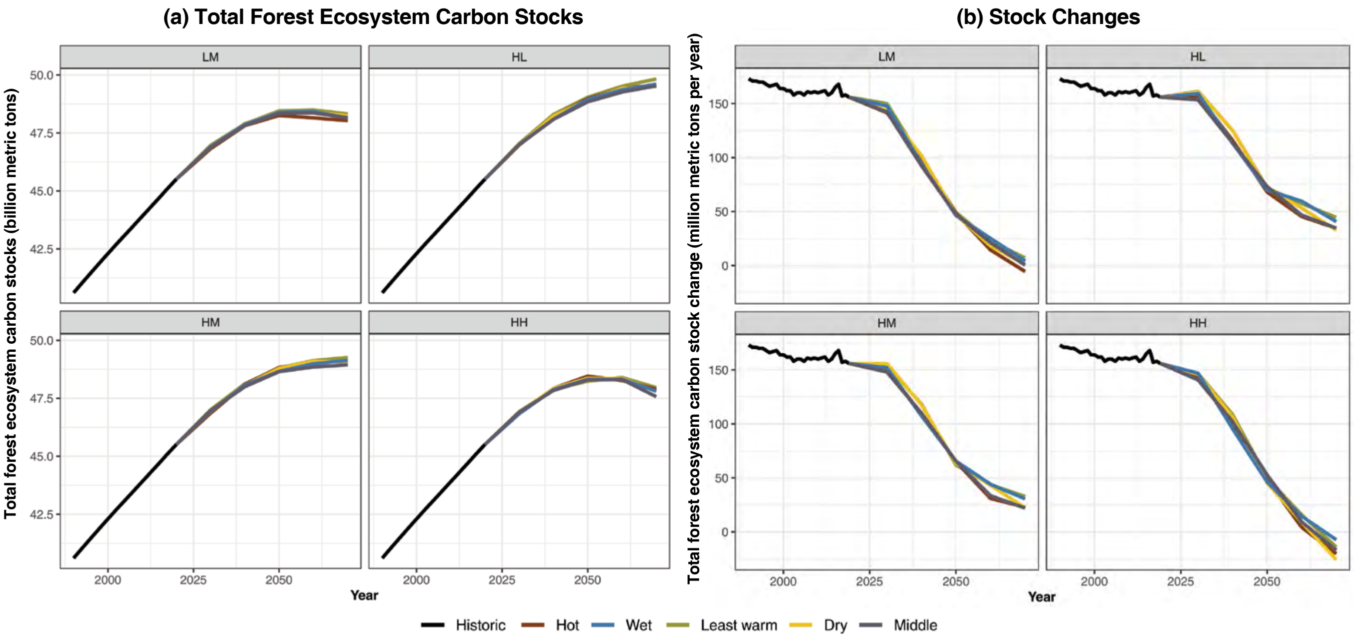
C = carbon.

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

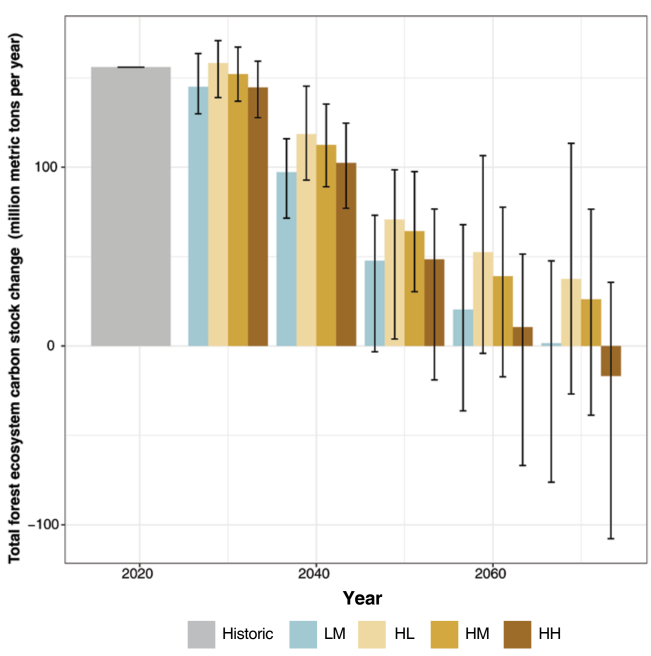
Total C stocks on forest remaining forest are projected to increase from 45.5 BMT C in 2020 to between 47.6 BMT C (HH-middle) and 49.8 BMT C (HL-least warm) in 2070 (figure 6-32a). C stock change in 2030 is projected to be relatively consistent with 2019 stock change estimates and then is projected to 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).



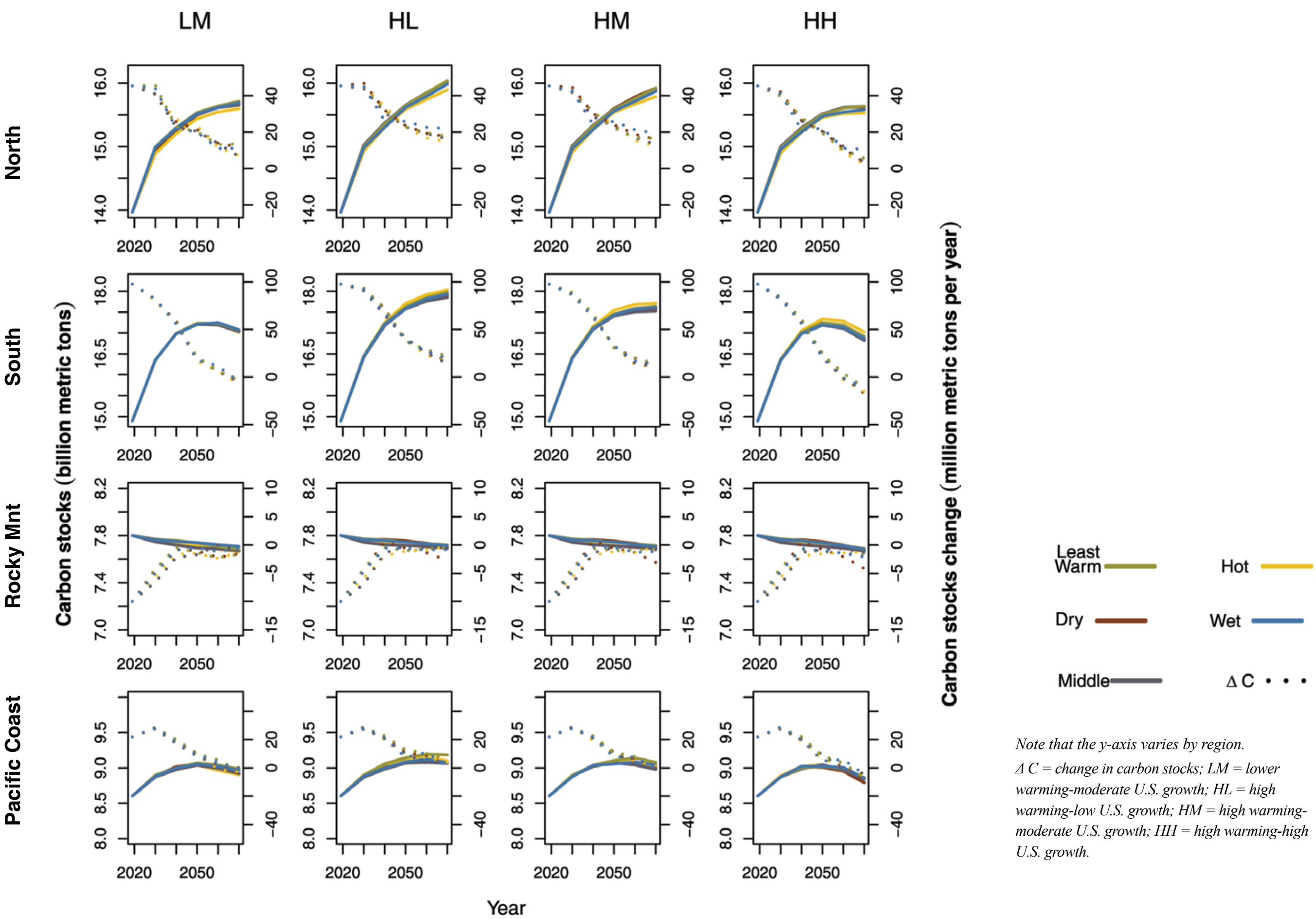
LM = lower warming-moderate U.S. growth; HL = high warming-low U.S. growth; HM = high warming-moderate U.S. growth; HH = high warming-high U.S. growth.

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.

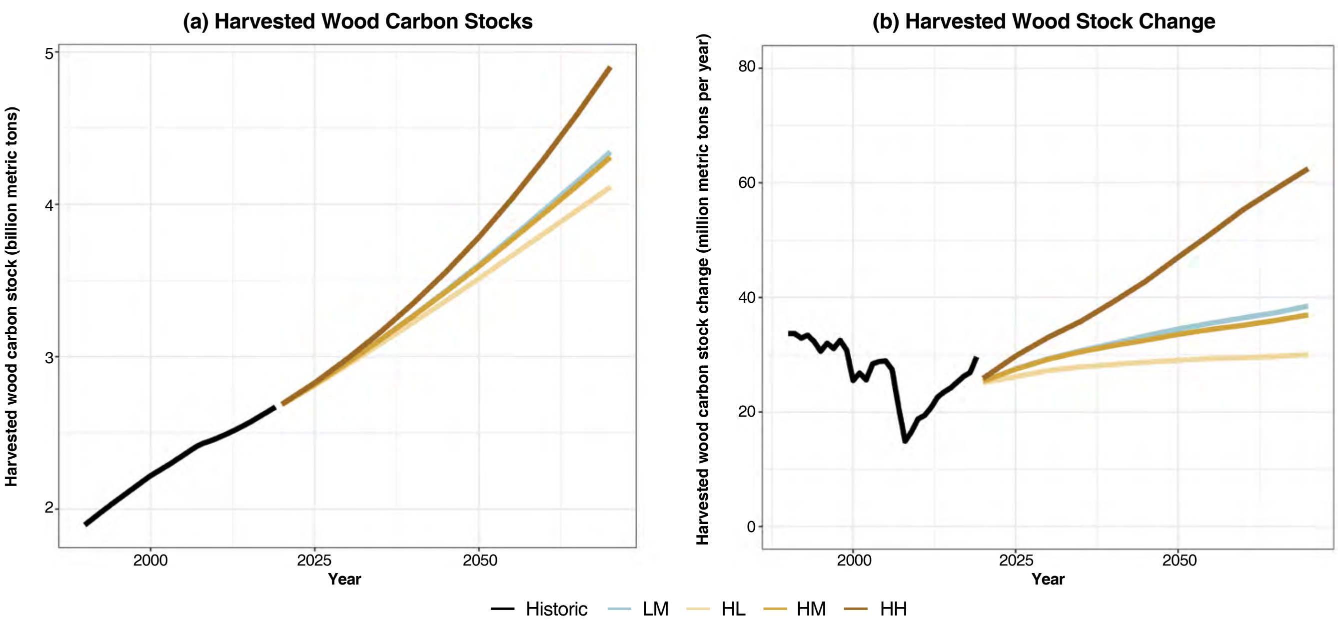
Other Land Converted to Forest

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)

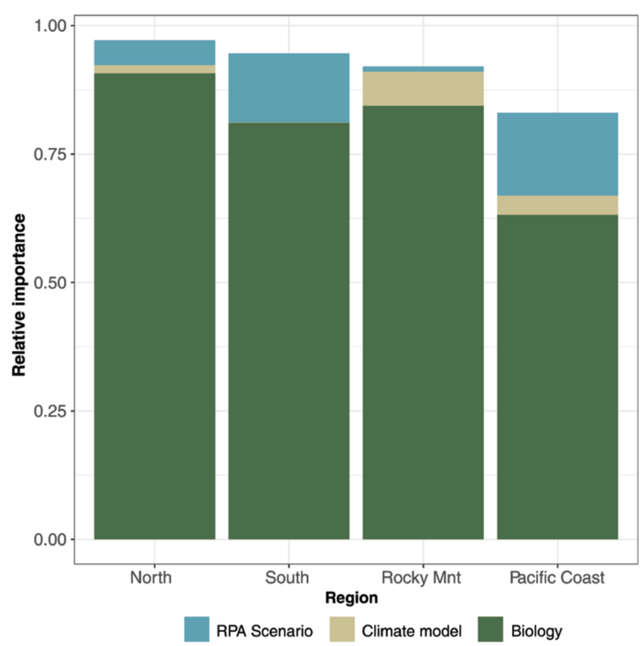
BMT = billion metric tons; C = carbon; MMT = million metric tons; yr = year; LM = lower warming-moderate U.S. growth; HL = high warming-low U.S. growth; HM = high warming-moderate U.S. growth; HH = high warming-high U.S. growth.

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.

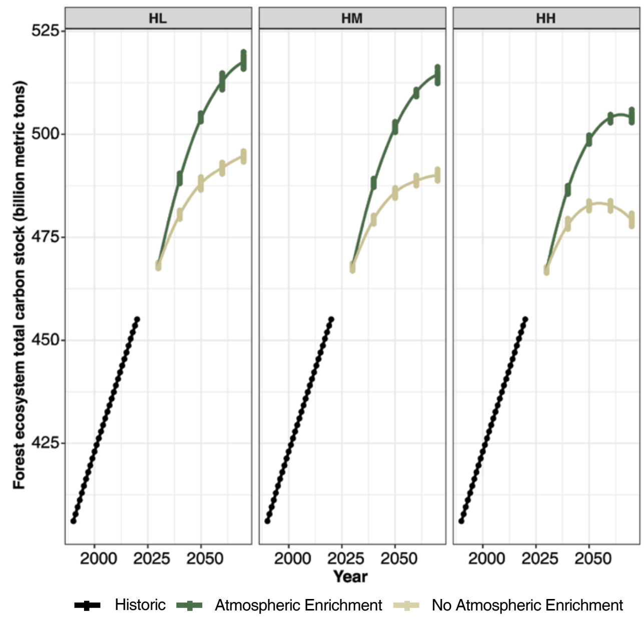
Atmospheric Enrichment

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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