ADVANCING EARTH AND SPACE SCIENCES

Earth's Future

RESEARCH ARTICLE

10.1029/2024EF005904

Old-Growth Forest Area Projected to Increase on United States Federal Lands Under Alternative Future Scenarios

Jennifer K. Costanza[1], **Kevin M. Potter**[1], **David M. Walker**[2], **Frank H. Koch**[1], **Andrew N. Gray**[3], **and John W. Coulston**[4]

[1]Southern Research Station, United States Department of Agriculture, Forest Service, Research Triangle Park, NC, USA, [2]Oak Ridge Institute for Science Education, Blacksburg, VA, USA, [3]Pacific Northwest Research Station, United States Department of Agriculture, Forest Service, Corvallis, OR, USA, [4]Southern Research Station, United States Department of Agriculture, Forest Service, Blacksburg, VA, USA

Jennifer K. Costanza and Kevin M. Potter contributed equally to this work.

Key Points:

- Natural succession of mature forests is expected to offset future losses of old-growth forests to climate, wildfire and harvests
- Old growth is projected to increase for most important forest type groups; mature forest increases for some and decreases for others
- Some loss of older tree volume is projected to occur from fire and harvests, but this is a small proportion of total volume

Supporting Information:

Supporting Information may be found in the online version of this article.

Correspondence to:

K. M. Potter,
kevin.potter@usda.gov

Citation:

Costanza, J. K., Potter, K. M., Walker, D. M., Koch, F. H., Gray, A. N., & Coulston, J. W. (2025). Old-growth forest area projected to increase on United States federal lands under alternative future scenarios. *Earth's Future*, *13*, e2024EF005904. https://doi.org/10.1029/2024EF005904

Received 14 JAN 2025
Accepted 18 JUN 2025

Author Contributions:

Conceptualization: Jennifer K. Costanza, Kevin M. Potter, David M. Walker, Frank H. Koch, Andrew N. Gray, John W. Coulston
Data curation: Jennifer K. Costanza, David M. Walker, Frank H. Koch, Andrew N. Gray
Methodology: Jennifer K. Costanza, David M. Walker, Frank H. Koch, John W. Coulston

Abstract Changing climate conditions, wildfires, and tree harvests could affect the area of mature and old-growth forests in the United States. We used a stochastic modeling system to project future areal extents of mature and old-growth forests on National Forest System (NFS) and Bureau of Land Management (BLM) land across the conterminous United States, and to assess threats to these forests under a variety of socioeconomic and climate futures, to 2070. The area of old-growth forest is expected to increase 19%–27% on NFS and BLM lands while mature forest trends (0.8% decrease to 2.5% increase) depend on the socioeconomic and climate future. Trends vary regionally, with old-growth area increasing everywhere but the South, where it is projected to remain approximately the same, while the area of mature forest remains relatively flat everywhere but the Pacific Northwest, where an increase is expected. Old growth is projected to increase for most major forest types while mature forest increases for some and decreases for others. The volume of trees killed by fire annually is projected to increase by as much as 48% for old-growth and 22%–100% for mature forests, while harvested volume could increase by 367%–441% in old-growth and 125%–150% in mature forests under some scenarios. Fire and cutting would cause only a small proportional decrease in overall tree volume, however. By identifying the ecosystems susceptible to loss of older forest, these results can inform management and conservation efforts to retain such forests and help them adapt to future change.

Plain Language Summary Mature and old-growth forests have declined to a fraction of their historical global extent. Efforts to conserve and manage remaining older forests will require understanding how much is likely to persist and how much is vulnerable to stressors and disturbances. We applied national forest inventory data within a forest dynamics modeling system to project old-growth trends under multiple socioeconomic scenarios and climate models. We project that old-growth forest area will continue to increase on federal lands across the conterminous United States from 2020 to 2070 despite pressures associated with climate, wildfire, and harvests, as losses are more than offset by the aging and natural succession of mature forests. Trends vary regionally and among major forest ecosystem types. These results can help inform managers and policy makers seeking to sustain these forests and the benefits they provide.

1. Introduction

Mature and old-growth forests offer a wide variety of ecological services, including carbon sequestration (Hoover et al., 2012; Luyssaert et al., 2008; Maxwell et al., 2019), wildlife habitat (Welsh, 1990; Yezerinac & Moola, 2006), habitat refugia (Betts et al., 2018; Frey et al., 2016), biodiversity (Traylor et al., 2024; Wagner et al., 2014), soil nutrient cycling (Schrumpf et al., 2014; Weber et al., 2008), and water provisioning (Jones et al., 2022; Schrumpf et al., 2011). These forests provide recreational opportunities and esthetic, spiritual, and cultural value to people who interact with them (Blicharska & Mikusinski, 2014; Connell et al., 2015; Moore, 2007). They are also important reference locations for scientific assessments of baseline forest ecosystem functions, processes, and services (Anand et al., 2013; Laughlin et al., 2004). The areal extent of mature and old-growth forests has declined markedly around the world as a result of land conversion and logging (Knorn et al., 2013; Smith et al., 2021; Strittholt et al., 2006) while remaining older forests are degraded in many places by direct human activities (Margono et al., 2012; Souza et al., 2003), changes to historical fire frequencies and severities (Binkley et al., 2007; Gilliam & Platt, 1999; Taylor, 2010), severe climate events such as droughts

Project administration: Jennifer K. Costanza
Visualization: Jennifer K. Costanza, Kevin M. Potter
Writing – original draft: Kevin M. Potter
Writing – review & editing: Jennifer K. Costanza, Kevin M. Potter, David M. Walker, Frank H. Koch, Andrew N. Gray, John W. Coulston

(Liu et al., 2021; Piovesan et al., 2008; Silva et al., 2013), and invasive species (Flinn et al., 2022; Knapp & Canham, 2000).

Recent research estimated that National Forest System (NFS) and Bureau of Land Management (BLM) forest lands in the United States encompass 13.4 million ha of old-growth forest and an additional 32.7 million ha of mature forest, representing 19 and 45% of the forest land managed by the agencies, respectively (Pelz et al., 2023; Woodall et al., 2023). Federal forests in the West are dominated by mature and old-growth conditions while those in the East are mostly mature or younger except in the Appalachian Mountains of the south-central United States, where old-growth and mature forests dominate (Woodall et al., 2023). Appropriately conserving and managing these mature and old-growth forests requires an understanding of the threats that may contribute to the persistent loss or degradation of their characteristic conditions, functions, and values. A national threat analysis found that half of old-growth forests and two-thirds of mature forests on NFS and BLM lands are vulnerable to disturbances and stressors, most importantly wildfire and insect and disease infestation and, less importantly, tree harvest (U.S. Department of Agriculture Forest Service & U.S. Department of the Interior Bureau of Land Management, 2024). Since 2000, wildfires led to decreases of 1.05 million ha of mature (3.2%) and 283,000 ha of old growth (2.2%), insects and disease led to losses of 769,000 ha and 74,000 ha (2.3% and 0.6%), and tree cutting resulted in decreases of 81,000 ha and 4,000 ha (0.3% and 0.03%) (U.S. Department of Agriculture Forest Service & U.S. Department of the Interior Bureau of Land Management, 2024). After accounting for ingrowth from younger forests, mature forests have declined a net 1.02 million ha while old-growth forests have had a net increase of 113,000 ha.

Mature and old-growth forests of the NFS and BLM, like those of the rest of the United States, are likely to face continued and potentially worsening disturbances in the coming decades (Costanza, Koch, Reeves, et al., 2023) as climate warms and human population pressures intensify. These disturbances may affect ecosystem services provided by old-growth forests. They also may result in greater overall structural homogenization of forests, which could have implications for forest function and the diversity of species that inhabit them (Acil et al., 2025). The interactions between threats, changes, and ecosystem services will be affected by the degree to which climate changes locally and regionally, which will in turn depend upon global socioeconomic trends (Joyce & Coulson, 2020).

Broad-scale planning and finer-scale management efforts will benefit from a better understanding of how much mature and old-growth forest may exist in the future under different socioeconomic and climate scenarios, where it will be, and how vulnerable it will be to stressors and disturbances. To quantify potential future areal extents of mature and old-growth forests, and to assess threats to them under a variety of climate and socioeconomic futures, we used the Forest Dynamics Model (FDM) stochastic modeling system and data from a systematic national forest inventory network (Coulston, Domke, et al., 2023). We generated projections of mature and old-growth forest area from 2020 to 2070 on NFS and BLM land across the conterminous United States (U.S.) within four regions and for major forest types using expert-derived definitions of old-growth and mature forests that vary by region and forest type (Pelz et al., 2023; Woodall et al., 2023). The modeling system used four scenarios of socioeconomic growth and warming from the Intergovernmental Panel on Climate Change Shared Socioeconomic Pathways and Representative Concentration Pathways: lower warming/moderate U.S. growth (LM), high warming/low U.S. growth (HL), high warming/moderate U.S. growth (HM), and high warming/high U.S. growth (HH) (O'Dea et al., 2023). Each was coupled with five climate models representing the envelope of projected future temperature and precipitation across the U.S. We additionally quantified projected trends in mature and old-growth tree mortality due to wildfire, as well as expected tree harvest rates (Joyce & Coulson, 2020).

2. Data

The modeling system relied on data from the Forest Inventory and Analysis (FIA) program, the main source of information about the extent, condition, and composition of U.S. forests across all ownerships and through time (Smith, 2002). FIA maintains a known-probability sample of forests across the United States in which each plot represents approximately 2428 ha for the base grid (Bechtold & Patterson, 2005). Since approximately 2000 (depending on the state), FIA field crews have regularly visited plots (McRoberts et al., 2005) that meet the FIA definition of forest (Burrill et al., 2018). Plots are split into multiple conditions if more than one forest type or land use exists on the plot. Plot conditions are assigned a forest type based on the predominant species or group of tree species. Live trees and standing dead trees are measured through time on a 0.07 ha plot footprint. The systematic

FIA sample design enables area estimates for vegetation types within a population of interest (such as mature, old-growth, or young forest) by summing the amount of forest land (the "expansion factor") represented by all plot conditions for that population within a region (Bechtold & Patterson, 2005).

3. Methods

3.1. Forest Dynamics Model

The FDM is a stochastic modeling system developed for the 2020 Resources Planning Act (RPA) Assessment (U. S. Department of Agriculture Forest Service, 2023) that incorporates projections of forest conditions and areas for the conterminous U.S. for 2020–2070. Full documentation of the FDM can be found elsewhere (Coulston, Domke, et al., 2023), but we briefly summarize the most relevant aspects here. The FDM projects FIA plot conditions, including mature or old-growth classification, into the future using an imputation approach (Coulston, Domke, et al., 2023), allowing for consistent projections that are based on the observed relationships among FIA variables at the plot level through the projection period. The FDM is informed by exogenous variables including climate, timber prices, global timber demand, human population, and income, as well as by a set of submodels governing harvest choices, harvest volume, fire, growth, aging, regeneration, and forest type transitions over time. The model was applied only to FIA plots that met international forest land definitions, which include a minimum height requirement and therefore exclude some woodlands, primarily in the southwestern United States (Oswalt et al., 2019). The FDM contains a submodel that projects the future fire occurrence and tree mortality based on field observations of fire occurrence and mortality, and links to other submodels that modify forest characteristics over time, including basal area, down woody material that can act as fuel for fires, stand age, species composition, and harvest probability. Because of the limited ability of FIA field crews to detect the effects of low-severity fires (including prescribed fires), fires that do not lead to tree mortality are omitted from the FDM, and the projections reflect the effects of only moderate and high severity wildfires over time (Costanza, Koch, Reeves, et al., 2023). Additionally, the FDM contains a submodel that projects harvest choices and the proportion of tree volume removed during harvest, and, like the wildfire submodel, links to other submodels that modify forest characteristics over time. In the model, choices about harvests are linked to forest conditions, prices, and demand for wood over time nationally and globally, and reflect the empirical relationships between those endogenous and exogenous drivers and harvest. These relationships are modeled separately by geographic region and vary by ownership, so that the historic price sensitivities and management approaches of different forest ownership categories are captured empirically.

3.2. Application of the FDM for Mature and Old-Growth Forest

For our assessment, each condition on FIA plots inventoried since the annualization of data collection ca. 2000 was classified as old growth, mature, or younger. Old growth classification was determined based on regional criteria developed by NFS experts and officially approved by the NFS regions for specific vegetation types following public engagement (Pelz et al., 2023; Pelz et al., 2023) These regional old growth definitions were initially developed in response to a 1989 directive from the Chief of the Forest Service to establish definitions specific to local ecosystems that fit into a generic definition of old-growth forests as ecosystems distinguished by old trees and related structural attributes, with the understanding that old growth encompasses the later stages of stand development that typically differ from earlier stages in a variety of characteristics including tree size, accumulation of large woody material, number of canopy layers, species composition, and ecosystem function. The NFS regional forest type definitions focus on forest structural characteristics appropriate to those forest types, commonly including minimum abundance of large live trees (in eight of nine NFS regions), tree or stand age (in eight of nine NFS regions), and dead large tree density (in three of nine NFS regions) (Pelz et al., 2023). Mature forest classification, meanwhile, was defined using a Forest Inventory Growth Stage System (FIGSS) that informs inverse modeling of the structural thresholds associated with the mature structural stage of stand development that precedes old growth (Woodall et al., 2023). FIGSS identifies key structural attributes of old-growth forests and "walks down" these metrics by vegetation type to values associated with the onset of maturity based on assumptions about physiological maximum ages and growth attributes (Woodall et al., 2023). We classified forest conditions as "younger" if they did not meet the definitions of mature or old growth.

We summarized the national FDM projections for old-growth, mature, and younger forests on NFS and BLM lands by decade from 2020 to 2070. The 2020 values were empirical estimates using FIA data collected around

10.1029/2024EF005904

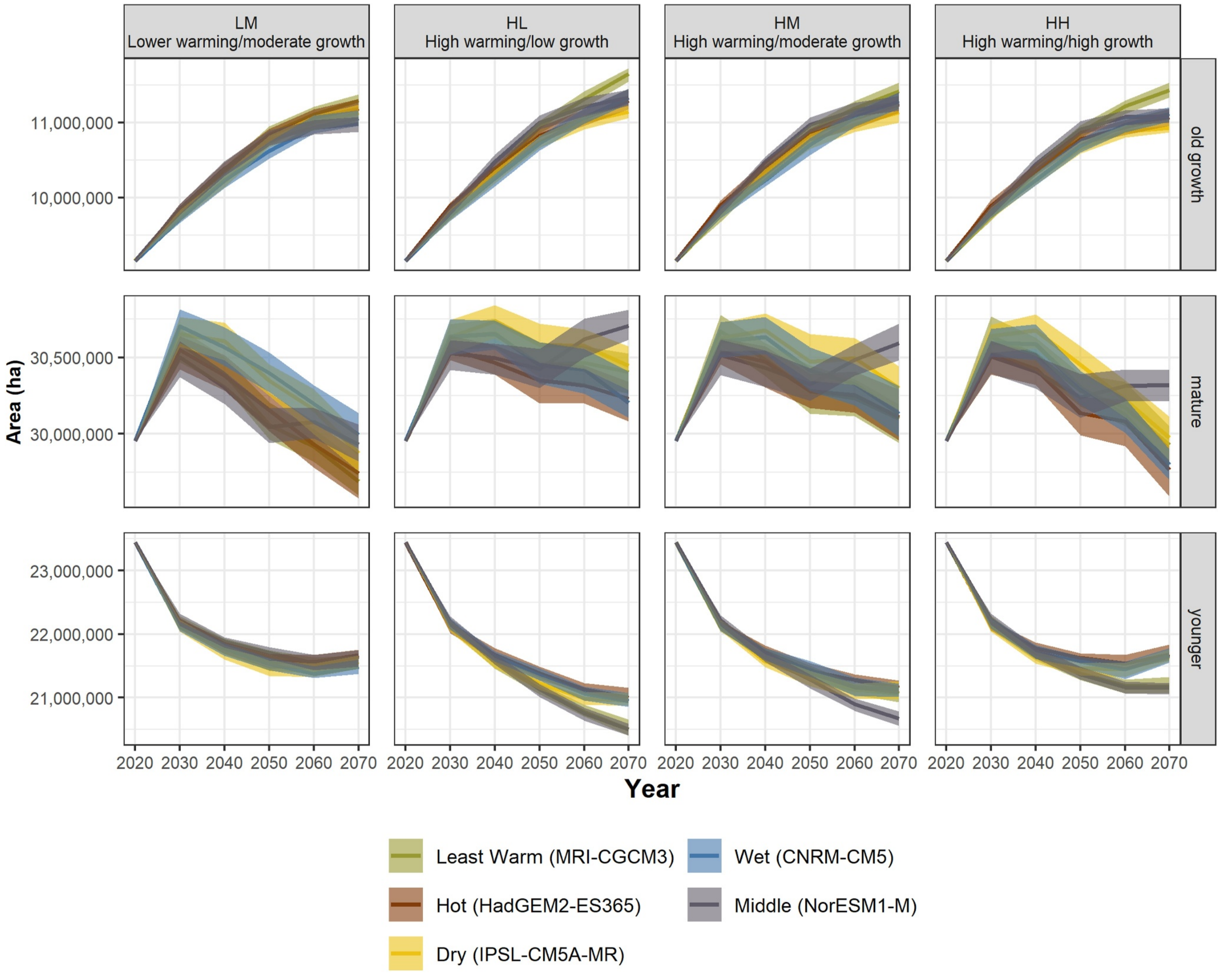

Figure 1. Projections of old-growth, mature and younger forest area. Area of old-growth, mature, and younger forest on Forest Service and Bureau of Land Management land in the continental United States from 2020 to 2070, projected by the Forest Dynamics Model for the four scenarios. For each curve, the dark line represents the median projection across 100 replications of the model. The shading represents the interquartile range (middle 50%) of the 100 replications. Note the difference in the scale of the *y*-axes in each row. Climate models are represented by colors, and results for each scenario are shown in separate panels. Scenarios are abbreviated as follows: LM = lower warming/moderate growth, HL = high warming/low growth, HM = high warming/moderate growth, HH = high warming/high growth.

that year. For each subsequent decade, we generated 100 stochastic realizations for each of the 20 potential future combinations of four RPA socioeconomic scenarios with five climate models (2,000 realizations per decade). The four 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 growth (LM)), RCP 8.5 and SSP3 (high warming/low growth (HL)), RCP 8.5 and SSP2 (high warming/moderate growth (HM)), and RCP 8.5 and SSP5 (high warming/high growth (HH)) (O'Dea et al., 2023). The five climate models, meanwhile, capture the wide range of projected future temperature and precipitation across the conterminous United States (Joyce & Coulson, 2020; O'Dea et al., 2023). In all cases, the results from each RPA scenario/climate model combination were plotted by year, with the median and interquartile range (between the 25th and 75th percentiles) of the 100 realizations shown in the figures.

We presented projected trends in mature and old-growth forest areas across the U.S., within four regions (Figure 2a), and by forest type group. We focused on 12 forest type groups that included the most old-growth forest area on FIA and BLM lands in 2020 (Figure 3a, Table S1 in Supporting Information S1). The most

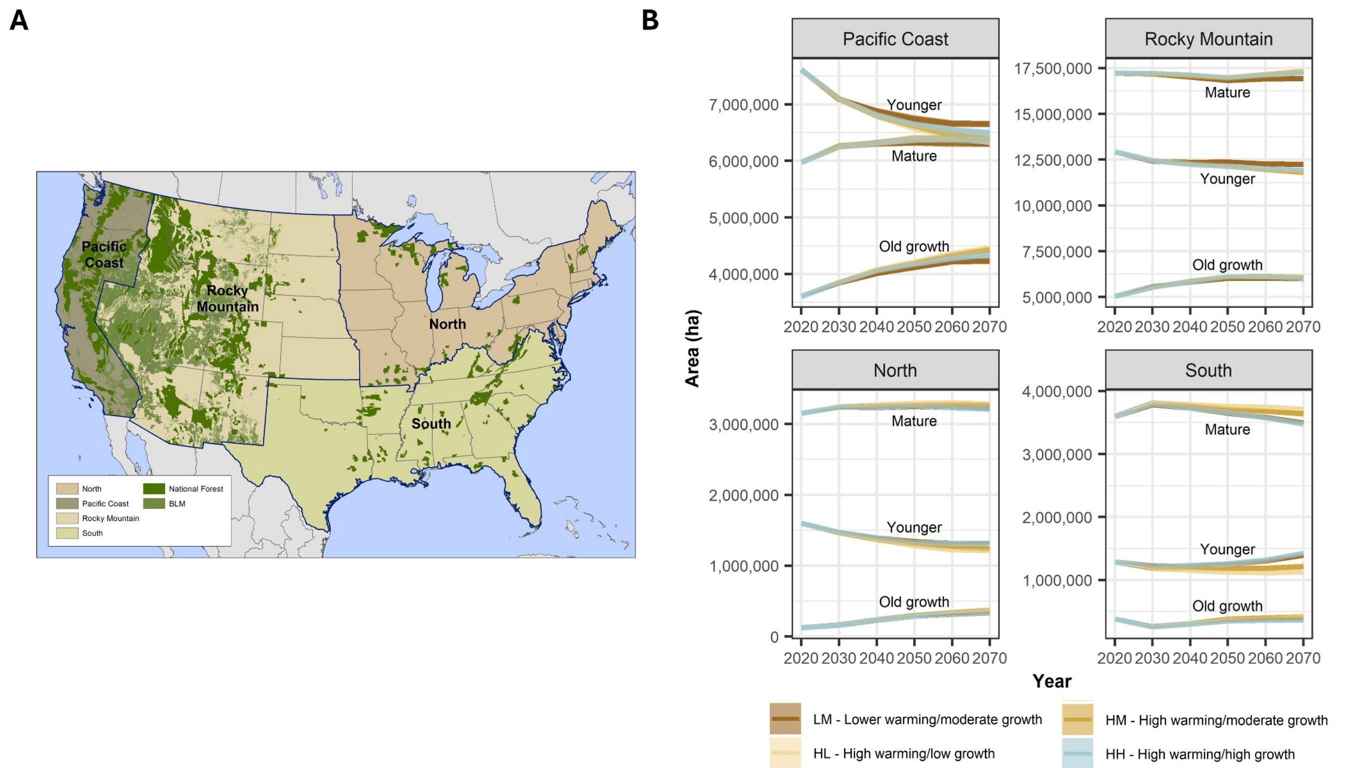

Figure 2. Regional projections of old-growth, mature, and younger forest area. (a) National Forest and Bureau of Land Management (BLM) lands included in the analyses, along with the four reporting regions for the conterminous United States. (b) Area (in hectares) of old-growth, mature, and younger forest on Forest Service and BLM land by region from 2020 to 2070, projected by the Forest Dynamics Model, for the middle climate model only. For each curve, the dark line represents the median projection across 100 replications of the model. The shading represents the interquartile range (middle 50%) of the 100 replications. Scenarios are represented by colors. The other four climate models showed similar trends and are depicted in Figure S1 in Supporting Information S1. Note the difference in the scale of the *y*-axes on each panel.

widespread forest type groups were primarily in the West, especially the Rocky Mountain region (Figure S5 in Supporting Information S1). We also summarized trends in tree volumes killed by moderate and high severity wildfires and volumes of harvested trees (identified as "removed" in the FIA database). Sparse observed FIA data on wildfire in some forest types or regions resulted in higher uncertainty in FDM results. While the areas of mature, old-growth, and younger forests are projected to change over time in these projections, no land use change occurs on NFS and BLM lands in the FDM, so the total area of forest land remains constant over time at 1,546,000 km^2 for these ownerships, though areal shifts occur among forest type groups.

4. Results

4.1. Projected Mature and Old-Growth Forest Area

In 2020, NFS and BLM land in the conterminous U.S contained 9,152,000 ha of old growth (14.6% of total forest), 29,953,000 ha of mature (47.9%), and 23,446,000 ha of younger forest (37.5%), based on empirical estimates from nationwide forest inventory (NFI) data. Projections suggest an increase between 2020 and 2070 in old-growth forest area. This trend was consistent across scenarios that combine levels of warming and socio-economic growth, and for climate models within each of those scenarios (Figure 1). Projections indicated a potential increase in old-growth forest area of 19%–27% between 2020 and 2070 depending on the climate model and scenario. In all scenarios and climate models, except for the least warm climate model in the three high warming scenarios, the projected rate of increase in old-growth forest area slowed starting in 2050 through the end of the future period. In contrast, the area of mature forests generally increased by 2030 and then declined after, to a greater extent under the high warming/high growth (HH) and lower warming/moderate growth (LM) scenarios, and to a lesser extent under the high warming/low growth (HL) and high warming/moderate growth (HM) scenarios, resulting in a slight decrease (0.8%) to a slight increase (2.5%) by 2070. The HH and LM scenarios,

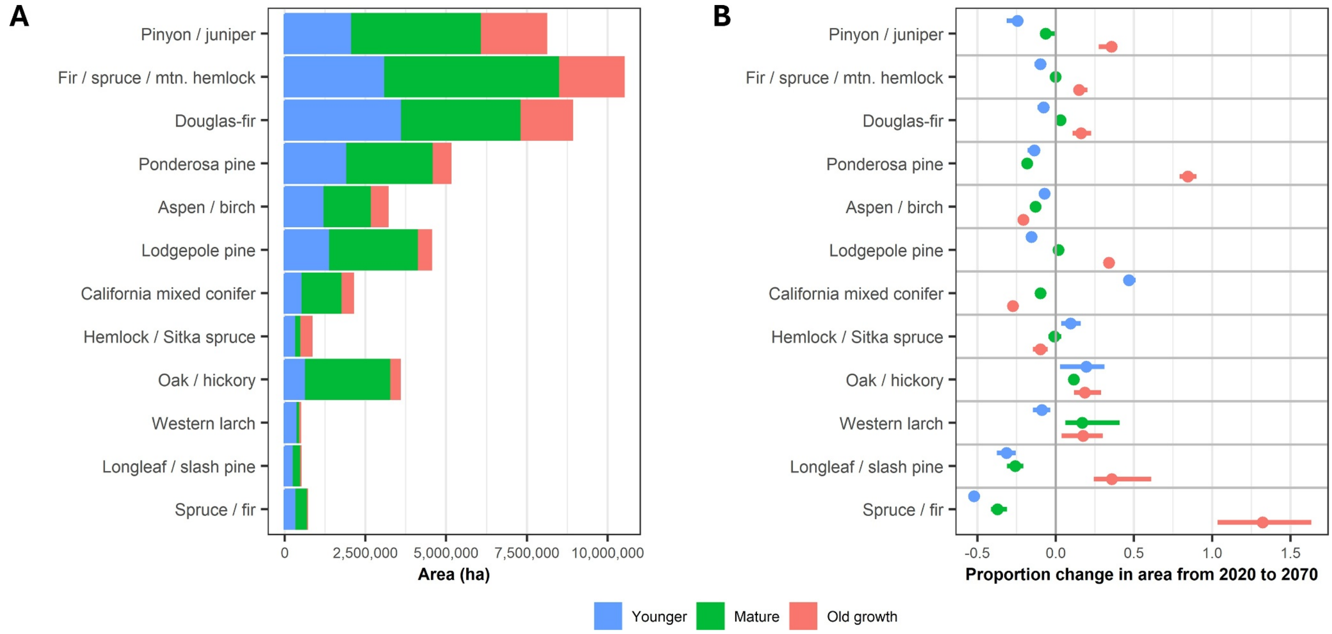

Figure 3. Current area and projected area change of old-growth, mature, and younger forest by forest type group. (a) Area in 2020 and (b) proportion change in area from 2020 to 2070 of old-growth, mature, and younger forest on Forest Service and Bureau of Land Management land by major forest type group. Proportion changes displayed here are based on the median trend lines of the 2020 Forest Inventory and Analysis data with the 2070 Forest Dynamics Model projections for each of the 20 future combinations of four socioeconomic scenarios with five climate models (based on 100 realizations for each of the 20 scenarios). Dots represent the median of the 20 trend lines, and horizontal bars indicate the range of values across those 20 trend lines. Forest type groups are listed in descending order of old-growth forest area in 2020. For full projections of area over time in old-growth, mature, and younger forest from 2020 to 2070, see Figure S2 in Supporting Information S1.

which both project mature forest loss under most future climates, assume the highest and lowest levels of global energy usage, respectively, while both predicting a greater future reliance on forests as a source of bioenergy (O'Dea et al., 2023). Projections consistently resulted in a decrease in younger forest across all scenarios and climate models, with 8%–13% less expected in 2070 than 2020. For summaries of forest area change by region, we focus on the middle climate model in the four scenarios (Figure 2) and include projections under all 20 futures in Figure S1 in Supporting Information S1.

Regional trends indicate the likely increase in old-growth forest on NFS and BLM lands except in the South, where the old-growth area was projected to decrease in the short term and then return to approximately 2020 levels (Figure 2). In all regions but the Pacific Coast, mature forests in 2020 made up the largest proportion of forest, followed by younger forest, then old growth. In the Pacific Coast region, younger forests represented the plurality of forest area (44%) in 2020, with mature forests making up a smaller share (34%), followed by old growth (21%), but the projected decrease in younger forests and increase in mature forests resulted in converging proportions of the two maturity classes by 2070. The model projected a loss of younger Pacific Coast forest mirrored by a gain of older forest between 2020 and 2030 in this region (also apparent in Figure 1), indicating a relatively large area of younger forest on the threshold of becoming mature. Old-growth area was projected to increase by 2070 in the Rocky Mountains (19%–20%), the Pacific Coast (17%–27%), and the North (172%–203%). In the South, old-growth area was projected to initially decline in all scenarios and then return to a level either greater than (maximum of 12% increase under HL) or less than (minimum of 4.2% decrease under HH) in 2020.

4.2. Projections for Major Forest Types

Old-growth area was projected to increase for most forest type groups, mirroring the national results (Figure 3b). Most forest type groups saw decreases in mature forest area under at least some futures (Figure S2 in Supporting Information S1). Ponderosa pine, spruce/fir, and longleaf/slash pine were expected to have offsetting increases in old growth and decreases in mature forest area. Two forest type groups—aspen/birch and California mixed

10.1029/2024EF005904

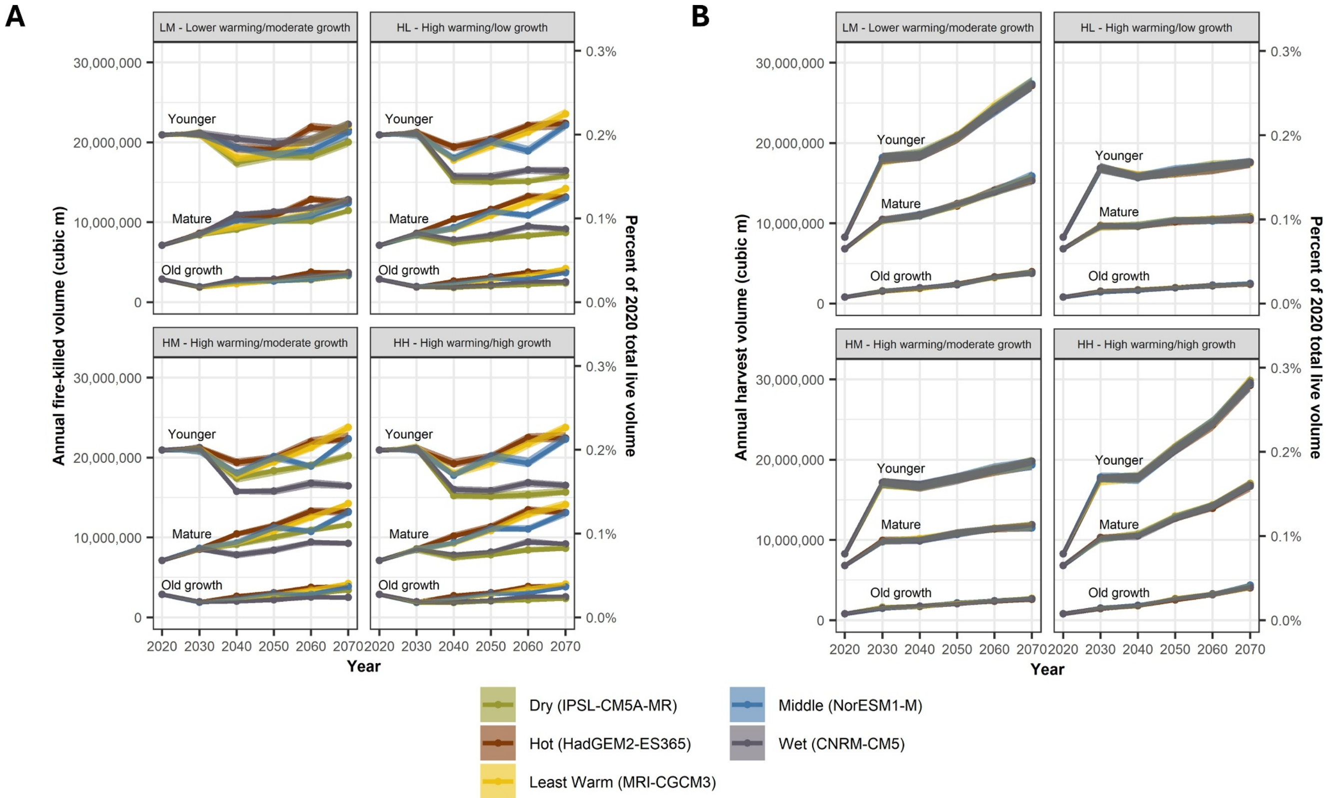

Figure 4. Projections of old-growth, mature and younger forest volume loss to fire and tree harvest. (a) Annual fire-killed volume and (b) annual harvested volume of trees (in cubic meters) in old-growth, mature, and younger forest on Forest Service and Bureau of Land Management (BLM) land in the conterminous United States from 2020 to 2070, projected by the Forest Dynamics Model. For each curve, the dark line represents the median projection across 100 replications of the model. The shading represents the interquartile range (middle 50%) of the 100 replications. Climate models are represented by colors, and results for each scenario are shown in separate panels. HH: high warming/high growth, HL: high warming/low growth, HM: high warming/moderate growth, LM: lower warming/moderate growth. The secondary *y*-axis in each panel indicates the proportion of total live volume on Forest Service and BLM forest land in 2020 that corresponds to the given annual fire-killed or harvested volume.

conifer—were projected to experience a marked decline in both mature and old-growth area under all futures (Figure 3b).

4.3. Projected Mature and Old-Growth Annual Fire-Killed Volumes

For projections of the impact of fire, we focused on change in tree volume because this is an ecologically meaningful metric (Gonzalez-Benecke et al., 2014) while burned area may not be well-correlated with the ecological effects of fire (Lutz et al., 2011). Increases in annual fire-killed volumes were projected across scenarios and climate models for mature forest, and in most scenarios and climate models for old growth (Figure 4a). However, the range in projected change by 2070 was relatively wide for both classes. For old growth, annual fire-killed volume was expected to increase in the hot, dry, and wet climate models in all scenarios, with the largest increases of 45%–48% in the dry model under the three high warming scenarios. Decreases of 11%–18% were projected for five futures: the least warm (MRI-CGCM3) climate model in the HH and HL scenarios, and the middle (NorESM1-M) model in those two scenarios as well as in the HM scenario. For mature forests, annual fire-killed volume was expected to increase by 22%–100%, with the greatest increases expected in the dry models in the three scenarios with high warming. In all futures and time steps, the annual fire-killed volume was relatively small compared to the total live tree volume (secondary axis in Figure 4a).

The projected tree volume killed annually in old-growth forests by moderate to high severity wildfires was projected to generally increase by 2070 across scenarios and climate models for the Rocky Mountain and North regions, and to remain relatively steady or decrease in the South and the Pacific Coast regions (Figure S3 in Supporting Information S1). Meanwhile, annual fire-killed volume in mature forests was projected to increase across all scenarios and models in the Pacific Coast and North regions and for most in the Rocky Mountain and South regions.

4.4. Projected Mature and Old-Growth Annual Tree Harvest Volumes

Increases in annual tree harvest volumes from all forest maturity classes were projected from 2020 to 2070 (Figure 4b). Annual harvest volumes for climate models in the LM and HH scenarios increased 367%–441% in old-growth forest and 125%–150% in mature forest. While these projections indicate increases in harvest in all forests, annual volumes harvested were projected to be much less than 1% of 2020 total live volume by 2070.

Increases in tree harvest were steeper in the Pacific Coast and South than in the Rocky Mountain and North regions (Figure S4 in Supporting Information S1). Old growth tree harvesting was projected to increase more in the Pacific Coast region from a relatively low number in 2020. Tree harvests include forest management activities other than clearcutting, some of which are important for conserving or restoring old-growth forests (Bauhus et al., 2009).

5. Discussion

Our projections offer a clearer understanding of how much mature and old-growth forest is projected to exist over the next half century on NFS and BLM lands across regions and forest types, and how vulnerable these forests may be to fire and harvest pressures. The area of old-growth forest was expected to increase nationally, while mature forest trends depended on socioeconomic and climate futures. The trends varied by region, with old-growth forest area increasing everywhere but the South, where we project it to remain relatively unchanged, and mature forest area remaining relatively flat everywhere but the Pacific Northwest, where we expect it to increase. Old-growth area was projected to increase for many forest type groups, while mature forest increased for some and decreased for others. The model projected some mortality of mature and old growth from fire and harvesting, but this was a relatively small proportion of the overall tree volume.

5.1. Projected Trends in Mature and Old-Growth Forest Area

Rapidly changing climate conditions are already affecting the distributions of tree species (Fei et al., 2017) and the composition of forests (Knott et al., 2020), and are associated with widespread mortality following hot drought events (Lawal et al., 2024) and insect and disease outbreaks, often in combination with other extreme weather (Anderegg et al., 2015). Forest disturbances that cause tree mortality, including fire and drought, are projected to become more frequent, widespread, or severe throughout the U.S. over the next half century (Costanza, Koch, & Reeves, 2023; Costanza, Koch, Reeves, et al., 2023). Our projections suggest that NFS and BLM old-growth forest area will continue to increase nationally and in most regions despite the pressures associated with climate change, as losses are more than offset by the aging and natural succession of mature forests. The rate of this growth is expected to decline starting around 2050. It is important to note that while "newer" old-growth forests would meet structural definitions determined by the Forest Service, their attributes may differ from established old-growth in meaningful ways (Spies, 2004). The area of mature forests, meanwhile, was projected to generally increase by 2030 and then decline after. The old-growth and mature forest trends suggest an accumulation of both threats and successional trends that could slow the increase of these forests over time, emphasizing the potential effectiveness of management decisions that increase the resilience of existing old-growth forests and encourage the development of old-growth attributes in mature forests. Finally, the area of younger forests is projected to decline steeply across scenarios and climate models. These projections are consistent with forest succession and aging trends projected across U.S. forests (Coulston, Brooks, et al., 2023).

The initial old-growth forest decline in the South, the only region where old growth on NFS and BLM lands is not projected to increase, is mainly due to loss in the oak/hickory forest type group in the short term (Figure S2 in Supporting Information S1). Complex interactions among stress factors, including drought, fungal pathogens, and extreme temperature events, have recently caused decline in southern oak forests (Yang et al., 2021). Our results project that trend to continue for old-growth through 2030 but then reverse over the longer term, consistent with projected increases in oak/hickory forest (Coulston, Brooks, et al., 2023). The broader regional relationships between the mature and younger forest trends show mature forests generally increasing at the same rate that younger forests decrease (Figure S2 in Supporting Information S1), indicating the unfolding of forest successional processes. This relationship is particularly pronounced in the Pacific Coast region, the only region where younger forest area currently exceeds mature forest area. The projected convergence of the amount of area of younger and mature forests here, along with the increase in old-growth, likely reflects age-class dynamics initiated by the shift in the Pacific Northwest from even-age management via clearcutting on federal forests to the preservation of older forests (Johnson & Swanson, 2009).

Projected trends in the mature and old-growth area of forest type groups result from interactions between disturbance dynamics and successional processes influenced by past management. The four groups expected to experience increases in both mature and old growth—Douglas-fir, lodgepole pine, oak/hickory, and western larch—have an abundance of younger forest expected to succeed to older forest in coming decades. Other groups—ponderosa pine, spruce/fir, longleaf/slash pine, and pinyon/juniper—are projected to experience increases in old-growth area offset by decreases in mature forest. These groups do not currently have as much area of younger forest to feed the pipeline for older forests. For example, the area of the longleaf pine forest type (part of the longleaf/slash pine group) has expanded in recent decades as a result of widespread restoration efforts, but this has been accompanied by a decreased proportion of small trees because of a surfeit of natural regeneration (Potter et al., 2024). Two other forest type groups—California mixed conifer and aspen/birch—are projected to experience a decline in both mature and old-growth area, suggesting both a small regeneration pipeline and the potential for widespread disturbance. The California mixed conifer trends would continue recent dramatic declines due to wildfire, drought, and bark-beetle epidemics (Steel et al., 2023).

5.2. Projected Trends in Wildland Fire

While wildfire is an essential regulating process that maintains forest health, structure and function of some forest ecosystems (Pausas & Keeley, 2019), evidence suggests that few purely natural fire regimes remain in North America (Parisien et al., 2016) and that severe fires in combination with climate change are contributing to widespread challenges to natural regeneration (Davis et al., 2019). Meanwhile, research indicates that climate change, via more common hot droughts, has already played a role in increased wildfire activity (Abatzoglou & Williams, 2016). Between 2000 and 2020, 3.2% of mature and 2.2% of old-growth forests on NFS and BLM lands were lost to wildfires (U.S. Department of Agriculture Forest Service & & U.S. Department of the Interior Bureau of Land Management, 2024). In this context, tree mortality caused by moderate- and high-severity fire is expected to increase by 2070, with the highest rates of mortality occurring under hot or dry climate futures (Costanza, Koch, Reeves, et al., 2023). However, the degree to which changing climate conditions could increase fire mortality specifically in mature and old-growth forests has not been investigated previously. The projected volume of trees in NFS and BLM mature and old-growth forest killed annually by moderate- and high-severity fires is relatively small compared to the total live volume in these forests in 2020. At the same time, we project the volume of trees killed by fires in federal old-growth forests to increase under the hot, dry, and wet climate models in all scenarios. Old-growth fire-killed volumes under the least warm and middle climate models, however, are projected to decrease or remain relatively stable. These results are largely consistent with projections of increasing fire probabilities in the U.S. under both higher and lower global warming futures (Gao et al., 2021), with fire severity and frequency also potentially increasing depending on local factors, extreme weather events, and ecological context (Littell et al., 2016).

Recent modeling work has predicted sometimes-conflicting regional differences in the extent and severity of future wildland fire. Parks et al. (2016) projected the widespread potential reduction in fire severity across much of the West, including the Rocky Mountains, because of climate-induced changes in vegetation types, fuel loads, and fire frequencies. Separate model results published by Gao et al. (2021) predict only slightly higher fire probabilities in the West but considerably higher probabilities in the South. Our regional results predict increased mature forest tree volume killed annually by moderate and high-severity fires on NFS and BLM lands across most climate models and scenarios, with the greatest increase generally in the Rocky Mountain region, most similar to Peterson and Littell (2014) and Heidari et al. (2021). This region contains most of the forest on NFS and BLM lands (Figure S5 in Supporting Information S1) and the plurality of old-growth forests. We found high variability in fire-killed volumes across climate models for the Rocky Mountains (both mature and old growth), with the greatest increases in fire-killed volumes under the lower warming scenario and the hot, dry, and wet models in the high warming scenarios. We note the relatively high degree of uncertainty in our regional projections, especially in the North and South, likely the result of sparse FIA observations of moderate- and high-severity fires in mature and old-growth forests.

5.3. Projected Trends in Tree Harvests

Tree cutting was the leading disturbance to National Forests following World War II, resulting in the loss of substantial mature and old-growth forest from 1950 through 1990, although this was no longer the case following changes in Forest Service tree harvesting policy (Johnson & Swanson, 2009). The ecological and socioeconomic aspects of tree harvests are complex and represent both potential threats to older forests and opportunities to enhance their composition (U.S. Department of Agriculture Forest Service & U.S. Department of the Interior Bureau of Land Management, 2024) such as in forest types that require regular minor disturbances to maintain their structure (Bauhus et al., 2009). Our model incorporates a range of tree harvest intensities, from light thinning to total removal of trees in a stand, but it assumes no change in recent policies and reflects global and domestic market forces under different socioeconomic and climate futures. Our results project increases in tree harvest volumes from mature and old-growth federal forests, although these represent a very small proportion of total tree volume in older forests. The largest increases are projected to come under the high warming/high growth and the lower warming/moderate growth scenarios. This is consistent with harvest projections for all forest lands, attributed to the greater demand for bioenergy, including from forest sources like wood pellets, under those two scenarios (Coulston, Brooks, et al., 2023). We emphasize that our scenario-based framework enabled us to explore a breadth of realistic potential futures, including those that encompass increased timber harvests from public lands compared to the recent past. We applied these scenarios in the context of the FDM stochastic modeling system developed for the 2020 RPA Assessment. A version of the FDM under development for the 2030 RPA Assessment, along with updated socioeconomic scenarios and global climate models, may specifically explore the implications of increased levels of timber demand from federal lands and of more intense management actions to mitigate fire risk and achieve other forest health objectives.

5.4. Uncertainties and Other Considerations

We acknowledge the "wicked problem" of defining mature and old-growth forest, which requires some degree of arbitrariness in establishing the thresholds of the characteristics that must be met and does not incorporate the continuum of conditions that exist at both fine and broader scales (Gray et al., 2023). Old growth is simultaneously an ecological state, a value-laden social complex, and a polarizing political phenomenon that incorporates science, management, and values; requires multiple disciplines; and can be applied using contradictory approaches (Pesklevits et al., 2011). Other approaches for identifying and quantifying mature and old-growth forests also exist, but we used an approach that is consistent with old-growth definitions developed over 30 years by the USDA Forest Service, has been well-documented in scientific literature, is readily interpretable by resource managers working at different scales, and could be applied to the FIA national forest inventory database across the U.S. While there are many benefits to using the FIA data in this context, including that it is a strategic nationwide inventory across forest conditions and ownerships, potential limitations also exist, including that it does not include the collection of certain old-growth indicators for some forest types and that it relies on relatively small field-sampled plots that may not reliably assess the presence of old growth attributes relevant at a larger scale (Pelz et al., 2023). We acknowledge that using a different set of rules to categorize old-growth and mature forest could lead to different results. For example, a system that focuses exclusively on the age of trees would likely predict the existence of more old-growth and mature forest and arguably would not capture other important facets of older forests such as species composition, accumulation of snags and down woody material, the diversity of canopy layers, and ecosystem function (Pelz et al., 2023).

We selected climate models to span the largest plausible range of climate futures by 2070 for the conterminous United States. However, other climate models may project a more extreme climate for a specific region, so their potential effects on older forests would not be captured in our results. Our empirical model of forest dynamics was parameterized using FIA observations recorded mainly during 2000–2020, the period for which there were available FIA data collected in a standardized way across the conterminous U.S. The strength of this approach is in the ability to project future forest attributes in a consistent way nationwide. Other modeling approaches such as individual- or cohort-based ecological process models are not feasible to run across a large domain. However, the relatively short parameterization period in this study means that the model is sensitive to recent trends in forest conditions and forest disturbances. e.g., we likely underestimate the occurrence of relatively rare extreme events and their impacts on forest dynamics in some places where the recent period does not capture observed occurrences of those events. New versions of the Forest Dynamics Model (FDM) could project greater impacts on forests from extreme events as the period of training data lengthens (i.e., FIA data after 2020 are available to be included in the model) and is thus able to encompass more extreme events and their resulting effects on forests.

This study, to our knowledge, is the first to project future trends in older forests at the broad extent of all FS and BLM lands of the U.S. Other studies have projected trends across smaller regions and found either expected increases or decreases in the areas of older forests. For example, Turner et al. (2022) projected declines in forest age across the Greater Yellowstone Ecosystem (GYE) for a range of climate scenarios, while Creutzburg et al. (2017) projected increases in old forest under alternative management scenarios in the Oregon Coast Range. Those and other studies vary in their definitions of older forests and in the modeling methods used, making direct comparisons among results difficult. However, we emphasize that the increase in older forests that we project across the U.S. and for most forest types does not necessarily mean that all landscapes are expected to have the same trajectory. The composition of forest ages, as well as the relative importance of disturbances like fire and harvest, can vary locally and lead to different outcomes at smaller extents. For example, relatively large projected increases in the area of stand-replacing fires under most futures in GYE based on local empirical information on fire regimes and fire-climate relationships may at least partially account for the declines in stand age projected by Turner et al. (2022), and may not be well captured in our work. Further work could leverage the FDM and the standardized definitions of mature and old-growth forests to examine trends on landscapes of interest using local data that capture the key landscape drivers of interest.

While our results project changes in the area of older forests over time, management of mature and old-growth forests across multiple scales would be additionally aided by a spatially explicit assessment of how ecological integrity and ecosystem services could change over time for existing mature and old-growth forests, particularly those exposed to disturbances such as moderate- and high-severity fire and drought. Such an assessment, across all forest lands of the United States, could incorporate metrics of structural complexity and diversity (Crockett et al., 2023; LaRue et al., 2023) and/or essential biodiversity variables (Crowe et al., 2023; Dias et al., 2023). Including all forest lands, regardless of ownership, would enable assessment of the degree to which land use surrounding mature and old-growth forests is expected to change in the future as another potential threat.

6. Conclusions

Our results altogether suggest that the area of old-growth forests on federal lands in the U.S. will increase over the next 50 years due to the natural maturation of younger forests, although the rate of increase could slow by 2050 as threats associated with warming climate and socioeconomic drivers accumulate. The projected decline in mature forest area after 2030 indicates that the pipeline of succession and recruitment into old growth will decline. Our results provide insights into the potential future of older forests across the U.S. and can help inform managers and other decision makers seeking to sustain these forests and their benefits for nature and people. These analyses are limited to U.S. federal forests, but older forests also occur on private and other government (state, local, and tribal) ownerships. Understanding the extent and dynamics of older forests on these other ownerships, as well as their interaction with older forests on federal lands, will be important for the long-term sustainable management of older forests and the services they provide.

Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

Data Availability Statement

All data, code, and materials used in this study are openly available. The USFS FDM requires U.S. nationwide forest inventory (NFI) data, climate data, and land use change projections. The NFI data are available at https://apps.fs.usda.gov/fia/datamart/datamart.html. Historical gridded climate data are available from Coulson and Joyce (2020) and modeled gridded climate data (both historical and modeled) are available from Joyce et al. (2018). Land use change projections are available from Mihiar et al. (2023). Projections of forest area, annual fire-killed tree volume, and annual tree harvest volume for old-growth, mature, and younger forest age classes by United States region and year; projections of forest area in old-growth, mature, and younger forest

10.1029/2024EF005904

age classes for the 12 forest type groups summarized in the manuscript by year (both data sets with 100 replicates per socioeconomic scenario/GCM combination); and estimates with standard error of forest area in 2020 for old-growth, mature and younger forests are available from Walker et al. (2025).

Acknowledgments
The authors thank the Forest Inventory and Analysis field crew members who collected the data used in this study and members of the threat analysis technical team of the U.S. Department of Agriculture Forest Service and the U.S. Department of Interior Bureau of Land Management. They also appreciate thoughtful comments from Linda Heath and Claire O'Dea and from two anonymous reviewers. David Walker's work on this project was supported by agreement number 21-IA-11330180-032 between the U.S. Department of Agriculture, Forest Service, Southern Research Station, and the Oak Ridge Institute for Science Education.

References

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

Acil, N., Sadler, J. P., Senf, C., Suvanto, S., & Pugh, T. A. M. (2025). Landscape patterns in stand-replacing disturbances across the world's forests. *Nature Sustainability*, *8*(1), 16–98. https://doi.org/10.1038/s41893-024-01450-3

Anand, M., Leithead, M., Silva, L. C. R., Wagner, C., Ashiq, M. W., Cecile, J., et al. (2013). The scientific value of the largest remaining old-growth red pine forests in North America. *Biodiversity & Conservation*, *22*(8), 1847–1861. https://doi.org/10.1007/s10531-013-0497-1

Anderegg, W. R. L., Hicke, J. A., Fisher, R. A., Allen, C. D., Aukema, J., Bentz, B., et al. (2015). Tree mortality from drought, insects, and their interactions in a changing climate. *New Phytologist*, *208*(3), 674–683. https://doi.org/10.1111/nph.13477

Bauhus, J., Puettmann, K., & Messier, C. (2009). Silviculture for old-growth attributes. *Forest Ecology and Management*, *258*(4), 525–537. https://doi.org/10.1016/j.foreco.2009.01.053

Bechtold, W. A., & Patterson, P. L. (2005). The enhanced forest inventory and analysis program: National sampling design and estimation procedures. *Asheville, North Carolina: United States Department of Agriculture, Forest Service, Southern Research Station*, 85. https://doi.org/10.2737/SRS-GTR-80

Betts, M. G., Phalan, B., Frey, S. J. K., Rousseau, J. S., & Yang, Z. Q. (2018). Old-growth forests buffer climate-sensitive bird populations from warming. *Diversity and Distributions*, *24*(4), 439–447. https://doi.org/10.1111/ddi.12688

Binkley, D., Sisk, T., Chambers, C., Springer, J., & Block, W. (2007). The role of old-growth forests in frequent-fire landscapes. *Ecology and Society*, *12*(2), 17. https://doi.org/10.5751/es-02170-120218

Blicharska, M., & Mikusinski, G. (2014). Incorporating social and cultural significance of large old trees in conservation policy. *Conservation Biology*, *28*(6), 1558–1567. https://doi.org/10.1111/cobi.12341

Burrill, E. A., Wilson, A. M., Turner, J. A., Pugh, S. A., Menlove, J., Christiansen, G., et al. (2018). The forest inventory and analysis database: Database description and user guide version 8.0 for phase 2. Retrieved from http://www.fia.fs.fed.us/library/database-documentation

Connell, D. J., Shapiro, J., & Lavallee, L. (2015). Old-growth forest values: A case study of the ancient cedars of British Columbia. *Society and Natural Resources*, *28*(12), 1323–1339. https://doi.org/10.1080/08941920.2015.1041660

Costanza, J. K., Koch, F. H., Reeves, M., Potter, K. M., Schleeweis, K., Riitters, K. H., et al. (2023). Disturbances to forests and rangelands. In *Future of America's Forest and rangelands: Forest Service 2020 Resources Planning Act assessment* (Gen. Tech. Rep. WO-102, pp. 5-1–5-55). United States Department of Agriculture, Forest Service. https://doi.org/10.2737/WO-GTR-102-Chap5

Costanza, J. K., Koch, F. H., & Reeves, M. C. (2023). Future exposure of forest ecosystems to multi-year drought in the United States. *Ecosphere*, *14*(5), 19. https://doi.org/10.1002/ecs2.4525

Coulson, D. P., & Joyce, L. A. (2020). RPA Historical observational data (1979-2015) for the conterminous United States at the 1/24 degree grid scale based on MACA training data (METDATA). (2nd ed.). *Forest Service Research Data Archive*. https://doi.org/10.2737/RDS-2017-0070-2

Coulston, J. W., Brooks, E. B., Butler, B. J., Costanza, J. K., Walker, D. M., Domke, G. M., et al. (2023a). Forest resources. In *Future of America's Forest and rangelands: Forest Service 2020 Resources Planning Act assessment* (Gen. Tech. Rep. WO-102, pp. 6-1–6-38). United States Department of Agriculture, Forest Service. https://doi.org/10.2737/WO-GTR-102-Chap6

Coulston, J. W., Domke, G. M., Walker, D. M., Brooks, E. B., & O'Dea, C. B. (2023). Near-term investments in forest management support long-term carbon sequestration capacity in forests of the United States. *PNAS Nexus*, *2*(11), 4. https://doi.org/10.1093/pnasnexus/pgad345

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

Crockett, E. T. H., Atkins, J. W., Guo, Q. F., Sun, G., Potter, K. M., Ollinger, S., et al. (2023). Structural and species diversity explain aboveground carbon storage in forests across the United States: Evidence from GEDI and forest inventory data. *Remote Sensing of Environment*, *295*, 15. https://doi.org/10.1016/j.rse.2023.113703

Crowe, O., Beresford, A. E., Buchanan, G. M., Grantham, H. S., Simkins, A. T., Watson, J. E. M., & Butchart, S. H. M. (2023). A global assessment of forest integrity within key biodiversity areas. *Biological Conservation*, *286*, 7. https://doi.org/10.1016/j.biocon.2023.110293

Davis, K. T., Dobrowski, S. Z., Higuera, P. E., Holden, Z. A., Veblen, T. T., Rother, M. T., et al. (2019). Wildfires and climate change push low-elevation forests across a critical climate threshold for tree regeneration. *Proceedings of the National Academy of Sciences of the United States of America*, *116*(13), 6193–6198. https://doi.org/10.1073/pnas.1815107116

Dias, A., Van Houdt, S., Meschin, K., Von Stackelberg, K., Bago, M. L., Baldarelli, L., et al. (2023). Using essential biodiversity variables to assess forest ecosystem integrity. *Frontiers in Forests and Global Change*, *6*, 10. https://doi.org/10.3389/ffgc.2023.1098901

Fei, S. L., Desprez, J. M., Potter, K. M., Jo, I., Knott, J. A., & Oswalt, C. M. (2017). Divergence of species responses to climate change. *Science Advances*, *3*(5), 9. https://doi.org/10.1126/sciadv.1603055

Flinn, K. M., Dolnicek, M. N., & Cox, A. L. (2022). Gap dynamics and disease-causing invasive species drive the development of an old-growth forest over 250 years. *Forest Ecology and Management*, *508*, 9. https://doi.org/10.1016/j.foreco.2022.120045

Frey, S. J. K., Hadley, A. S., Johnson, S. L., Schulze, M., Jones, J. A., & Betts, M. G. (2016). Spatial models reveal the microclimatic buffering capacity of old-growth forests. *Science Advances*, *2*(4), 9. https://doi.org/10.1126/sciadv.1501392

Gao, P., Terando, A. J., Kupfer, J. A., Varner, J. M., Stambaugh, M. C., Lei, T. L., & Hiers, J. K. (2021). Robust projections of future fire probability for the conterminous United States. *Science of the Total Environment*, *789*, 13. https://doi.org/10.1016/j.scitotenv.2021.147872

Gilliam, F. S., & Platt, W. J. (1999). Effects of long-term fire exclusion on tree species composition and stand structure in an old-growth *Pinus palustris* (Longleaf pine) forest. *Plant Ecology*, *140*(1), 15–26. https://doi.org/10.1023/a:1009776020438

Gonzalez-Benecke, C. A., Gezan, S. A., Martin, T. A., Cropper, W. P., Samuelson, L. J., & Leduc, D. J. (2014). Individual tree diameter, height, and volume functions for longleaf pine. *Forest Science*, *60*(1), 43–56. https://doi.org/10.5849/forsci.12-074

Gray, A. N., Pelz, K., Hayward, G. D., Schuler, T., Salverson, W., Palmer, M., et al. (2023). Perspectives: The wicked problem of defining and inventorying mature and old-growth forests. *Forest Ecology and Management*, *546*, 11. https://doi.org/10.1016/j.foreco.2023.121350

Heidari, H., Arabi, M., & Warziniack, T. (2021). Effects of climate change on natural-caused fire activity in Western US national forests. *Atmosphere*, *12*(8), 16. https://doi.org/10.3390/atmos12080981

Hoover, C. M., Leak, W. B., & Keel, B. G. (2012). Benchmark carbon stocks from old-growth forests in northern New England, USA. *Forest Ecology and Management*, *266*, 108–114. https://doi.org/10.1016/j.foreco.2011.11.010

Johnson, K. N., & Swanson, F. J. (2009). Historical context of old-growth forests in the Pacific Northwest: Policy, practices and competing worldviews. In T. A. Spies & S. L. Duncan (Eds.), *Old growth in a new world: A Pacific Northwest icon reexamined* (pp. 12–28). Island Press.

Jones, J., Ellison, D., Ferraz, S., Lara, A., Wei, X. H., & Zhang, Z. Q. (2022). Forest restoration and hydrology. *Forest Ecology and Management*, *520*, 11. https://doi.org/10.1016/j.foreco.2022.120342

Joyce, L. A., Abatzoglou, J. T., & Coulson, D. P. (2018). Climate data for RPA 2020 assessment: MACAv2 (METDATA) historical modeled (1950-2005) and future (2006-2099) projections for the conterminous United States at the 1/24 degree grid scale. *Forest Service Research Data Archive*. https://doi.org/10.2737/RDS-2018-0014

Joyce, L. A., & Coulson, D. (2020). Climate scenarios and projections: A technical document supporting the USDA Forest service 2020 RPA assessment *(Gen. Tech. Rep. RMRS-GTR-413)*. United States Department of Agriculture, Forest Service, Rocky Mountain Research Station. https://doi.org/10.2737/RMRS-GTR-413

Knapp, L. B., & Canham, C. D. (2000). Invasion of an old-growth forest in New York by *Ailanthus altissima*: Sapling growth and recruitment in canopy gaps. *Journal of the Torrey Botanical Society*, *127*(4), 307–315. https://doi.org/10.2307/3088649

Knorn, J., Kuemmerle, T., Radeloff, V. C., Keeton, W. S., Gancz, V., Biris, I. A., et al. (2013). Continued loss of temperate old-growth forests in the Romanian Carpathians despite an increasing protected area network. *Environmental Conservation*, *40*(2), 182–193. https://doi.org/10.1017/s0376892912000355

Knott, J. A., Jenkins, M. A., Oswalt, C. M., & Fei, S. L. (2020). Community-level responses to climate change in forests of the eastern United States. *Global Ecology and Biogeography*, *29*(8), 1299–1314. https://doi.org/10.1111/geb.13102

LaRue, E. A., Knott, J. A., Domke, G. M., Chen, H. Y. H., Guo, Q. F., Hisano, M., et al. (2023). Structural diversity as a reliable and novel predictor for ecosystem productivity. *Frontiers in Ecology and the Environment*, *21*(1), 33–39. https://doi.org/10.1002/fee.2586

Laughlin, D. C., Bakker, J. D., Stoddard, M. T., Daniels, M. L., Springer, J. D., Gildar, C. N., et al. (2004). Toward reference conditions: Wildfire effects on flora in an old-growth ponderosa pine forest. *Forest Ecology and Management*, *199*(1), 137–152. https://doi.org/10.1016/j.foreco.2004.05.034

Lawal, S., Costanza, J., Koch, F. H., & Scheller, R. M. (2024). Modeling the impacts of hot drought on forests in Texas. *Frontiers in Forests and Global Change*, *7*, 17. https://doi.org/10.3389/ffgc.2024.1280254

Littell, J. S., Peterson, D. L., Riley, K. L., Liu, Y. Q., & Luce, C. H. (2016). A review of the relationships between drought and forest fire in the United States. *Global Change Biology*, *22*(7), 2353–2369. https://doi.org/10.1111/gcb.13275

Liu, F., Liu, H. Y., Xu, C. Y., Shi, L., Zhu, X. R., Qi, Y., & He, W. Q. (2021). Old-growth forests show low canopy resilience to droughts at the southern edge of the taiga. *Global Change Biology*, *27*(11), 2392–2402. https://doi.org/10.1111/gcb.15605

Lutz, J. A., Key, C. H., Kolden, C. A., Kane, J. T., & van Wagtendonk, J. W. (2011). Fire frequency, area burned, and severity: A quantitative approach to defining a normal fire year. *Fire Ecology*, *7*(2), 51–65. https://doi.org/10.4996/fireecology.0702051

Luyssaert, S., Schulze, E. D., Börner, A., Knohl, A., Hessenmöller, D., Law, B. E., et al. (2008). Old-growth forests as global carbon sinks. *Nature*, *455*(7210), 213–215. https://doi.org/10.1038/nature07276

Margono, B. A., Turubanova, S., Zhuravleva, I., Potapov, P., Tyukavina, A., Baccini, A., et al. (2012). Mapping and monitoring deforestation and forest degradation in Sumatra (Indonesia) using Landsat time series data sets from 1990 to 2010. *Environmental Research Letters*, *7*(3), 16. https://doi.org/10.1088/1748-9326/7/3/034010

Maxwell, S. L., Evans, T., Watson, J. E. M., Morel, A., Grantham, H., Duncan, A., et al. (2019). Degradation and forgone removals increase the carbon impact of intact forest loss by 626%. *Science Advances*, *5*(10), 10. https://doi.org/10.1126/sciadv.aax2546

McRoberts, R. E., Bechtold, W. A., Patterson, P. L., Scott, C. T., & Reams, G. A. (2005). The enhanced forest inventory and analysis program of the USDA Forest Service: Historical perspective and announcement of statistical documentation. *Journal of Forestry*, *103*(6), 304–308. https://doi.org/10.1093/jof/103.6.304

Mihiar, C. M., Lewis, D. J., & Coulston, J. W. (2023). County-level land-use projections for the conterminous United States, 2020-2070, used in the 2020 RPA Assessment. *Forest Service Research Data Archive*. https://doi.org/10.2737/RDS-2023-0026

Moore, K. D. (2007). In the shadow of the cedars: The spiritual values of old-growth forests. *Conservation Biology*, *21*(4), 1120–1123. https://doi.org/10.1111/j.1523-1739.2007.00669.x

O'Dea, C. B., Langner, L. L., Joyce, L. A., Prestemon, J. P., & Wear, D. N. (2023). Future scenarios. In *Future of America's Forest and rangelands: Forest Service 2020 Resources Planning Act assessment* (Gen. Tech. Rep. WO-102, pp. 3-1–3-13). United States Department of Agriculture, Forest Service. https://doi.org/10.2737/WO-GTR-102-Chap3

Oswalt, S. N., Smith, W. B., Miles, P. D., & Pugh, S. A. (2019). Forest Resources of the United States, 2017: A Technical Document Supporting the Forest Service 2020 RPA Assessment *(Gen. Tech. Rep. WO-97)*. United States Department of Agriculture, Forest Service. https://doi.org/10.2737/WO-GTR-97

Parisien, M. A., Miller, C., Parks, S. A., DeLancey, E. R., Robinne, F. N., & Flannigan, M. D. (2016). The spatially varying influence of humans on fire probability in North America. *Environmental Research Letters*, *11*(7), 18. https://doi.org/10.1088/1748-9326/11/7/075005

Parks, S. A., Miller, C., Abatzoglou, J. T., Holsinger, L. M., Parisien, M. A., & Dobrowski, S. Z. (2016). How will climate change affect wildland fire severity in the Western US? *Environmental Research Letters*, *11*(3), 10. https://doi.org/10.1088/1748-9326/11/3/035002

Pausas, J. G., & Keeley, J. E. (2019). Wildfires as an ecosystem service. *Frontiers in Ecology and the Environment*, *17*(5), 289–295. https://doi.org/10.1002/fee.2044

Pelz, K. A., Hayward, G., Gray, A. N., Berryman, E. M., Woodall, C. W., Nathanson, A., & Morgan, N. A. (2023). Quantifying old-growth forest of United States Forest service public lands. *Forest Ecology and Management*, *549*, 9. https://doi.org/10.1016/j.foreco.2023.121437

Pesklevits, A., Duinker, P. N., & Bush, P. G. (2011). Old-growth forests: Anatomy of a wicked problem. *Forests*, *2*(1), 343–356. https://doi.org/10.3390/f2010343

Peterson, D. L., & Littell, J. S. (2014). Risk assessment for wildfire in the Western United States. In D. L. Peterson, J. M. Vose, & T. Patel-Weynand (Eds.), *Climate change and United States forests* (pp. 232–235). Springer.

Piovesan, G., Biondi, F., Di Filippo, A., Alessandrini, A., & Maugeri, M. (2008). Drought-driven growth reduction in old beech (*Fagus sylvatica* L.) forests of the central Apennines, Italy. *Global Change Biology*, *14*(6), 1265–1281. https://doi.org/10.1111/j.1365-2486.2008.01570.x

Potter, K. M., Oswalt, C. M., & Guldin, J. M. (2024). Range-wide assessment of recent longleaf pine (*Pinus palustris* Mill.) area and regeneration trends. *Forests*, *15*(7), 15. https://doi.org/10.3390/f15071255

Schrumpf, M., Axmacher, J. C., Zech, W., & Lyaruu, H. V. M. (2011). Net precipitation and soil water dynamics in clearings, old secondary and old-growth forests in the montane rain forest belt of Mount Kilimanjaro, Tanzania. *Hydrological Processes*, *25*(3), 418–428. https://doi.org/10.1002/hyp.7798

Schrumpf, M., Kaiser, K., & Schulze, E. D. (2014). Soil organic carbon and total nitrogen gains in an old growth deciduous forest in Germany. *PLoS One*, *9*(2), 8. https://doi.org/10.1371/journal.pone.0089364

Silva, C. E., Kellner, J. R., Clark, D. B., & Clark, D. A. (2013). Response of an old-growth tropical rainforest to transient high temperature and drought. *Global Change Biology*, *19*(11), 3423–3434. https://doi.org/10.1111/gcb.12312

Smith, C. C., Healey, J. R., Berenguer, E., Young, P. J., Taylor, B., Elias, F., et al. (2021). Old-growth forest loss and secondary forest recovery across Amazonian countries. *Environmental Research Letters*, *16*(8), 14. https://doi.org/10.1088/1748-9326/ac1701

Smith, W. B. (2002). Forest inventory and analysis: A national inventory and monitoring program. *Environmental Pollution*, *116*, S233–S242. https://doi.org/10.1016/S0269-7491(01)00255-X

Souza, C., Firestone, L., Silva, L. M., & Roberts, D. (2003). Mapping forest degradation in the Eastern Amazon from SPOT 4 through spectral mixture models. *Remote Sensing of Environment*, *87*(4), 494–506. https://doi.org/10.1016/j.rse.2002.08.002

Spies, T. A. (2004). Ecological concepts and diversity of old-growth forests. *Journal of Forestry*, *102*(3), 14–20. https://doi.org/10.1093/jof/102.3.14

Steel, Z. L., Jones, G. M., Collins, B. M., Green, R., Koltunov, A., Purcell, K. L., et al. (2023). Mega-disturbances cause rapid decline of mature conifer forest habitat in California. *Ecological Applications*, *33*(2), 19. https://doi.org/10.1002/eap.2763

Strittholt, J. R., DellaSala, D. A., & Jiang, H. (2006). Status of mature and old-growth forests in the Pacific Northwest. *Conservation Biology*, *20*(2), 363–374. https://doi.org/10.1111/j.1523-1739.2006.00384.x

Taylor, A. H. (2010). Fire disturbance and forest structure in an old-growth *Pinus ponderosa* forest, southern Cascades, USA. *Journal of Vegetation Science*, *21*(3), 561–572. https://doi.org/10.1111/j.1654-1103.2009.01164.x

Traylor, C. R., Ulyshen, M. D., McHugh, J., & Burner, R. C. (2024). Forest age is a primary trait filter for saproxylic beetles in the southeastern United States. *Forest Ecology and Management*, *553*, 13. https://doi.org/10.1016/j.foreco.2023.121545

Turner, M. G., Braziunas, K. H., Hansen, W. D., Hoecker, T. J., Rammer, W., Ratajczak, Z., et al. (2022). The magnitude, direction, and tempo of forest change in Greater Yellowstone in a warmer world with more fire. *Ecological Monographs*, *92*(1), 27. https://doi.org/10.1002/ecm.1485

U.S. Department of Agriculture Forest Service. (2023). Future of America's Forest and rangelands: Forest Service 2020 Resources Planning Act assessment *(Gen. Tech. Rep. WO-102)*. United States Department of Agriculture, Forest Service. https://doi.org/10.2737/WO-GTR-102

U.S. Department of Agriculture Forest Service, and U.S. Department of the Interior Bureau of Land Management. (2024). *Mature and old-growth forests: Analysis of threats on lands managed by the Forest service and bureau of land management*. United States Department of Agriculture, Forest Service.

Wagner, C., Schram, L. J., McMullin, R. T., Hunt, S. L., & Anand, M. (2014). Lichen communities in two old-growth pine (*Pinus*) forests. *The Lichenologist*, *46*(5), 697–709. https://doi.org/10.1017/s002428291400022x

Walker, D. M., Costanza, J. K., Potter, K. M., Koch, F. H., Gray, A. N., & Coulston, J. W. (2025). Future projections of U.S. forest succession classes on federal lands. *Forest Service Research Data Archive*. https://doi.org/10.2737/RDS-2025-0039

Weber, P., Bol, R., Dixon, L., & Bardgett, R. D. (2008). Large old trees influence patterns of $\delta^{13}C$ and $\delta^{15}N$ in forests. *Rapid Communications in Mass Spectrometry*, *22*(11), 1627–1630. https://doi.org/10.1002/rcm.3433

Welsh, H. H. (1990). Relictual amphibians and old-growth forests. *Conservation Biology*, *4*(3), 309–319. https://doi.org/10.1111/j.1523-1739.1990.tb00293.x

Woodall, C. W., Kamoske, A. G., Hayward, G. D., Schuler, T. M., Hiemstra, C. A., Palmer, M., & Gray, A. N. (2023). Classifying mature federal forests in the United States: The forest inventory growth stage system. *Forest Ecology and Management*, *546*, 14. https://doi.org/10.1016/j.foreco.2023.121361

Yang, S. Y., Spetich, M. A., & Fan, Z. F. (2021). Spatiotemporal dynamics and risk factors of oak decline and mortality in the Missouri Ozarks of the United States based on repeatedly measured FIA data. *Forest Ecology and Management*, *502*, 10. https://doi.org/10.1016/j.foreco.2021.119745

Yezerinac, S., & Moola, F. (2006). Conservation status and threats to species associated with old-growth forests within the range of the northern spotted owl (*Strix occidentalis caurina*) in British Columbia, Canada. *Biodiversity*, *6*(4), 3–9. https://doi.org/10.1080/14888386.2005.9712778