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Effects of Forest Management & Wood Utilization on Carbon Sequestration & Storage in Oregon

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March 09, 2026

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Acknowledgements

The research team is grateful to Werner Kurz, Scott Morken, and other staff of the Carbon Accounting Team of the Canadian Forest Service of Natural Resources Canada for invaluable advice and support on this project and for providing the training, models, and code templates necessary for this work; to Glenn Christensen, Andy Gray, Charles Maxwell, Daniel Swann, Joe Stewart, Todd Morgan, William Anderegg, Andy McEvoy, Chris Dunn, and Ian Rickert for sharing data and analysis approaches; and to Andy Gray at the USDA Forest Service and Brian Kittler, Brian Morris, and Gwyn Myer at American Forests for invaluable input and revisions.

Recommended Citation

Davidson, K. J., DeLyser Roney, K., Clay, K., Magnan, M., Bartowitz, K., Gadoth-Goodman, D., Papa, C., Ontl, T., Cooper, L., Truettner, C., Yost, A., Norlander, D., Hubner, D., Tokarczyk, J. A. (2026). Effects of Forest Management & Wood Utilization on Carbon Sequestration & Storage in Oregon. American Forests. https://doi.org/10.5281/zenodo.18876396

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Table of Contents

Table of Contents 3
Glossary of Terms 4
Summary and Implications for Decision Makers 7
- Forests as a Natural Climate Solution 7
- Modeling Forest Management and Wood Utilization in Oregon 8
- Climate-Smart Forestry in Oregon 10
- Other Considerations 21

Introduction 24
- Forests as a Natural Climate Solution 24
- Assessing Forest Climate Benefits in Oregon 25

Research and Modeling Process 26
- Systems-Based Forest Carbon Modeling 26
- Identifying Forest Management Priorities 33
- Developing Modeling Scenarios 36

Results and Discussion 45
- Influence of Future Climate 45
- Effects of Alternative Management Scenarios 58
- Uncertainties and Limitations 88

Takeaways and Policy Opportunities 90
References 94
Appendix 111
- Model Development Methodology 111
- Scenario Parameterization Methodology 134

Glossary of Terms

Business-as-Usual (BAU) – A scenario in which average historical (2000-2021) rates of forest management, land-use change, natural disturbance, and harvested wood product (HWP) utilization are continued each year through 2100.

Carbon Storage or Carbon Stocks – The amount of carbon physically held by living and dead trees, contained in the soil and forest floor material, and carried in wood products throughout the economy.

Climate Adjusted Business-as-Usual (CBAU) – A scenario based on the Business-as-Usual (BAU) that also includes projected future climate change impacts. These impacts, based on an RCP 8.5 future emissions scenario, include more frequent and severe natural disturbance, decadal declines in productivity, and post-fire regeneration failure following a fraction of high-severity wildfire.

Dead Organic Matter (DOM) – Carbon, originally contained in a live biomass pool, which is transferred to the forest floor and within mineral soils as the result of litterfall, tree mortality, natural disturbances, and harvest. DOM is subject to decomposition, at a rate proportional to its size and its location (above or belowground).

Decomposition Emissions – Emissions from the forest ecosystem resulting from the decay and decomposition of dead organic matter and soil carbon stocks.

Disturbance Emissions – Emissions from the forest ecosystem resulting from wildfires and other disturbance events.

Ecosystem Emissions – Total carbon emissions from the forest ecosystem, including decomposition of dead organic matter and soil carbon stocks, and carbon emissions that result from wildfires and other disturbance events.

Harvested Wood Products (HWP) – Products and commodities produced from woody material removed from the forest typically, though not exclusively, during harvest or other management events.

Harvested Wood Products (HWP) Emissions – Emissions from the forest products sector resulting from decomposition of HWP in landfills, combustion of harvested wood and wood residues used as a fuel source, and from HWP energy recapture.

Harvest Transfers – The movement of carbon from the forest to the forest products sector resulting from harvest. From the perspective of net ecosystem carbon flux, harvest transfers are a net loss of carbon. From the perspective of net HWP carbon balance, harvest transfers are a net gain of carbon. From the perspective of net carbon balance, harvest transfers are a lateral movement of carbon from one carbon storage pool to another (neither a loss nor a gain).

Land-Use Change (LUC) – A process by which management activities alter the total forest area. Afforestation and silvopasture practices contribute to an increase in total forest area. Deforestation contributes to a decrease in total forest area. Post-fire regeneration failure is not considered a land-use change event, as the total forest area remains the same, though the productive forest area decreases.

Landscape Resilience – A set of scenarios based on CBAU that also includes management practices which aim to make the forest landscape better adapted to future disturbance events. This is accompanied either by reducing carbon stocks via thinning or prescribed fire treatments (Wildfire Resilience) or by reducing the density of pest and pathogen vectors via thinning with harvest removal (Pest Resilience).

Landscape Restoration – A scenario based on CBAU that also includes management practices which aim to restore growth and productivity in forests in a state of post-fire regeneration failure. Landscape Restoration treatments include site preparation and salvage (where legally permissible) and subsequent replanting at low stand density.

Net Carbon Balance (NCB) – A metric which sums net ecosystem carbon flux and net HWP carbon balance to provide a system-wide carbon balance estimate from both the forest and HWP. Net carbon balance is presented from the atmospheric perspective, where negative values indicate carbon sequestered from the atmosphere and stored in forests and wood products (a net carbon sink) and positive values indicate carbon emitted to the atmosphere from forests and wood products (a net carbon source).

Net Carbon Sequestration - The annual rate of carbon capture from the atmosphere by forests, affected by rates of tree growth, mortality, decomposition, and disturbance.

Net Carbon Source vs Net Carbon Sink – A descriptor of whether the forest and/or the forest sector emits more carbon than it sequesters and stores (carbon source) or emits less carbon than it sequesters and stores (carbon sink).

Net Ecosystem Carbon Flux (NECF) – A metric which sums net yearly sequestration of carbon by forests across all ecosystem carbon pools, after accounting for decomposition, natural disturbance emissions, and harvest transfers. Net ecosystem carbon flux is presented from the atmospheric perspective, where negative numbers represent a net carbon sink (less carbon in the atmosphere) and positive numbers represent a net carbon source (more carbon in the atmosphere).

Net Primary Productivity (NPP) – The measure of net sequestration of carbon in forests from growth, after accounting for annual losses of carbon to decomposition.

Net HWP Carbon Balance – A metric which sums transfers of HWP from the forest to the forest products sector, emissions from wood products in use and in landfills, substitution benefits (which can be positive or negative) in years where harvest is different than CBAU, and leakage in years where harvest is less than CBAU. Negative values for net HWP carbon balance denote net carbon storage in the wood products sector, whereas positive values denote net carbon emissions (a net carbon source) from the wood products sector.

Post-fire Regeneration Failure – A landscape state in which the forest fails to naturally regenerate following high-severity wildfire, leading to decreased forest productivity. During post-fire regeneration failure, forests do not grow and therefore remain at age zero, and they do not sequester additional carbon each year, though they still store carbon in soil and dead organic matter stocks. These carbon stocks are subject to emissions from decomposition and disturbance.

Product Substitution or Substitution Benefits – A change in economy-wide emissions resulting from a change in the production of certain wood commodities which can substitute for more emissions-intensive alternatives. This change in commodity production is calculated relative to the commodity production expected under CBAU, and not all commodities are assumed to have substitutes. Because of the difference in embodied emissions between wood and non-wood alternatives, increasing the production of wood commodities leads to a reduction in non-wood alternatives and displaced emissions (an overall emissions reduction, or a positive substitution benefit). Likewise, a decrease in the production of wood commodities leads to an increase in non-wood alternatives (an overall emissions increase, or a negative substitution benefit).

Productive Forest Area – The total forest area not in a state of post-fire regeneration failure. We use the term "productive" here to denote whether or not trees are actively growing. This does not imply that all productive forest area has an equal rate of net primary productivity and does not distinguish between various forest productivity classes.

Silvopasture – A management practice which involves the low-density planting of trees in active pasture without disrupting its pastureland use. Silvopastoral tree planting increases total (and productive) forest area.

Harvest Leakage – An increase in out-of-state harvest activity which is assumed to occur when there is a decrease in harvesting in-state but demand for HWP is assumed to remain constant. Leakage is only applied to scenarios and years where annual harvest rates are less than CBAU. Leakage appears as an increase in HWP emissions, and is meant to account for HWP emissions not otherwise captured within the bounds of the model.

Urban Growth Boundary (UGB) – An area, designated by a municipality in Oregon, in which that municipality expects to grow over a 20-year period. Development of land outside the UGB for urban uses (e.g., housing, industrial facilities, businesses, or public facilities such as utilities) is strongly restricted, effectively limiting the potential for suburban sprawl into forest and farmland.

Summary and Implications for Decision Makers

Forests as a Natural Climate Solution

Climate change presents a global challenge to society and the ecosystems we rely on. In turn, forests have become increasingly important in international climate change dialogue, as seen in the Paris Agreement, the COP26 Glasgow Leaders' Declaration on Forests and Land, and the Intergovernmental Panel on Climate Change (IPCC) Sixth Assessment Report (COP26 2021; Popkin 2019; Calvin et al. 2023). There is also increasing scholarly recognition of forests' importance as a nature-based solution to climate change, or natural climate solution (NCS; (Drever et al. 2021; Griscom et al. 2017; Fargione et al. 2018; Ellis et al. 2024; Buma et al. 2024).

US forests and the forest products sector already play an important role in mitigating climate change, a benefit which can be significantly impacted by forest management decisions and policies as well as future climate conditions (EPA 2024; Fargione et al. 2018; Wear and Coulston 2015; Oswalt et al. 2019; Anderegg et al. 2020). The overall climate mitigation benefit of the forestry sector is determined not only by the trees growing in a forest, but also by what they are used to produce (i.e., harvested wood products, HWP) and how HWP are used and ultimately retired. The largest NCS opportunities for forests typically come through reforestation, forest conservation, or forest management pathways (Griscom et al. 2017; Fargione et al. 2018; Drever et al. 2021; Buma et al. 2024), which can include long-term carbon storage in HWP such as mass timber (Xie et al. 2021). However, these benefits can be constrained or even negated in fire-prone ecosystems if wildfire hazards and the intensity and frequency of wildfire impacts on forests are not curtailed (Jerrett et al. 2022).

To maintain and strengthen the NCS capacity of forests, future management and policy decisions will need to mesh mitigation goals with adaptation to future climate conditions. This dynamic is central to the concept of *climate-smart forestry (CSF)*, a sustainable forest management approach that seeks to balance the ability of forests to adapt to and mitigate climate change while continuing to provide fundamental wood products and ecosystem services (Nabuurs et al. 2018; Bowditch et al. 2020; Verkerk et al. 2020). This approach acknowledges the importance of maintaining or increasing carbon storage in forests and forest products as a climate solution but also emphasizes the need for robust carbon sequestration rates to continue to draw carbon out of the atmosphere as part of a global effort to mitigate climate change. CSF techniques focus on long-term forest health and resilience in the face of climate change as part of sustainability in forest management, and they aim to accomplish all these goals while supporting a strong forest products sector. According to the IPCC, meeting our global climate goals is not possible without forests (Calvin et al. 2023), and forests need the health and resilience benefits provided by CSF to play their part. Therefore, the most promising future NCS practices for forests will need to follow a CSF approach.

Oregon is important from the perspective of forests, the forest economy, and climate change. The forests of Oregon hold large volumes of carbon relative to many other states, and the forest products sector is a leader in softwood lumber and plywood production. The state of Oregon first set greenhouse gas (GHG) emissions reduction goals in 2007 (ORS 468A.205), which require the state to reduce GHG emissions to at least 75% below 1990 levels by 2050. This goal was updated in 2020, when Governor Kate Brown issued Executive Order 20-04 (Brown, 2020), and was most recently modified in the Oregon Climate Action Commission's (OCAC, known as the Oregon Global Warming Commission until 2024) Roadmap to 2030 (Oregon Global Warming Commission 2023), which sets a target of a 95% reduction below 1990 levels by 2050. Within the Roadmap to 2030, OCAC clarifies that natural and working lands, including forests, should have a set of sequestration goals separate from, and in addition to, Oregon's sector-based emission reduction targets. These goals, as outlined in the 2021 Natural and Working Lands Proposal (Oregon Global Warming Commission 2021a), are to sequester at least an

additional 5 teragrams of carbon dioxide equivalent ($TgCO_2e$) per year in Oregon's natural and working lands and waters by 2030, and at least 9.5 $TgCO_2e$ per year by 2050, relative to a 2010 to 2019 activity-based, business-as-usual net carbon sequestration baseline, representing a 23% and 44% increase respectively. However, there is increasing uncertainty in the long term viability of Oregon's forests acting as a net carbon sink, largely due to projected declines in forest health and productivity fueled by the effects of climate change (Wear and Coulston 2015; Oswalt et al. 2019; Halofsky et al. 2022). As such, future policy and planning efforts aimed at meeting and exceeding these goals could be hampered without a clear understanding of the current baseline of forest management and the wood products economy, the scale of potential future climate impacts, and the effectiveness of different CSF practices at mitigating climate change effects on Oregon's forests.

This report is designed to guide Oregon toward identifying promising CSF practices and to encourage the inclusion of forests and the forest products sector in state-level climate action planning. Here, we present comprehensive forest sector carbon modeling results for a broad range of forward-looking forest management and innovative wood utilization scenarios and assess the carbon sequestered in forests and stored in HWP for each one, along with an analysis of potential leakage impacts and the substitution benefits from using wood in place of other emissions-intensive materials. These results will provide information about forest climate mitigation and adaptation opportunities that can integrate with and inform statewide efforts, including OCAC's Roadmap to 2030, OCAC's Natural and Working Lands Goals, and the Oregon Department of Forestry's (ODF) Landscape Resiliency Program and 20-Year Landscape Resiliency Strategy (Oregon Global Warming Commission 2023, 2021a; Oregon Department of Forestry 2023a).

Modeling Forest Management and Wood Utilization in Oregon

Following previous work (Dugan et al. 2018, 2019, 2021; DeLyser et al. 2022a, 2022b; Papa et al. 2023; DeLyser et al. 2025), we assess carbon trends and management scenarios in the forest ecosystem and forest products sector for Oregon utilizing a systems-based approach. This systems approach accounts for the influence of forest management activities beyond the forest itself and allows us to examine potential trade-offs or synergies between management strategies that enhance or alter forest ecosystem carbon stocks, HWP volumes, or other important forest ecosystem services (Dugan et al. 2018). Our scenario development and modeling process includes:

1) Consultation with state natural resource agency staff and forestry experts to understand forest management priorities, concerns, and goals in Oregon, based on current conditions and a landscape resilience needs assessment;

2) Development of business-as-usual (BAU) and climate-adjusted BAU (CBAU) scenarios and alternative forest scenarios – including forest management, natural disturbance, and land-use change – to project future forest carbon trends under various management practices and future climate conditions;

3) Scenario modeling with i) a growth and yield-based forest ecosystem model - the Carbon Budget Model of the Canadian Forest Sector (CBM-CFS3; Kurz et al. 2009) - parameterized for conditions in Oregon, ii) a customized harvested wood products dynamics model (CBM-HWP-OR) built using the Abstract Network Simulation Engine framework (ANSE; CFS 2024), iii) potential leakage factors applied to changing harvest rates, iv) displacement factors to evaluate substitution benefits from using wood products and bioenergy in place of more emissions-intensive materials; and

4) Engagement and discussion with state agency staff to explore modeling results and consider implications for Oregon.

Through a series of meetings with ODF, Oregon Department of Environmental Quality (DEQ), and USDA Forest Service (USFS) staff, along with academics and forestry practitioners in the state, we identified several management priorities and concerns for forests in Oregon: **land use and land cover, harvest practices and stand rotations, forest resilience to wildfire and pests, forest regeneration and reforestation,** and **wood utilization and HWP efficiency**. From these stated priorities we developed 23 modeling scenarios to forecast potential CSF pathways represented by a broad range of forest management and wood utilization practices (**Table E1**). We constructed a business-as-usual scenario (BAU) and a climate-adjusted version (CBAU) to illustrate the influence of future climate on forests if future management practices did not change from current trends. All additional scenarios were built upon the CBAU scenario to illustrate the potential impact of each alternative management and wood utilization approach in the context of our projected future climate. As much as possible, we also integrated and aligned with priorities and recommendations highlighted in other statewide efforts when developing our scenarios, including Oregon's 20-Year Landscape Resiliency Strategy (Oregon Department of Forestry 2023c) and OCAC's 2021 Natural and Working Lands Proposal (Institute for Natural Resources 2023; Oregon Global Warming Commission 2021a). We collected historical data from 2000-2021 for model validation and used this as the basis for our forward-looking scenario projections over a 79-year period from 2022-2100. See **Report Tables 2** and **4** for full scenario descriptions and parameters.

Table E1. Names, descriptions, and differences in model prescription from BAU/CBAU for our 15 forest management scenarios and portfolios, and 2 alternate harvested wood products scenarios. CBAU and alternative wood product scenarios are modified from BAU. Forest management scenarios and portfolios are modified from CBAU.

	Scenario name and description	Difference from BAU/CBAU
	Business-as-usual (BAU) Continuation of average historical rates of management, land-use change, and natural disturbance	-
	Climate-adjusted business-as-usual (CBAU) Continuation of average historical rates of management and land-use change. Inclusion of projected future climate change impacts including more frequent and severe natural disturbance, productivity declines, and post-fire regeneration failure	+206,431 ac yr^{-1} high-severity wildfire Post-fire regeneration failure on an average of 73% of high-severity wildfire acres 57% average decline in forest productivity (annual growth rates) by 2100
Forest management scenarios (run on CBAU)	Wildfire Resilience Fire resilience treatments (a combination of thinning and/or prescribed fire) to reduce future wildfire severity	+641,858 ac yr^{-1} wildfire resilience treatments (thin and Rx fire) 365,423 ac yr^{-1} wildfire at lower severity
	Pest Resilience Pest resilience treatments (thinning to reduce insect pest prevalence and replacement of trees impacted by Swiss needle cast) to reduce future insect and disease outbreak severity	+272,194 ac yr^{-1} pest resilience treatments (thin and remove slash) 267,831 ac yr^{-1} insect and disease disturbance at lower severity
	Landscape Restoration Post-fire salvage/site prep and reforestation, addressing both current backlog and projected future need	+16,969 ac yr^{-1} post-fire reforestation from 2022-2050 (backlog) +105,803 ac yr^{-1} salvage/site prep and reforestation in areas with post-fire regeneration failure (2022-2100)
	Net Zero Forest Loss via Increased Afforestation (NZA) Increase the rate of afforestation to ensure net zero permanent forest loss from land-use change	+32,252 ac yr^{-1} of afforestation (203% of CBAU afforestation rate)
	Net Zero Forest Loss via Decreased Deforestation (NZD) Decrease the rate of deforestation to ensure net zero permanent forest loss from land-use change	-32,252 ac yr^{-1} of deforestation (43.9% of CBAU deforestation rate)

Table E1, cont. Names, descriptions, and differences in model prescription from BAU/CBAU for our 15 forest management scenarios and portfolios, and 2 alternate harvested wood products scenarios. CBAU and alternative wood product scenarios are modified from BAU. Forest management scenarios and portfolios are modified from CBAU.

	Scenario name and description	Difference from BAU/CBAU
Forest management scenarios (run on CBAU)	**No Deforestation Outside of the Urban Growth Boundary (UGB)** Prevent all permanent forest loss from land-use change outside of the 2023 urban growth boundaries (UGB)	-62,556 ac yr^{-1} of deforestation (99.2% of CBAU deforestation rate)
	Silvopasture Integration of low-density native tree cover in active pastureland without removing the land from pasture use	+24,928 ac yr^{-1} planted as silvopasture (2022-2050)
	80-Year Rotations Increase minimum even-aged harvest age from 40, 50, or 60 years to 80 years on all forestlands	381,241 ac yr^{-1} eligible for altered rotation lengths (84% of CBAU harvest volume)
	CMAI Based Rotations Change the minimum even-aged harvest age to the forest type group specific CMAI on all forestlands	381,241 ac yr^{-1} eligible for altered rotation lengths (83% of CBAU harvest volume)
	Uneven-Aged Management Replace high-intensity harvest with group selection on all forestlands east of the Cascade divide (Eastern Oregon, Blue Mountains, and East Cascades and Modoc)	23,961 ac yr^{-1} from high-intensity harvest to group selection (99% of CBAU harvest volume)
Portfolios (combined scenarios)	**Combined Resilience and Restoration (CRR)** Wildfire Resilience + Pest Resilience + Landscape Restoration	+31,155 ac yr^{-1} post-fire reforestation (2022-2100) +914,052 ac yr^{-1} resilience treatments (Wildfire and Pest) 365,423 ac yr^{-1} wildfire at lower severity 267,831 ac yr^{-1} insect and disease disturbance at lower severity
	Maximum Forest Area and Carbon (Max FAC) UGB + Silvopasture + 80-Year rotations	56,221 ac yr^{-1} of avoided deforestation +24,928 ac yr^{-1} planted as silvopasture (2022-2050)
	Maximum Forest as Natural Climate Solutions (Max NCS) Wildfire Resilience + Pest Resilience + Landscape Restoration + UGB + Silvopasture + 80-Year Rotations	+31,155 ac yr^{-1} post-fire reforestation (2022-2100) +914,052 ac yr^{-1} resilience treatments (Wildfire and Pest) 365,423 ac yr^{-1} wildfire at lower severity 267,831 ac yr^{-1} insect and disease disturbance at lower severity 56,221 ac yr^{-1} of avoided deforestation +24,928 ac yr^{-1} planted as silvopasture (2022-2050)
Alternate wood utilization scenarios	**Innovative wood utilization** Allocate harvested wood from wildfire and/or pest resilience treatments to innovative wood products which more accurately reflect their potential use. Applied to Wildfire Resilience, Pest Resilience, CRR, and Max NCS	50% of material removed from resilience treatments to lumber Up to 5% of material removed from resilience treatments to biochar by 2100 Remaining proportion of material removed from resilience treatments combusted for bioenergy
	Increased HWP efficiency Improve the efficiency and carbon storage potential of Oregon's forest products sector by increasing product half-lives and recycling rates. Increase the production of longer-lived wood products from roundwood and mill residue. Applied to CBAU, CRR, Max FAC, and Max NCS	50% increase in the half-life of lumber used in construction 25% increase in the recycling rate of lumber used in construction 25% of mill residue used in wood fiber products Up to 5% of hardwood roundwood commodity production is mass timber by 2100 Up to 5% of hardwood roundwood commodity production is mass plywood by 2100

Climate-Smart Forestry in Oregon

Results of this study show that when accounting for the effects of climate change, Oregon forests are projected to be a consistent net source of carbon emissions from 2029 through the end of the century. Though the forest products sector is currently a growing carbon storage pool for the state, holding a substantial fraction of the carbon removed as a result of timber harvest, its contributions are not enough to counteract projected trends in emissions from Oregon's forest ecosystems. These trends are partially driven by climate change and its projected effects, which drive larger and more severe natural

disturbances as well as declines in forest productivity. Our CBAU scenario projects that the annual area of high-severity wildfire will increase by 825% from 2022 to 2100 (from 55,235 ac yr^{-1} to 510,721 ac yr^{-1}), exposing large swaths of Oregon's forest to potential post-fire regeneration failure and driving substantial decreases in forest area and carbon stocks and increases in projected carbon emissions from forests over the next 79 years.

Despite this trajectory, the scenarios modeled in this analysis demonstrate various climate-smart practices that provide opportunities to minimize losses of forest area and carbon and create a more stable forest carbon sink in Oregon (**Box 1**). Our scenarios also illustrate the potential to deploy increased wood efficiency and innovative wood utilization to further improve future carbon trends. In combination, concurrent management actions and wood utilization practices offer substantial progress toward CSF objectives – balancing carbon sequestration and storage while improving the stability and resilience of forests in the state.

BOX 1. CLIMATE-SMART FORESTRY PRACTICES IN OREGON

- ✓ **Address post-fire regeneration failure** through *landscape restoration* activities such as site preparation techniques (including salvage of commercially viable timber where legally permissible) to prepare the landscape for safe planting efforts and reduce future fuel hazards in post-burn areas, and subsequent reforestation.
- ✓ **Reduce the impact and severity of future pest outbreaks and wildfires** through *resilience treatments*, including thinning and prescribed fire, at a landscape scale.
- ✓ **Use additional woody material** removed from landscape restoration and resilience treatments in *innovative wood products* to store carbon in durable wood products while gaining substitution benefits from using the wood in place of more emissions-intensive materials.
- ✓ **Increase the efficiency of the forest products sector** through shifting production toward longer-lived HWP, longer retention of products in use, and higher rates of reuse and recycling.
- ✓ **Reduce the rate of permanent forest loss** through *reduced deforestation, afforestation,* and management practices that prioritize *landscape restoration* and *silvopasture.*
- ✓ **Prepare for increasing negative impacts of climate change** and use climate-adapted species and stand structures to promote forest health and resilience.

A key factor for successful CSF will be addressing negative wildfire impacts, which we model in two ways. Post-fire reforestation and restoration is critical both for addressing the current reforestation need across the state (estimated at 492,000 acres; (McCarley et al. 2025)) and for combatting future regeneration failure as high-severity wildfires expand under future climate conditions (creating reforestation need on over 8 million additional acres from 2022-2100). This work includes site preparation techniques to prepare the landscape for safe planting efforts and reduce future fuel hazards in post-burn areas (including salvage of commercially viable timber where legally permissible), and subsequent reforestation at stand densities which will promote resilience to future climate impacts. Though not specifically modeled here, locally appropriate climate-informed reforestation techniques like planting climate-adapted species in variable stand structures, or long-term maintenance of open

space via prescribed burning, will also be important for fostering future forests more resilient to wildfire and a changing climate (Meyer et al. 2021; North et al. 2022; Rose and Haase 2005).

Fire resilience treatments, a combination of thinning and prescribed fire to reduce stand densities (North et al. 2022), provide a second climate-smart approach to addressing wildfire impacts, particularly in dry, historically fire-prone ecoregions (Reilly et al. 2022). These treatments help to create conditions where future wildfires will likely burn at a lower severity in treated areas (Davis et al. 2024). Based on projections from the 2023 Pacific Northwest Quantitative Wildfire Risk Assessment (McEvoy et al. 2024), we estimate that more than 8.6 million acres of forest across Oregon are currently in need of treatment to reduce future wildfire risk and severity. Treating these acres over the 29-year period we modeled, which aligns closely with ODF's 20-year Landscape Resiliency Strategy (Oregon Department of Forestry 2023c), can help restore critical resilience to the landscape before wildfires are projected to intensify in the 2050s. This can help reduce direct wildfire emissions and mortality from high-severity wildfires, can ease the future demand for reforestation in areas afflicted by post-fire regeneration failure, and can help bolster local economies once dependent on timber revenues (Hjerpe et al. 2024).

Though less of a pressing issue than wildfire, insect and disease outbreaks can also reduce carbon sequestration either through direct tree mortality or via defoliation or other conversions of live biomass to *dead organic matter* (DOM), which is subject to decay and decomposition emissions. Based on our assessment of the National Insect and Disease Risk Map (USDA Forest Service 2018b), more than 10.4 million forest acres across Oregon could benefit from insect pest resilience treatments. These treatments typically include thinning to reduce pest habitat prevalence, and disposal of slash to prevent it from becoming a further vector for pest outbreaks. While less conclusive than the studies surrounding wildfire treatments, research suggests that thinning can be effective for reducing pest prevalence and spread, and thus pest effects on tree mortality and defoliation (Coops et al. 2008; Whitehead et al. 2003).

Both wildfire and pest resilience treatments, modeled across millions of acres, include the cutting and removal of large amounts of additional wood. While Oregon's forest products sector is robust, there are limited uses and markets for the small diameter material typically removed as part of resilience treatments, especially as the annual volume of this material is expected to be up to 4.6 times greater than the commercial removal and utilization of similar material at present. In addition, the existing mills with the capacity to process this wood (mainly in western Oregon) may be geographically isolated from where the majority of treatments are occurring (mainly in central and eastern Oregon), making use of this wood difficult to justify economically (BBER 2022). To account for this, we developed an innovative wood utilization scenario in which material from wildfire and/or pest resilience treatments is prioritized for use in lumber products and biochar, with the remaining material combusted for bioenergy. When biomass that would otherwise be used in shorter-lived products such as pulp and paper products are instead used in longer-lived products like timber, composite panels, and biochar, a larger fraction of this carbon is locked away, enhancing the sink strength of the forest products sector.

In addition to innovative use of wood from resilience treatments, further emissions reduction benefits can be gained through more efficient wood use in the forest products sector. For example, utilizing timber in long-lived product categories such as construction lumber or mass timber means that carbon is retained in the forest product sector for longer than if the same material were used for paper or other industrial products such as mulch. Because long-lived products may also substitute for more emissions-intensive materials like concrete and steel, producing more of these wood products helps avoid (or displace) emissions from production and use of alternative products, reducing overall carbon emissions to the atmosphere. Concurrently, increased recycling of lumber products can also extend the residence time of the associated carbon in these wood products, that is the amount of time the product, and thus

the carbon within, spend in use or inert in the landfill. Finally, finding new uses for mill residues, such as in the production of wood fiber insulation, means that direct emissions from combustion of unused mill residues are lower and the carbon in these residues is now stored in a longer-lived wood product.

Beyond addressing the effects of natural disturbances like wildfire and pest outbreaks, strategies which curb the rate of permanent forest loss from land-use change can also stabilize forest carbon in Oregon. Potential opportunities for Oregon include active afforestation campaigns to counteract the trend of forest loss, strict enforcement of Urban Growth Boundaries and state land-use planning restrictions for forest lands to prevent widespread conversion of forests to other non-forest working-land categories, or low-density silvopasture plantings on existing agricultural lands. In all such cases, these approaches lead to higher forest carbon stocks and help reduce the rate of forest loss, though at a smaller scale than the losses associated with wildfire and post-fire regeneration failure. In addition, when the rate of deforestation is reduced, so too is the transfer of wood to the forest products sector, which creates the potential for leakage as harvest in neighboring states can increase to fill the demand for HWP (in which we assume that 84.4% of the annual harvest deficit is subject to leakage; Wear and Murray 2004).

This potential for leakage also applies to any actions that modify timber harvest practices in Oregon. Under CBAU, carbon removed from the forest via harvest is over four times more than what is lost from natural disturbances, demonstrating the large influence timber harvests exert on forest carbon dynamics in Oregon. Previous studies have suggested that practices such as extending rotations or reducing harvest intensities may lead to carbon benefits via increased forest carbon stocks (Graves et al. 2020, 2022). Results from our scenarios focused on changing harvest practices show that this can increase carbon stocks in the near term (e.g., prior to harvest) but can also result in lower cumulative ecosystem productivity for these practices than under CBAU. This occurs as with our modeled growth and yield curves, extending rotations means maintaining stands past their asymptote in productivity, during which they sequester carbon at a slower rate than a comparable stand subject to the CBAU rotation assumptions (Randazzo and Gordon 2023). In addition, because average timber volumes are lower during the period of harvest deferral, harvest demands again have the potential to leak to neighboring states, counteracting a substantial portion of possible wood product sector emissions reductions.

The consequences of not pursuing climate-smart forestry

Without the application of climate-smart forestry practices, it will be challenging to minimize future carbon losses as Oregon's forests are severely impacted by changing climate conditions. Our results show that the forest ecosystem in the state has been a fairly consistent net carbon source from 2000 to 2021, primarily driven by large scale harvest removals and, in recent years, an increase in the area of high-severity wildfire. While harvest removals are not a direct emission of carbon to the atmosphere like decomposition or disturbance emissions, they none-the-less lower forest ecosystem carbon stocks as wood is transferred to the forest products sector, a major dynamic in net ecosystem carbon flux (**Box 2**). Harvests also lead to an increase in DOM, and thus future decomposition and/or pile burn emissions from the fraction of biomass harvested but not utilized. Under our projected future climate conditions as represented by the CBAU scenario, Oregon's forests will become even more of a consistent net source of carbon emissions as natural disturbances, declining productivity, and post-fire regeneration failure intensify across the landscape. **This drives substantial decreases in productive forest area (-37%, a loss of 11.1 million acres) and carbon stocks (-24%, a loss of 2.4 petagrams (equal to one billion metric tons) of carbon dioxide equivalent, or $PgCO_2e$; Table E2). Consequently, from 2022-2100 cumulative carbon emissions from forests are almost six times higher under CBAU than BAU.**

Projected losses in productive forest area (**Box 3**) are largely due to the combination of more frequent high-severity wildfire, regeneration failure following roughly 73% of those high-severity events (based

on our analysis of data from Davis et al. 2023a), and forest loss from land-use change. We distinguish here between total forest area, including forests in a state of post-fire regeneration failure, and productive forest area, which only includes forests actively growing and with the capacity to sequester carbon (but does not imply that all forests are equally productive in terms of net primary productivity (NPP) or productivity class). The increased frequency of natural disturbance events and regeneration failure also have implications for ecosystem carbon stocks, both in the near- and long-term. First, as the frequency of natural disturbance events increases, so too does the volume of carbon directly emitted during a disturbance (e.g., wildfire emissions). Second, in the years directly following a disturbance, there is an increase in ecosystem emissions from decomposition of snags and other DOM generated as the result of the disturbance. Finally, because a fraction of the forest enters a state of post-fire regeneration failure, statewide NPP - and thus the future ability of the forest to sequester additional carbon - will be reduced.

From 2022-2100, the annual area of high-severity wildfire is projected to increase by about 825%, leading to 58% higher direct disturbance emissions over this period than are projected under BAU. Despite increases in total wildfire area, direct disturbance emissions per acre are projected to decline over time as the result of loss of biomass and DOM stock densities during successive disturbances. Due to aggressive contemporary fire suppression coupled with loss of traditional ecological practices, forests in some ecoregions in Oregon are largely overstocked relative to their historical densities (Serra-Diaz et al. 2018; Knight et al. 2022; Bernal et al. 2022), meaning that when wildfires initially occur, there is a large volume of biomass and DOM available to burn. During subsequent disturbances, less of this biomass and DOM is available, and thus per acre emissions are lower.

All remaining productive forests in the CBAU simulation also experience declining productivity due to climate adaptation mismatch, which occurs because climate conditions are changing more rapidly than trees can adapt (Falk et al. 2022). This mismatch, mainly a moisture limitation, causes forests to accumulate biomass more slowly or experience higher rates of mortality because they are now poorly adapted to their current climate (Stewart and Wright 2023). Across Oregon, average forest productivity is projected to decrease by about 57% by 2100 due to climate adaptation mismatch (based on our analysis of data from Stewart and Wright 2023), further depressing carbon accumulation and net ecosystem carbon flux (even on otherwise undisturbed lands) and contributing to the forest's carbon source status in the future.

USFS lands – those within the National Forest System – along with Native American and privately owned forests bear the brunt of future climate impacts in our results. USFS lands are projected to lose 52% of their productive area from 2022-2100 (decreasing from 14.0 to 7.2 million acres) and 29% of their carbon stocks (decreasing from 5.1 to 3.6 $PgCO_2e$) over the same period. USFS lands are also projected to accumulate 4.8 million acres of post-fire regeneration failure area by 2100, which is 25% of statewide productive forest area in the same year. Overall, USFS lands make up roughly 61% of the total forest area and 63% of the total carbon stocks lost under the CBAU scenario and contribute 44% of the additional net ecosystem carbon flux expected under future climate conditions.

Private and Native American lands also experience significant impacts under the CBAU scenario, losing 30% of forest area (decreasing from 11.1 to 7.8 million acres) and 22% of carbon stocks (decreasing from 3.2 to 2.5 $PgCO_2e$) from 2022-2100, with 2.4 million acres of post-fire regeneration failure and 612% higher cumulative net ecosystem carbon flux by 2100. This large percentage increase in emissions is because forests in this ownership class switch from being a small net carbon sink under the BAU scenario to a large net carbon source under CBAU, mainly due to climate-related declines in productivity. Under CBAU, private and Native American lands account for 30% of total losses of

productive forest area, 30% of the total loss in carbon stocks, and contribute to 38% of the additional net ecosystem carbon flux expected under CBAU.

Forests in the West Cascades, Klamath Mountains, and East Cascades & Modoc ecoregions are projected to experience the greatest changes in forest area and carbon stocks due to climate change (**Box 3**). These three ecoregions experienced the highest amounts of high-severity wildfire during our BAU period (2000-2021), so our model assumes they will continue experiencing higher rates of wildfire and associated post-fire regeneration failure, driving changes in forest area and carbon. Consequently, by the end of the simulation, the area of post-fire regeneration failure is greater than the area of productive forest for the West Cascades (2.8 of 4.4 million total acres; 64%) and East Cascades & Modoc ecoregions (2.9 of 5.6 million total acres; 51%) and is 47% of the total forest area (1.4 of 2.9 million total acres) for the Klamath Mountains ecoregion.

The West Cascades ecoregion loses 68% of its productive forest area (from 4.9 to 1.6 million acres) and 24% of its carbon stocks (from 2.1 to 1.6 $PgCO_2e$) from 2022-2100 under CBAU. This large loss of productive forest area, combined with a projected 55% decline in productivity by 2100, means that from 2022-2100 the West Cascades ecoregion is projected to switch from being a net carbon sink to a net carbon source, accounting for 30% of the additional net ecosystem carbon flux across the entire state despite only making up 8% of total forest area.

BOX 2. CARBON METRICS

Net ecosystem carbon flux refers to the net yearly sequestration of carbon by forests across all ecosystem carbon pools, after accounting for decomposition, natural disturbance emissions, and wood product transfers. Net ecosystem carbon flux is presented from the atmospheric perspective, where negative numbers represent a net carbon sink (less carbon in the atmosphere) and positive numbers represent a net carbon source (more carbon in the atmosphere).

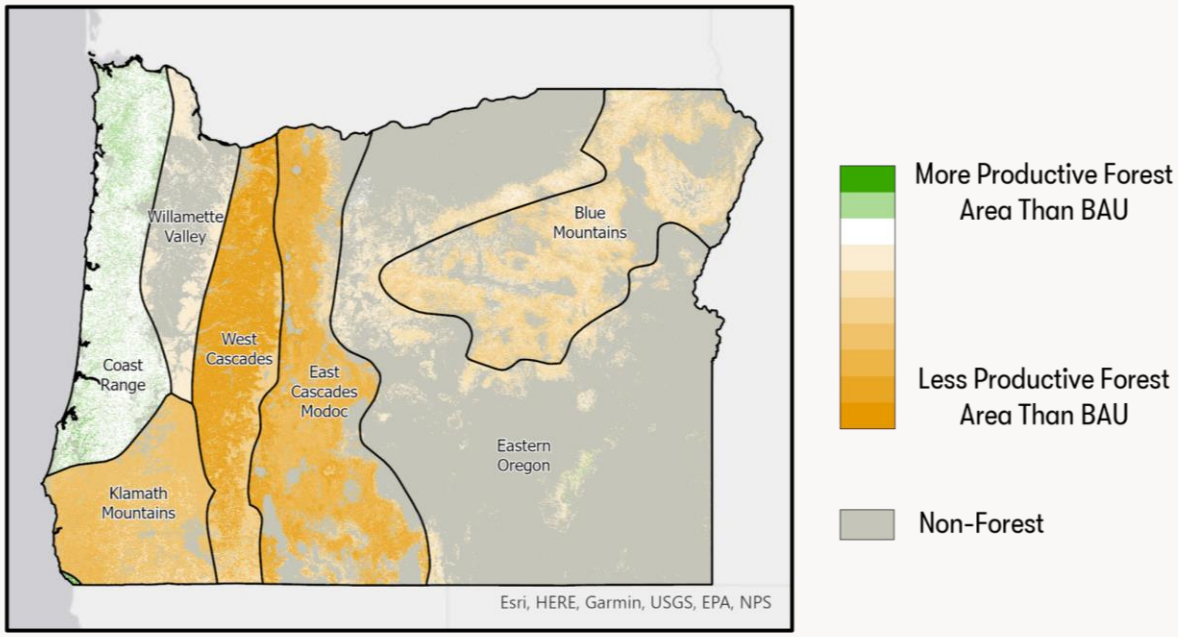
Net carbon balance includes net ecosystem flux in the forest, transfers to HWP, emissions from HWP in use and in landfills, substitution benefits (which can be positive or negative) in years where harvest is different than CBAU, and leakage in years where harvest is less than CBAU. Net carbon balance is presented from the atmospheric perspective, where negative values indicate carbon sequestered from the atmosphere and captured as carbon in forests and wood products (a net carbon sink) and positive values indicate carbon emitted to the atmosphere from forests and wood products (a net carbon source).

Similarly, the Klamath Mountains ecoregion loses 61% of its productive forest area (from 4.0 to 1.6 million acres) and 36% of its carbon stocks (from 1.6 to 1.0 $PgCO_2e$) from 2022-2100 in the CBAU scenario. As in the West Cascades ecoregion, substantial losses of productive forest area to post-fire regeneration failure and a 54% decline in productivity by 2100 mean that from 2022-2100 the Klamath Mountains ecoregion, which is a very slight net carbon sink under BAU assumptions, will switch to a net carbon source and account for 19% of the additional statewide net ecosystem carbon flux under CBAU.

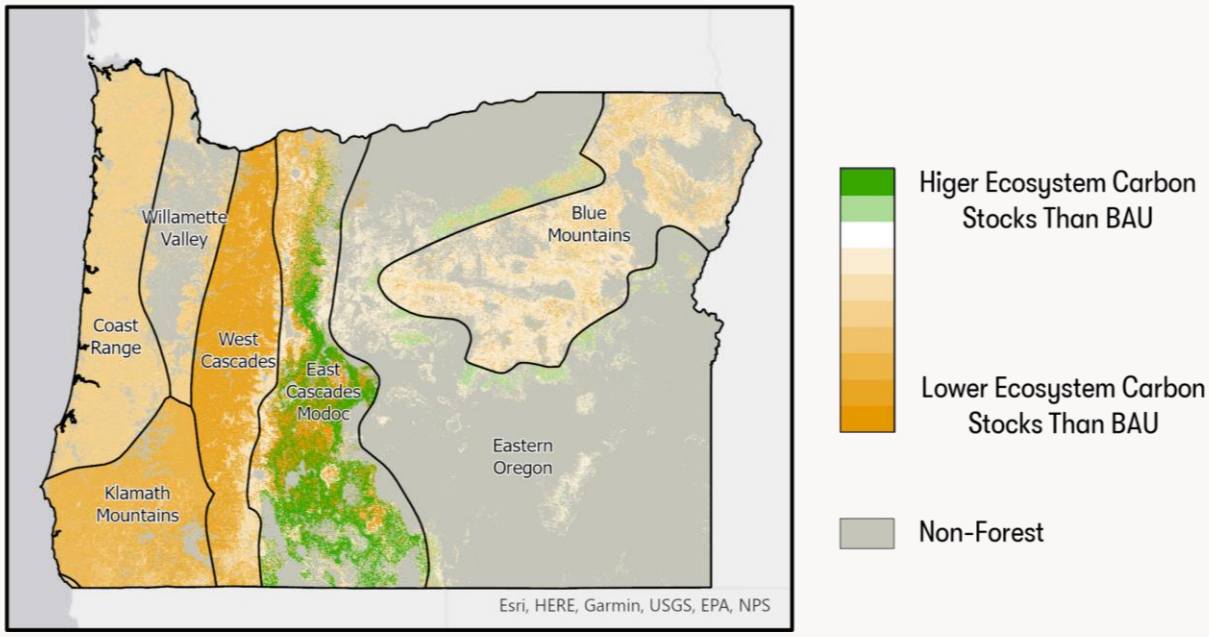
The East Cascades & Modoc ecoregion loses 57% of its productive forest area (from 6.5 to 2.8 million acres) and 34% of its carbon stocks (from 1.7 to 1.1 $PgCO_2e$) from 2022-2100 under the CBAU scenario. Interestingly, despite this large loss of productive forest area and an above average (60.3% vs 57.2%) projected decline in productivity, the East Cascades & Modoc ecoregion only accounts for 9% of additional statewide net ecosystem carbon flux under CBAU. This relatively small change may be due to the fact that even under BAU assumptions, the East Cascades & Modoc ecoregion is projected to be the largest net carbon source and thus has limited capacity for increased emissions from more frequent

BOX 3. PROJECTED CLIMATE IMPACTS ON PRODUCTIVE FOREST AREA AND ECOSYSTEM CARBON STOCKS

a) Difference in productive forest area between CBAU and BAU



b) Difference in ecosystem carbon stocks between CBAU and BAU



Differences in productive forest area and ecosystem carbon stocks, aggregated by ecoregion and forest type group circa 2019. The CBM-CFS3 is an aspatial model, where the exact locations of inventory records are not known or tracked, and inventory data are categorized by a series of *classifiers* that define relevant characteristics of the forest landscape (forest type group) or reference spatial units within the study area (ecoregion). This means that differences depicted here are not specific to an exact mapped location but rather represent dynamics across a grouping (ecoregion and forest type group) as a whole.

disturbances under the CBAU scenario. In addition, for much of the forest area in this ecoregion which burns but does not fail to regenerate, carbon stocks and productivity increase (**Box 3**), indicating that under current conditions these forests may have reached an age-related asymptote in net growth and productivity (mean stand age of 109 years old in 2022 vs the statewide average of 87 years old).

Overall, the ecoregions east of the Cascade crest (East Cascades & Modoc, Blue Mountains, Eastern Oregon) account for 41% of the loss of productive forest area and 45% of the loss of carbon stocks from 2022-2100 under CBAU. In addition, just 23% of the additional net ecosystem carbon flux in the CBAU scenario from 2022-2100 comes from these three ecoregions, each of which are a net carbon source under both BAU and CBAU. By contrast, the four west side ecoregions (Coast Range, Willamette Valley, Klamath Mountains, West Cascades) account for 77% of the additional net ecosystem carbon flux under CBAU, with two of four ecoregions (Coast Range and West Cascades) switching from a net carbon sink under BAU to a net carbon source in the CBAU scenario.

The benefits of expanding climate-smart forestry in Oregon

Depending on which CSF practice listed in **Box 1** is implemented, or how multiple management practices are concurrently applied across the landscape, CSF practices can accomplish up to a **45% decrease in annual emissions** from Oregon's forests over CBAU by 2100 (**Table E2**). This scale of potential emissions reductions from various CSF practices means that climate-smart forestry can help make significant progress towards Oregon's emissions reduction goals (Oregon Global Warming Commission 2023), and natural and working lands targets (Oregon Global Warming Commission 2021a). Though forests may not be able to act as a net carbon sink to offset emissions from other sectors, CSF practices like those modeled here, or others being investigated across Oregon (e.g., Rose and Coate 2000; Wightman, Gonzalez-Benecke, and Dinger 2019; Kim et al. 2017), can reduce net forest carbon emissions and confer other important landscape benefits.

In all scenarios modeled, forests and the forest products sector in Oregon remain a net carbon source from 2034-2100, as indicated by an annual *net carbon balance* above zero (**Table E2, Box 2**). However, several alternative management scenarios illustrate potential pathways to slow or reverse the influences of future climate on forest ecosystems, and when combined with alternative wood utilization, these pathways may offer progress toward CSF objectives. For example, in the Landscape Restoration scenario, the implementation of reforestation and restoration treatments in areas affected by post-fire regeneration failure, following a forecasted increase in high-severity wildfire, limits the decline of productive forest area to just -11% (3.4 million acres) rather than -37% (11.1 million acres) under CBAU (**Table E2**). Though net ecosystem carbon flux is higher than CBAU as a result of restoration treatments (an average of 25.2 $TgCO_2e\ yr^{-1}$ vs 18.4 $TgCO_2e\ yr^{-1}$ under CBAU), this is an expected behavior given the substantially increased wood product transfers from salvage logging. However, from a systems perspective, this increased removal of salvaged wood does not lead to direct carbon emissions, provided this wood is utilized in the forest products sector. Under our BAU wood utilization assumptions, most of this salvaged wood is expected to be used in durable lumber products, meaning the carbon it contains is effectively stored in the forest products sector for the lifetime of the product. In addition, when production of these products surpasses expected production under CBAU, these products can substitute for more emissions-intensive alternatives such as building materials produced from concrete and steel, further adding to emissions reductions under the Landscape Restoration scenario. Furthermore, the substantially higher growth rates in these newly restored forests push statewide productivity to be nearly 2.6% higher (on average 4.3 $TgCO_2e\ yr^{-1}$ more carbon sequestered through growth than CBAU), meaning that when these forests reach maturity, they may have sequestered much of the carbon that was emitted when the forest initially burned (on average 6.5 $TgCO_2e\ yr^{-1}$ of carbon emitted from all natural disturbance types). When taken together, these dynamics lead the Landscape Restoration

scenario to have a cumulative net carbon balance 45% lower (-475.7 $TgCO_2e$) than CBAU, meaning that from a whole system perspective this scenario leads to reduced emissions and increased carbon sequestration and storage relative to CBAU (**Table E2**).

Table E2. Comparison of change in forest area (million acres) and ecosystem carbon stocks ($TgCO_2e$) from 2022-2100, mean annual net carbon balance ($TgCO_2e\ yr^{-1}$), and cumulative net carbon balance ($TgCO_2e$) for our 23 modeled scenarios. Net carbon balance includes net ecosystem carbon flux in the forest, transfers to HWP, emissions from wood products in use and in landfills, substitution benefits in years where harvest is different than CBAU, and leakage in years where harvest is less than CBAU. Negative numbers for net carbon balance represent a net carbon sink and positive numbers represent a net carbon source. Negative numbers for % change from CBAU indicate lower emissions than CBAU, while positive numbers represent higher emissions than CBAU.

Scenario		Change in forest area 2022-2100 (million ac)		Ecosystem carbon stocks ($TgCO_2e$)		Average annual net carbon balance ($TgCO_2e\ yr^{-1}$)		Cumulative net carbon balance ($TgCO_2e$)	
		Productive forest area	Total forest area	2100	% change from 2022	2022-2050	2051-2100	2100	% change relative to CBAU
	BAU	-	-3.1	8,802.4	-14%	-6.4	-0.1	-322.5	-130%
	Climate-adjusted business-as-usual (CBAU)	-11.1	-3.1	7,674.3	-24%	5.2	21.2	1,062.4	-
Forest management scenarios	Wildfire Resilience	-4.0	-3.1	7,168.8	-29%	11.8	28.6	1,624.7	53%
	Pest Resilience	-11.1	-3.1	7,603.5	-24%	2.4	18.2	829.8	-22%
	Landscape Restoration	-3.4	-2.9	7,178.9	-29%	1.4	14.0	586.7	-45%
	Net Zero Forest Loss via Increased Afforestation (NZA)	-10.3	-2.2	7,876.5	-22%	3.9	19.7	948.6	-11%
	Net Zero Forest Loss via Decreased Deforestation (NZD)	-9.3	-1.0	8,281.2	-18%	4.9	20.8	1,029.2	-3%
	No Deforestation Outside of the Urban Growth Boundaries (UGB)	-7.4	+1.3	8,937.2	-11%	4.4	22.4	997.7	-6%
	Silvopasture	-10.4	-2.4	7,845.8	-22%	4.1	20.5	995.3	-6%
	80-Year Rotations	-11.1	-3.1	7,764.2	-23%	8.7	23.1	1,253.1	18%
	CMAI Based Rotations	-11.0	-3.1	7,762.9	-23%	8.8	23.4	1,227.1	20%
	Uneven-Aged Management	-11.1	-3.1	7,670.1	-24%	5.7	21.5	1,090.8	3%
Portfolios (combined scenarios)	Combined Resilience and Restoration (CRR)	-2.8	-2.8	7,171.3	-29%	7.6	24.7	1,298.9	22%
	Max Forest Area and Carbon (Max FAC)	-6.7	+1.9	9,195.7	-9%	7.2	22.1	1,160.3	9%
	Max Forests as Natural Climate Solutions (Max NCS)	+2.1	+2.3	8,525.9	-16%	13.0	26.5	1,549.3	46%
Alternate wood utilization scenarios	Wildfire Resilience + Innovative Wood Utilization	-4.0	-3.1	7,168.8	-29%	11.8	28.6	1,621.5	53%
	Pest Resilience + Innovative Wood Utilization	-11.1	-3.1	7,603.5	-24%	2.2	17.1	768.5	-28%
	CRR + Innovative Wood Utilization	-2.8	-2.8	7,171.3	-29%	7.3	23.6	1,234.3	16%

Table E2, cont. Comparison of change in forest area (million acres) and ecosystem carbon stocks ($TgCO_2e$) from 2022-2100, mean annual net carbon balance ($TgCO_2e\ yr^{-1}$), and cumulative net carbon balance ($TgCO_2e$) for our 23 modeled scenarios. Net carbon balance includes net ecosystem carbon flux in the forest, transfers to HWP, emissions from wood products in use and in landfills, substitution benefits in years where harvest is different than CBAU, and leakage in years where harvest is less than CBAU. Negative numbers for net carbon balance represent a net carbon sink and positive numbers represent a net carbon source. Negative numbers for % change from CBAU indicate lower emissions than CBAU, while positive numbers represent higher emissions than CBAU.

Scenario		Change in forest area 2022-2100 (million ac)		Ecosystem carbon stocks ($TgCO_2e$)		Average annual net carbon balance ($TgCO_2e\ yr^{-1}$)		Cumulative net carbon balance ($TgCO_2e$)	
		Productive forest area	Total forest area	2100	% change from 2022	2022-2050	2051-2100	2100	% change relative to CBAU
Alternate wood utilization scenarios	Max NCS + Innovative Wood Utilization	+2.1	+2.3	8,525.9	-16%	14.1	25.6	1,537.7	45%
	CBAU + Increased HWP Efficiency	-11.1	-3.1	7,647.3	-24%	1.9	18.1	805.6	-27%
	CRR + Increased HWP Efficiency	-2.8	-2.8	7,171.3	-29%	3.5	21.1	995.4	-6%
	Max FAC + Increased HWP Efficiency	-6.7	+1.9	9,195.7	-9%	6.5	20.3	1,041.5	-2%
	Max NCS + Increased HWP Efficiency	+2.1	+2.3	8,525.9	-16%	12.0	24.0	1,390.3	31%

The Wildfire Resilience scenario preserves a similar level of productive forest area as the Landscape Restoration scenario, limiting the decline of productive forest area to -13% (4.0 million acres; **Table E2**). This is accomplished via wildfire resilience treatments (including thinning and prescribed fire) which help to reduce the area of high-severity fire in treated areas. By design, these treatments also decrease ecosystem carbon stocks, leading to 5% (0.5 $PgCO_2e$) more carbon lost from 2022-2100 than CBAU. Despite this reduction in high-severity fire and associated emissions, the Wildfire Resilience scenario ends the simulation with a cumulative net carbon balance 53% greater (+562.3 $TgCO_2e$) than CBAU, meaning that from a whole system perspective this scenario leads to increased emissions and decreased carbon sequestration and storage relative to CBAU (**Table E2**). While this is not necessarily a desirable outcome from a climate mitigation prospective, there are other non-carbon co-benefits to this scenario which are not fully captured in the net carbon balance metric. These include decreased wildfire risks in mature and old growth forests (which may harbor unique habitats), preservation of existing forest habitats, improved human health outcomes from a reduction in wildfire smoke, greater economic stability for communities in fire prone areas, increased economic opportunities for local communities once dependent on timber revenues (Hjerpe et al. 2024), and an overall healthier and more climate-resilient forest landscape.

Many of these same non-carbon co-benefits also extend to the Pest Resilience scenario, which like the Wildfire Resilience scenario, sees resilience treatments implemented across a large portion of the forested landscape. Since these resilience treatments (which include forest thinning treatments with biomass removal) are focused on pests rather than wildfire, they do not meaningfully impact the loss of productive forest area relative to CBAU (**Table E2**). However, they do increase the loss of ecosystem carbon stocks by 1% (0.1 $PgCO_2e$ more carbon lost from 2022-2100 than CBAU) and cause a 6% increase in annual net ecosystem carbon flux (an average of 19.6 $TgCO_2e\ yr^{-1}$ vs 18.4 $TgCO_2e\ yr^{-1}$ under CBAU; **Table E2**). This increase in net ecosystem carbon flux comes from increased wood product transfers, as all pest resilience treatments include the removal of biomass after thinning (in place of more common disposal methods such as pile burning) as a means of reducing pest and pathogen vectors. Because we assume that this removed biomass is treated identically to any other harvest

removal (our BAU wood utilization assumptions), most of this biomass is converted into durable lumber products, leading to an increase in forest products sector carbon storage, as well as further emissions reductions from product substitution. Overall, the Pest Resilience scenario has a cumulative net carbon balance 22% lower (-232.6 $TgCO_2e$; **Table E2**) than CBAU. This means that in addition to providing additional resilience to future pest and pathogen outbreaks, the management actions contained within the Pest Resilience Scenario will lead the forest and forest products sector to become a net carbon sink relative to BAU management.

Other promising CSF practices focus on effects aside from natural disturbances. The Max Forest Area and Carbon (Max FAC) portfolio combines treatments for silvopasture, extended harvest rotations, and reductions in the rate of permanent forest loss to deforestation. This portfolio increases total forest area by 6% (1.9 million acres), and limits declines in ecosystem carbon stocks to -9% (-0.9 $PgCO_2e$) instead of -24% (-2.4 $PgCO_2e$) under CBAU (**Table E2**). As a result of these improvements, annual net ecosystem carbon flux is 23% lower (meaning lower ecosystem emissions) than CBAU from 2022-2100 (an average of 14.2 $TgCO_2e\ yr^{-1}$ vs 18.4 $TgCO_2e\ yr^{-1}$ under CBAU). However, despite these ecosystem carbon gains, the Max FAC portfolio has a net carbon balance 9% higher than CBAU, meaning that over the course of the simulation these management decisions will lead to 97.9 $TgCO_2e$ of additional emissions. These emissions largely come from leakage and product substitution. This occurs when altered harvest rotations and reduced deforestation lead to lower inputs to the forest products sector. Because we assume constant demand for HWP, if harvest is lower in Oregon, it is expected to increase elsewhere to compensate. In addition, where harvest demand cannot be met out of state, more emissions-intensive alternatives will be used in place of HWP, further increasing net carbon balance.

Improvements in efficiency within the forest products sector, along with novel wood products, can further improve carbon trajectories associated with forest management practices. For example, when paired with the Max FAC portfolio, policies aimed at increasing the lifespan and recycling rate of construction lumber and investing in the production of durable wood products such as mass timber and wood fiber insulation can reduce HWP emissions by 5% (-0.77 $TgCO_2e\ yr^{-1}$ on average). When these emissions reductions and an increase in product substitution are accounted for, cumulative net carbon balance is reduced by 118.8 $TgCO_2e$, making the Max FAC portfolio with increased HWP efficiency a net carbon sink (-20.9 $TgCO_2e$) relative to CBAU, though still a source (+235.8 $TgCO_2e$) relative to CBAU with increased HWP efficiency (**Table E2**).

Likewise, by prioritizing material removed from wildfire and pest resilience treatments in innovative wood products like lumber and biochar, further reductions in HWP emissions and net carbon balance are possible. For example, when paired with the Innovative Wood Products scenario, the Combined Resilience and Restoration portfolio (CRR), which combines treatments for pest resilience, wildfire resilience, and post-fire reforestation and restoration, has a cumulative net carbon balance 64.6 $TgCO_2e$ lower than when the same portfolio is assessed with BAU HWP assumptions (**Table E2**). This reduction in net carbon balance comes mainly from product substitution, where an increase in the production of lumber products is assumed to displace emissions associated with the production and use of non-wood alternatives such as plastic, linoleum, steel, and concrete.

These dynamics illustrate the potential of alternative HWP utilization to enhance the sink strength of Oregon's forest products sector beyond what would be possible if the current utilization scheme is maintained into the future. Expanded use of wood products and their substitution effects also indicate a potential pathway for maintaining current levels of emissions abatement, even if alternative management practices which increase emissions from the ecosystem through reduced productivity or increased decomposition emissions (e.g., wildfire resilience treatments) are implemented.

Other Considerations

The sooner these practices are implemented, the more impactful investments in CSF will be, especially when considering the global need for immediate climate action (IPCC 2022) and the potential to avoid the worst of future damages (e.g., permanent loss of forests to wildfire) and climate impacts. If wildfires and other natural disturbances ramp up in intensity following our CBAU scenario projections, high-severity wildfire acres will nearly double in the 2040s, and will be over 1200% higher by 2090 (Anderegg et al. 2022). **Increasing the pace and scale of restoration and resilience treatments before this intensification is in full swing is critical to reducing future natural disturbance impacts and fostering more carbon stability on the landscape.** This requires both a ramp up in the number of acres currently treated (414% increase in the annual area of thinning treatments and 84% increase in the annual area of prescribed burns) and an acceleration of the timeline over which these treatments must be carried out.

Building up this treatment capacity is critical not only for addressing current needs, but also for having the ability to respond to future needs and especially surge years like the 2020 and 2024 wildfire seasons. As restoration and reforestation needs are projected to grow across the landscape into the future, more investment will be needed in building capacity to close this gap (Dobrowski et al. 2024). The upcoming revision to OCAC's Natural and Working Lands Proposal and ODF's 20-Year Landscape Resiliency Strategy will provide two critical touchpoints to assess whether the scale of planned climate adaptation and mitigation plans meet this urgent need.

A major trend identified in our modeling and analysis is the influence of forest age and age class distribution on projected carbon outcomes. At a stand or landscape scale, aging forests often exhibit slowing rates of net growth and NPP, stemming from interacting competition and resource-use dynamics of individual trees (Binkley et al. 2002) and increases in mortality and stand-level respiration and decomposition (Gray et al. 2016; Xu et al. 2012; Foster et al. 2014; Coomes et al. 2012). While older forest stands tend to contain more carbon in biomass and DOM pools, they can also see diminishing potential for future biomass accumulation (Sleeter et al. 2018), a trend which has been extensively documented in productive forests in the Pacific Northwest (Gray et al. 2016).

These dynamics are central in the tradeoff between building and maintaining carbon storage capacity in the forest, and a desire for future carbon sequestration capacity to fuel further mitigation. As such, many forest management plans emphasize the need to maintain a somewhat balanced age class distribution across the forested landscape, to ensure continued carbon sequestration capacity while also safeguarding established mature forests which store large amounts of carbon in live biomass and stable DOM pools. These mature forests also provide critical co-benefits such as wildlife habitat and water resource stability (Ferrare, Sargis, and Janowiak 2019; Seidl et al. 2016; USDA Forest Service 2023b; Davis et al. 2022; Pelz et al. 2023; Vangi et al. 2024; Clifton et al. 2018).

Our results suggest that Oregon has the potential to rapidly lose its current age class distribution, as under CBAU projections, almost half of the productive forest area will be 140 years old or greater by 2100 (the upper limit for harvest eligibility in our model), compared with just 18% in 2000. While maintenance and expansion of mature forest area is a stated policy priority for many forest management plans in the Pacific Northwest (with these management plans propagated into our CBAU scenario), when such a large fraction of the forest grows beyond its growth and productivity asymptote (which typically occurs in forests 80-120 years old), average statewide productivity is expected to weaken. This weakening of overall productivity, combined with projected increases in emissions from decomposition, is expected to further drive the forest's carbon source status into the future.

Wildfire resilience treatments are expected to compound these trends, by reducing a major source of periodic stand-replacing disturbance, thereby further allowing a large fraction of Oregon's forest to shift into an older age class (mean forest age +18 years relative to CBAU). These effects of wildfire resilience treatments on stand age and productivity are expected to be the strongest in forests currently managed by the USDA Forest Service in the East and West Cascades ecoregions, accounting for over 58% of the overall difference in productivity from CBAU by 2100, and with mean stand ages +23 and +69 years (respectively) greater than the statewide average. Maintaining a stable age distribution in these forests, which are under the jurisdiction of the Northwest Forest Plan, may require active management such as regeneration harvests or periodic thinning in areas currently designated as reserves. While we did not model any scenarios which explicitly maintain or promote a balanced age class distribution across the landscape, our results suggest that such considerations should be top of mind when assessing the feasibility of implementing any of the CSF practices examined in this study.

We also did not directly model or assess the impacts of the large-scale Douglas-fir (*Psuedotsuga menziesii var. menziesii*) die-off currently occurring in Southwest Oregon (Bennett and Adlam 2023). This die-off is predicated by stress from warmer and drier climates, which exposes Douglas-fir trees to increased forest vulnerability to secondary mortality agents such as the flatheaded fir borer (*Phaenops drummondi*) or other biotic and abiotic stress factors, particularly in the Klamath Mountains ecoregion (Bennett et al. 2023). While we did model projected declines in productivity and climate-modified natural disturbance events as part of our CBAU and subsequent scenarios (**Table E1**), we did not specifically incorporate data on Douglas-fir die-off, in part as the rate of die-off has increased substantially since 2022, while our model's "historical" observation period covers 2000-2021 (Buhl et al. 2024; Cline et al. 2025). Current projections indicate that Douglas-fir die-off could radically alter DOM dynamics, decrease productivity, and increase fire risk across Southwestern Oregon (Bennett and Adlam 2023; Bennett et al. 2023), potentially exposing the forest to a loss of ecosystem carbon stocks beyond what was modeled in our assessment.

The assumptions made in constructing each scenario represent one of many possible ways to implement each forest management and wood utilization practice. Where these assumptions are inaccurate for local conditions, actual climate mitigation results will vary. Our scenarios represent simplified versions of likely future dynamics intended to support forest management and policy decision makers in understanding the climate mitigation potential of forests in Oregon. We do not make assumptions based on the feasibility of implementing each modeled management practice; rather, we focus on our state partners' objectives for forest management and land use and offer our assessment of the climate benefits of a given implementation level. Each practice should be further examined for biophysical, social, and economic feasibility by land managers and decision makers in planning and policymaking processes. This is especially important for management practices which increase the transfer of wood to the forest products sector, as we assume that any additional material, regardless of where in the state it is harvested, can be utilized while maintaining the current timber product production and export ratio. For novel product pathways, we have designed a gradual increase in product production, but we acknowledge that these assumed timelines may not fully align with what is feasible given current and projected market dynamics and production capacity.

The practices listed in **Box 1** are considered climate-smart because they balance both carbon storage and sequestration rates with forest health and resilience. However, a "one size fits all" approach may not be appropriate for Oregon, especially across the diversity of forest types and biophysical settings in the state. Focusing primarily on preserving existing ecosystem carbon storage and sequestration may not lead to lasting mitigation in the face of climate change, and as modeled in older stands in the West Cascades, East Cascades and Modoc and Klamath Mountains ecoregions, carbon stocks and forest productivity may reach a saturation point beyond which additional climate mitigation benefits

diminish. Further, in this modeling framework, for Landscape Restoration treatments to provide mitigation benefits, the forest must incur an upfront cost (high-severity wildfire and post-fire regeneration failure), which can have catastrophic consequences for local habitats, human health, and property values. Likewise, any strategy which focuses primarily on increased harvest levels as a means of storing additional carbon in durable wood products may come at the cost of future forest health, ignoring essential ecosystem services forests provide. To make the necessary progress in mitigating climate change through CSF practices, forests in Oregon must both maintain their current carbon stores and sequester as much additional carbon from the atmosphere as possible.

Oregon may work to achieve these outcomes by adjusting management priorities and interventions on public lands, promoting forest markets aligned with the scale and type of active forest management activities in CSF scenarios, and through education, incentives, and engagement with consulting forestry professionals to reach private actors. Given the strong impacts of climate change projected in our CBAU scenario on USFS, private, and Native American lands, coordinating resilience and restoration treatments across both public and private forests with these land managers will be key. Given the large modeled benefits from post-fire reforestation, essential actions here include building more robust seed and seedling supply chains, developing a year-round workforce of reforestation professionals, and sharing information about reforestation needs and progress through centralized, cross-agency data hubs. Focusing on resilience treatments in the West Cascades, East Cascades and Modoc, and Klamath ecoregions will also be crucial for minimizing future forest carbon losses from those areas. Future projections for Oregon are not optimistic, with a continuation of business-as-usual management leaving forests vulnerable to future climate and wildfire impacts (losses of 24% of forest area and 37% of forest carbon) potentially destabilizing the future climate mitigation potential of forests in the state. To prepare for this future, and maintain forest health and carbon storage, Oregon must consider what balance of climate adaptation, mitigation, and resilience is most appropriate, how widespread these actions will be, and critically - as the cost of inaction will be significant - over what timeframe they should be carried out.

Introduction

Forests as a Natural Climate Solution

Climate change presents a global challenge to society and the ecosystems we rely on. In turn, forests have become increasingly important in international climate change dialogue, as seen in the Paris Agreement, the COP26 Glasgow Leaders' Declaration on Forests and Land, and the Intergovernmental Panel on Climate Change (IPCC) Sixth Assessment Report (COP26 2021; Popkin 2019; Calvin et al. 2023). There is also increasing scholarly recognition of forests' importance as a nature-based solution to climate change, and also as a natural climate solution (NCS; Drever et al. 2021; Griscom et al. 2017; Fargione et al. 2018; Ellis et al. 2024; Buma et al. 2024).

High-level NCS assessments have considered various potential nature-based climate solutions both in terms of opportunity scale (e.g., metric tons of carbon dioxide equivalent, or tCO_2e) and cost of implementation. Results of these assessments at the international (Griscom et al. 2017; Buma et al. 2024) and US national levels (Fargione et al. 2018) point to forested land as the dominant opportunity, through reforestation and sustainable management practices, for nature-based climate change mitigation by reducing emissions and increasing carbon sequestration from the atmosphere. The overall climate mitigation benefit of the forestry sector is determined not only by the trees growing in a forest, but also by what they are used to produce (i.e., harvested wood products, HWP) and how HWPs are used and ultimately retired. The largest NCS opportunities for forests typically come through reforestation, forest conservation, or forest management pathways (Griscom et al. 2017; Fargione et al. 2018; Drever et al. 2021; Buma et al. 2024), which can include long-term carbon storage in HWP such as mass timber (Xie et al. 2021). However, these benefits can be constrained or even negated in fire-prone ecosystems if wildfire hazards and the intensity and frequency of wildfire impacts on forests are not curtailed (Jerrett et al. 2022).

US forests and the forest products sector already play an important role in mitigating climate change, a benefit which can be significantly impacted by forest management decisions and policies. In 2023, US forests and forest products captured and stored nearly 889 teragrams of carbon dioxide ($TgCO_2e$), enough to offset nearly 20% of carbon emissions from fossil fuels in that same year (EPA 2025). Almost 90% of this climate benefit was provided by existing forests and forest products, and assessments of NCS potential indicate that we could nearly double the carbon-capturing power of forests with the right set of actions (Fargione et al. 2018). However, this carbon savings potential is expected to decrease in the future due to ageing forests, forest loss, and forest health declines fueled by the effects of climate change, like increasing drought severity and tree mortality (Wear and Coulston 2015; Oswalt et al. 2019).

To maintain and strengthen the NCS capacity of forests, future management and policy decisions will need to mesh mitigation goals with adaptation to future climate conditions. This dynamic is central to the concept of *climate-smart forestry (CSF)*, a sustainable forest management approach that seeks to balance the ability of forests to adapt to and mitigate climate change while continuing to provide fundamental wood products and ecosystem services (Nabuurs et al. 2018; Bowditch et al. 2020; Verkerk et al. 2020). This approach acknowledges the importance of maintaining or increasing carbon storage in forests and forest products as a natural climate solution but also emphasizes the need for robust carbon sequestration rates to continue to draw carbon out of the atmosphere as part of a global effort to mitigate climate change. CSF techniques focus on long-term forest health and resilience in the face of climate change as part of sustainability in forest management, and they aim to accomplish all these goals while supporting a strong forest products sector. According to the IPCC, meeting our global climate goals is not possible without forests (Calvin et al. 2023), and forests need the health and

resilience benefits provided by CSF to play their part. Therefore, the most promising future NCS practices for forests will need to follow a CSF approach.

Assessing Forest Climate Benefits in Oregon

The state of Oregon first set greenhouse gas (GHG) emissions reduction goals in 2007 (ORS 468A.205), which requires the state to reduce GHG emissions to at least 75% below 1990 levels by 2050. This goal was updated in 2020, when Governor Kate Brown issued Executive Order 20-04 (Brown, 2020), and was most recently modified in the Oregon Climate Action Commission's (OCAC, known as the Oregon Global Warming Commission until 2024) Roadmap to 2030 (Oregon Global Warming Commission 2023), which sets a target of a 95% reduction below 1990 levels by 2050. Within the Roadmap to 2030, OCAC clarifies that natural and working lands, including forests, should have a set of sequestration goals separate from, and in addition to, Oregon's sector-based emission reduction targets. These goals, as outlined in the 2021 Natural and Working Lands Proposal (Oregon Global Warming Commission 2021a), are to sequester at least an additional 5 $TgCO_2e$ per year in Oregon's natural and working lands and waters by 2030, and at least 9.5 $TgCO_2e$ per year by 2050, relative to a 2010 to 2019 activity-based, business-as-usual net carbon sequestration baseline, representing a 23% and 44% increase respectively. OCAC further estimates that between 2001 and 2016, Oregon's forests and forest products sector sequestered a net of 21.7 $TgCO_2e\ yr^{-1}$ (Oregon Global Warming Commission 2021a), and that additional sequestration may be possible through a combination of actions which minimize carbon losses from future climate impacts, prioritize CSF management, and provide technical and financial support for forest landowners (Cathcart et al. 2007; Law et al. 2018; Latta et al. 2016; Graves et al. 2022). However, without proactive management, there is uncertainty in the long term viability of Oregon's forests acting as a net carbon sink, largely due to projected declines in forest health fueled by the effects of climate change (Wear and Coulston 2015; Oswalt et al. 2019; Halofsky et al. 2022).

Spurred by the urgent threat of climate change to forest and non-forest lands alike, Oregon and other US states are striving to develop policies and programs that lower GHG emissions, maintain current carbon storage, increase stored carbon pools, and enhance sequestration rates. As part of this push, more states are supporting lateral efforts (e.g., participating in the US Climate Alliance) and undertaking assessment, planning, and monitoring within their jurisdictions to support climate policies and targets like those mentioned above. Given the NCS power and potential of forests, states like Oregon are exploring measures to demonstrate, promote, and support an active sustainable forest industry and are considering options for increasing the role of forests and HWP in state climate mitigation plans.

This report is designed to guide Oregon toward identifying promising CSF practices and to encourage the inclusion of forests and the forest products sector in state-level climate action planning. Here, we present comprehensive forest sector carbon modeling results for a broad range of forward-looking forest management and innovative wood utilization scenarios and assess the carbon sequestered in forests and stored in HWP for each one, along with an analysis of potential leakage impacts and the substitution benefits from using wood in place of other emissions-intensive materials. These results will provide information about forest climate mitigation and adaptation opportunities that can integrate with and inform statewide efforts, including OCAC's Roadmap to 2030, OCAC's Natural and Working Lands Goals, and the Oregon Department of Forestry's (ODF) Landscape Resiliency Program and 20-Year Landscape Resiliency Strategy (Oregon Global Warming Commission 2023, 2021a; Oregon Department of Forestry 2023a). By leveraging this work with a related study being conducted for California and other regional collaboratives like the Pacific Northwest Research Station Carbon Initiative (USDA Forest Service 2023a), Oregon and partners can learn about regionally shared forest management challenges and goals and collaborate to develop effective management and policy strategies.

Research and Modeling Process

Following previous work (Dugan et al. 2018, 2019, 2021; DeLyser et al. 2022a, 2022b; Papa et al. 2023; DeLyser et al. 2025), we assess carbon trends and management scenarios in the forest ecosystem and forest products sector for Oregon utilizing a systems-based approach. This systems approach accounts for the influence of forest management activities beyond the forest itself and allows us to examine potential trade-offs or synergies between management strategies that enhance forest ecosystem carbon stocks, HWP volumes, or other important forest ecosystem services (Dugan et al. 2018). Our scenario development and modeling process includes:

1) Consultation with state agency staff and forestry experts to understand forest management priorities, concerns, and goals in Oregon, based on current conditions and a landscape resilience needs assessment;
2) Development of business-as-usual (BAU) and climate-adjusted BAU (CBAU) scenarios, and alternative forest management scenarios – including forest management, natural disturbance, and land-use change – to project future forest carbon trends under various management practices and future climate conditions;
3) Scenario modeling with i) a growth and yield-based forest ecosystem model - the Carbon Budget Model of the Canadian Forest Sector (CBM-CFS3) - parameterized for conditions in Oregon, ii) a customized harvested wood products dynamics model (CBM-HWP-OR) built using the Abstract Network Simulation Engine (ANSE) framework, iii) potential leakage factors applied to changing harvest rates, and iv) displacement factors to evaluate substitution benefits from using wood products and bioenergy in place of more emissions-intensive materials; and
4) Engagement and discussion with state agency staff to explore modeling results and consider implications for Oregon.

The sections below summarize our process for each of these steps. Specific data sources and model parameterization methods can be found in the **Appendix**.

Systems-Based Forest Carbon Modeling

Forest Carbon Accounting

Trees capture carbon as they grow, which then cycles through various components of the forest. Accrual of carbon in the forest ecosystem also depends on accumulation of dead wood, leaf litter, and soil (Smith et al. 2006), as well as decomposition – all complicated dynamics that affect the carbon sequestration and storage potential of forests. Here, *carbon storage*, or *carbon stocks*, refers to the amount of carbon physically held by living and dead trees, contained in the soil and forest floor material, and carried in wood products throughout the economy (**Figure 1**). *Carbon sequestration*, or *carbon flux*, refers to the annual rate of carbon capture from the atmosphere by forests, affected by rates of tree growth, mortality, decomposition, and disturbance. Forests that sequester and store more carbon than they release from decomposition, respiration, harvest removals, and emissions from disturbance (e.g., wildfire) each year represent a *net carbon sink*; conversely, forests that release more carbon than they sequester and store become a *net carbon source*.

To understand the role forests can play in mitigating climate change, we need accurate assessments of these forest carbon dynamics and interactions with other sectors. The systems approach used in this analysis provides a comprehensive look at not only the forest ecosystem dynamics at play, but also interactions with land-use change, the forest products sector in terms of emissions from wood products

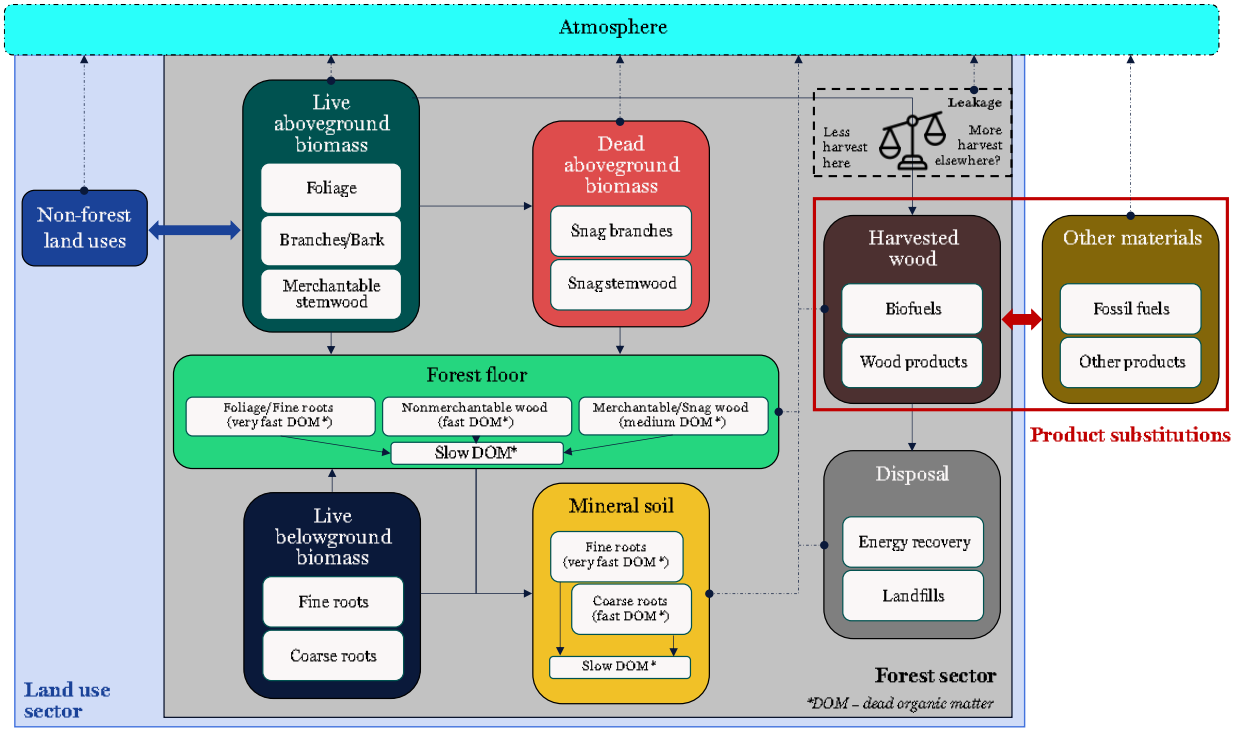


Figure 1. Simplified systems view of land uses and sectors influencing forest carbon stocks and sequestration. The forest sector (gray box) shows the forest carbon pools and transfers used in the CBM-CFS3 and CBM-HWP-OR models. For DOM (dead organic matter) pools, "very fast", "fast", "medium", and "slow" refer to various decomposition rates of dead organic matter in the forest ecosystem. Transfers between the land use sector (blue box) and the forest sector (gray box) represent land use changes (either forest loss or forest gain). Leakage (black dashed outline) represents the potential for harvest activities and associated emissions to leak outside of the accounting system boundaries (i.e. to the neighboring state) in response to decreased harvest within the system. Product substitutions (red outline) represent the use of harvested wood in place of other materials in the economy. Adapted from Kull et al. 2019 and Nabuurs et al. 2007.

while in use and during disposal, potential leakage from changing harvest rates, and substitution of wood products in place of more emissions-intensive materials (**Figure 1**). Excluding any one of these components would lead to an incomplete accounting of forest carbon, misrepresenting net forest emissions and climate mitigation potential – therefore, a systems approach is necessary (Smith et al. 2006; Dugan et al. 2018; Kurz et al. 2009; Nabuurs et al. 2007). Our approach follows IPCC Tier 3 Good Practice Guidance for systems-level accounting of forest carbon, which allocates emissions from harvest, transportation, and manufacturing of HWP to other sectors rather than the forestry sector (Kurz et al. 2009), so these elements are not included in this analysis. We also follow IPCC's production approach, meaning we report carbon in forests and trees grown in Oregon and their ultimate destination as HWP (including exports) but do not consider carbon from out-of-state trees that are later imported and used in-state.

CBM-CFS3 partitions carbon into 14 ecosystem pools, including living vegetation (above- and belowground biomass), dead wood (biomass in standing dead, downed wood, and forest floor material), and soil carbon (**Figure 1**). Ecosystem carbon moves from live trees to downstream pools and the atmosphere in each year of the model, representing typical flows in the forest carbon cycle and creating an annual carbon budget for the forest sector. Carbon can enter or leave this budget as land transitions between forest and alternative land uses (though changing the land-use classification from forest to non-forest, for example, does not necessarily mean that all carbon is immediately emitted – instead, it has moved into the carbon budget for a different sector). Carbon can also leave the forest through harvested wood, which is further assessed for storage and emissions through its usage (in wood products

and energy), decay, and end of life (e.g., landfill storage and wood energy) via the CBM-HWP-OR model. Wood products from sustainable forest management that are used in place of more emissions-intensive products like concrete and steel are also counted as a NCS by providing renewable and lower-emissions materials alternatives (McKinley et al. 2011). If harvest levels decrease within the system boundary, there is a chance that harvest activities and associated emissions will increase, or "leak" outside the system to make up for any unmet HWP demand (Nabuurs et al. 2007). Our methodology, and common practice in carbon offset protocols (Haya et al. 2023), requires we also account for this possibility of leakage.

In this analysis, we calculate various metrics to represent these dynamics and determine the carbon sink or carbon source status of forests and the forest sector. *Net ecosystem carbon flux* refers to the net yearly sequestration of carbon by forests across all 14 ecosystem carbon pools, after accounting for decomposition, natural disturbance emissions, and wood product transfers from the ecosystem to the forest products sector. Net ecosystem carbon flux is presented from the atmospheric perspective, where negative numbers represent a net carbon sink (less carbon in the atmosphere) and positive numbers represent a net carbon source (more carbon in the atmosphere). We combine net ecosystem carbon flux with carbon storage and emissions from HWP, potential leakage, and substitution benefits to calculate the *net carbon balance* of the forest sector. Net carbon balance presents the system-wide view of carbon dynamics and is therefore the final metric used to assess the climate mitigation potential for each of our modeled scenarios.

Forest Ecosystem Model

CBM-CFS3 is an operational-scale carbon model designed to simulate the dynamics of forest carbon stocks over time, following guidelines and carbon pools established by the Intergovernmental Panel on Climate Change (Kull et al. 2019; Kurz and Apps 1999; Kurz et al. 2009). The model has had wide applications within Canada (Kurz et al. 2013, 2018; D. E. Foster et al. 2024), the United States (Dugan et al. 2018, 2019, 2021; DeLyser et al. 2022a, 2022b; Papa et al. 2023; DeLyser et al. 2025), and internationally (Olguin et al. 2018; Pilli et al. 2013, 2015, 2017, 2022; Cienciala and Melichar 2024) while being thoroughly evaluated against ground plots (Shaw et al. 2014) and with respect to model uncertainty (Metsaranta et al. 2011, 2017). Though originally developed for Canadian forest conditions, CBM-CFS3 is widely customizable and can be parameterized with location-specific data; for this analysis, we use state-specific data from the US Forest Service's Forest Inventory and Analysis (FIA) Program (USDA Forest Service 2021a) to ensure accuracy for Oregon forests. We used CBM-CFS3 for this study at the request of Oregon Department of Forestry staff, to expand on and maintain consistency with other modeling efforts conducted by our team in 6 additional states – Maryland, Pennsylvania, Minnesota, Michigan, Wisconsin, and California (DeLyser et al. 2022a, 2022b; Papa et al. 2023; DeLyser et al. 2025). CBM-CFS3 additionally provides more specificity for land managers than other models used in forest carbon modeling (e.g., CARB 2022a), as described below.

CBM-CFS3 utilizes forest inventory data and empirically derived growth and yield curves, in combination with schedules of management activities, natural disturbances, and land-use change, to calculate forest carbon trends throughout a simulation (**Figure 2**). The forest inventory is spatially referenced (i.e., aspatial) rather than spatially explicit, meaning that exact locations of inventory records are not known or tracked. Instead, inventory data are categorized by a series of *classifiers* that define relevant characteristics of the forest landscape (i.e., forest type, ownership, or productivity class) or reference spatial units within the study area. For this analysis, we report data aggregated by ecoregion, ownership, and forest type (**Figure 3**; see **Appendix** for full list of classifiers used in this project).

These classifiers are also used to develop specific volume-age curves, or yield curves, so that growth and yield trends can be appropriately linked to inventory records in the simulation. This step accounts for evident differences in growth and yield for various classifiers (especially those like forest type and productivity class) in Oregon, affecting the current performance of these forests and the climate mitigation potential of management activities tied to these classifiers (Christensen et al. 2021). CBM-CFS3 uses allometric equations to predict wood volume-to-biomass relationships during model runs (Boudewyn et al. 2007), which have been customized for this project to best match to Oregon tree species. Finally, CBM-CFS3 uses default equations to simulate dynamics between soil, dead organic matter (DOM), and forest processes like litter fall and decomposition (Kurz et al. 2009).

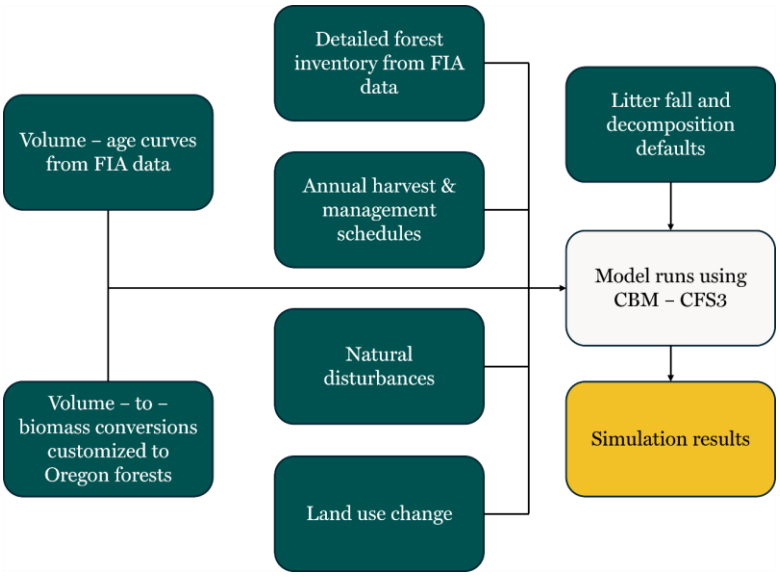
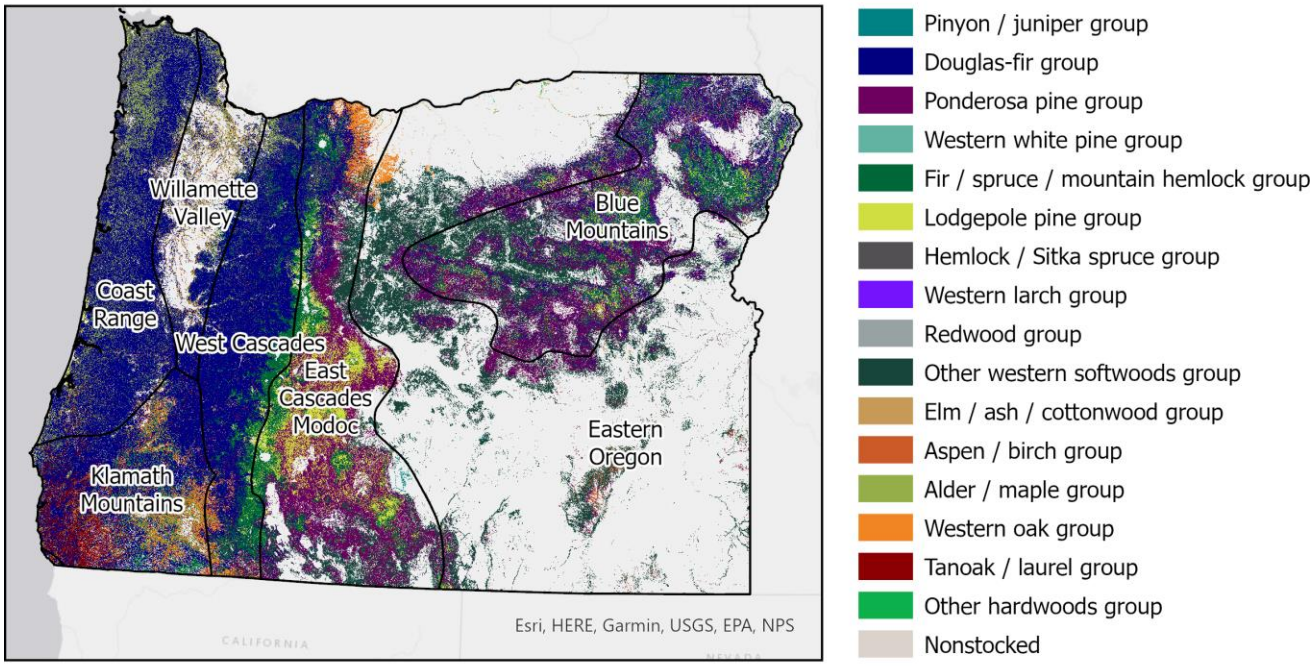


Figure 2. Modeling inputs and process for CBM-CFS3. Adapted from Kull et al. 2019.

Management and natural disturbance data are also necessary inputs – CBM-CFS3 does not independently predict future events but instead follows a user-determined schedule of annual management, natural disturbance, and land-use change events (collectively termed *disturbances*) for the simulation period. Disturbances can be targeted to certain classifiers and stand ages as appropriate. In addition to the disturbance event schedule, CBM-CFS3 utilizes *disturbance matrices* to represent specific impacts of each disturbance event on tree mortality, carbon transfers between pools, carbon transfers to the forest products sector, and carbon emissions to the atmosphere (Kurz et al. 2009).

For this analysis, we use FIA data (USDA Forest Service 2021a) for our inventory, yield curves, volume-to-biomass equation calibration, and disturbance stand age limits. Historical forest management data for 2000-2021 come from ODF's Forest Activity Electronic Reporting and Notification System (Oregon Department of Forestry 2022b), USDA Forest Service's Forest Service Activity Tracking System (USDA Forest Service 2021b), LANDFIRE (USGS 2016), and ODF's Burning and Smoke Management Reports (Oregon Department of Forestry 2022a). Historical wildfire footprints and severity data come from Monitoring Trends in Burn Severity (MTBS 2020), and the Rapid Assessment of Vegetation Condition after Wildfire Program (RAVG 2021). We use disturbance footprints and severity information for insects, disease, and abiotic disturbances from aerial surveys conducted by Forest Health staffs of ODF, Washington Department of Natural Resources, and the USDA Forest Service Pacific Northwest Region (Oregon Department of Forestry 2023b) as well as data from LANDFIRE (USGS 2016). We use data from the National Land Cover Database (NLCD; Dewitz and USGS 2021) to assess historical land-use change trends. The disturbance matrices used for this study have been customized to Oregon forest conditions and practices. See **Table 2** in the **Developing Modeling Scenarios** section for BAU and CBAU ecosystem disturbance parameters and the **Appendix** for more information on data and assumptions used in model parameterization.

a) Forest Type Groups



b) Ownerships

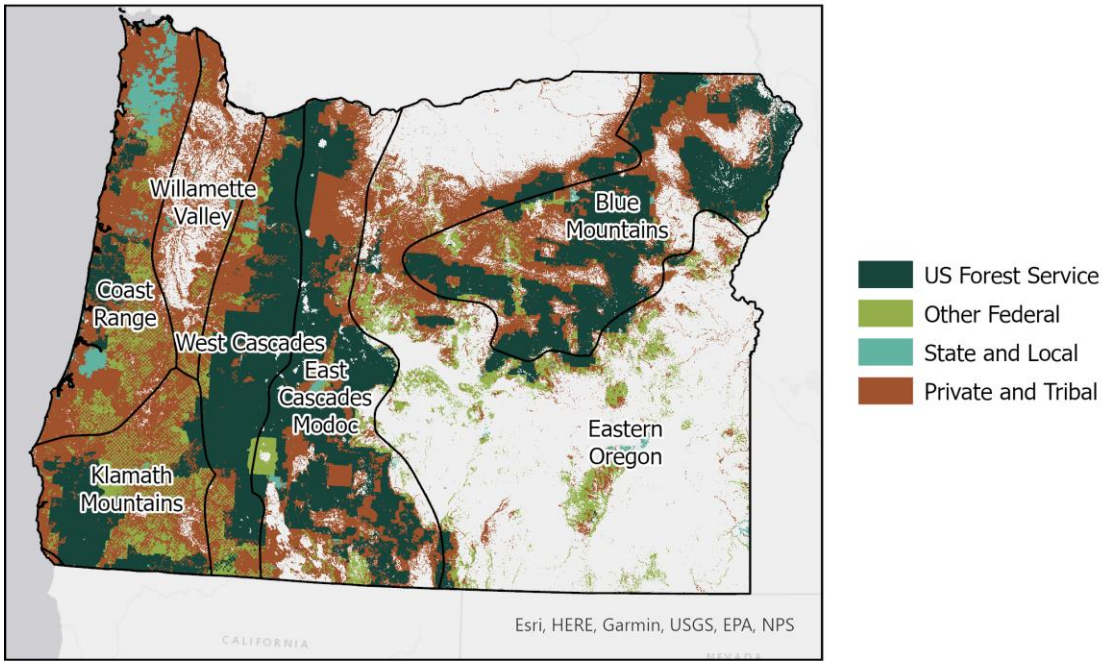


Figure 3. Maps of forest cover by a) forest type group and b) ownership for Oregon. Ecoregion boundaries are defined for both panels. Ecoregions depicted here are an aggregation of the USDA Ecological Sections and Subsections from Cleland et al. (2007). Forest Type Group data are adapted from GNN forest structure maps developed by LEMMA (2022). Land ownership data come from the Oregon Department of Forestry (2016) and are grouped according to relevant FIA ownership codes.

Harvested Wood Products Model

To calculate and assess carbon stored by, and GHG emitted from, forest products across diverse forest management scenarios, we employed the CBM-HWP-OR model. This model was built using the ANSE modeling framework, a carbon accounting tool developed by the Canadian Forest Service (CFS) and used for Canada's national GHG inventory reporting in tandem with CBM-CFS3 (CFS 2024). This framework facilitates tracking, modeling, and calculating carbon storage and emissions in the forest products sector associated with HWP from both historical and projected future harvest activities. Emissions from other related sectors, such as transportation and manufacturing of HWP, are not included in this framework. The CBM-HWP-OR model contains custom modeling flows and parameters, e.g., roundwood export proportions and destinations, commodity production proportions, product half-lives, wood recycling rates, and displacement factors, specific to Oregon products and markets.

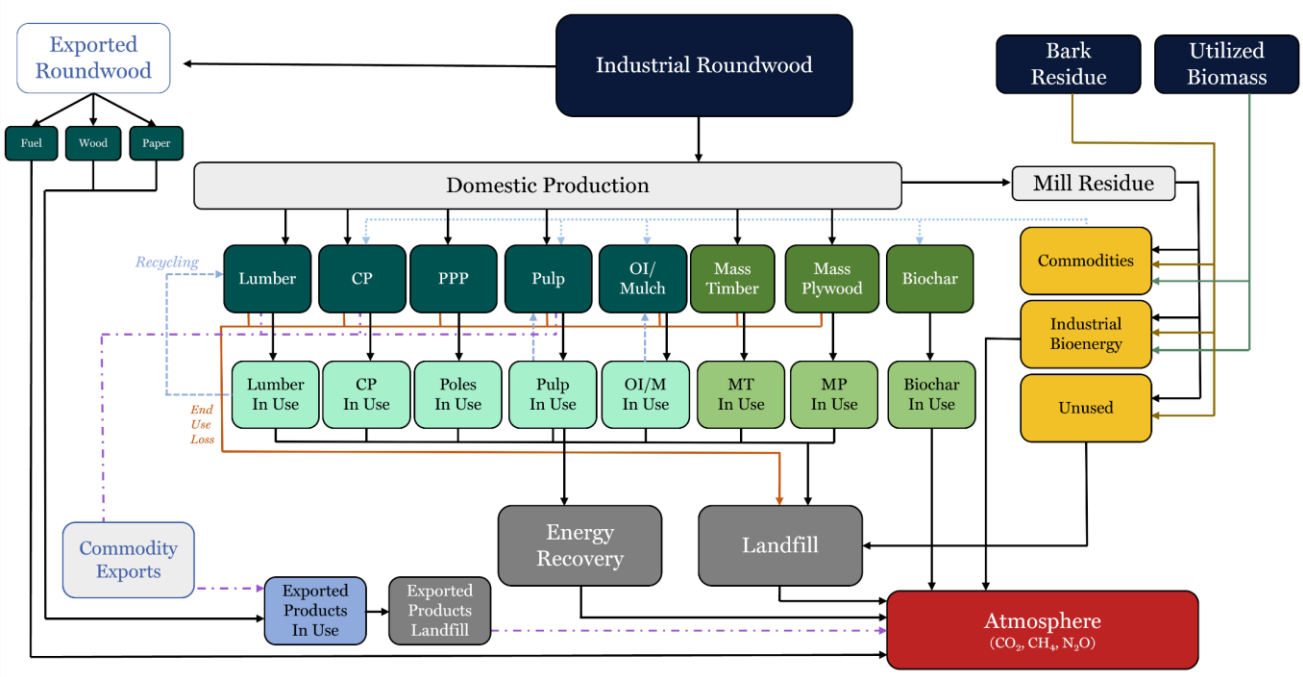


Figure 4. Pathways for carbon in harvested wood products in the CBM-HWP-OR model, which is used for analysis of the fate of harvested carbon in Oregon. HWP pool abbreviations are as follows: CP = composite panels, PPP = poles posts and pilings, OI = other industrial products. Mass Timber, Mass Plywood, and Biochar categories are included for alternative wood utilization scenarios and do not represent current active industries in Oregon.

Some *disturbance events* (particularly, though not exclusively, harvest events) in CBM-CFS3 transfer carbon to the forest products sector, providing annual wood removal volumes in units of carbon which in turn become the primary data input for the CBM-HWP-OR model. These carbon inputs are partitioned into various HWP streams based on current practices in the forest products sector in Oregon (**Figure 4;** data sources provided below). Of that which enters into the industrial roundwood stream, a portion is first allocated to roundwood exports. Exported roundwood is assumed to go toward wood, paper, and fuel products, the proportions of which are determined by importing country wood use weighted by their share of exported Oregon roundwood. All remaining industrial roundwood carbon is allocated toward domestic commodity production, with a certain proportion going toward mill residues that either become fuel, feed into additional commodity production, or go unused. Other wood product streams include bark residue, and utilized biomass (which includes tops, limbs, and other nonmerchantable biomass cut and removed during management activities). The majority of bark residue is used in commodity production, while we assume immediate combustion via fuel sources for utilized biomass. Each domestic commodity produced from roundwood or other sources has a

corresponding half-life that determines the longevity of the carbon in use before moving to a product retirement pathway (i.e., recycled, burned for energy, or sent to the landfill) and, eventually, being emitted back to the atmosphere. Emissions from landfilled wood and paper products are largely dictated by the proportion of their material assumed to be decomposable (we assume 23% for wood and 56% for paper) meaning the remaining material will not decompose or emit carbon to the atmosphere during our model timeframe (Morgan et al. 2019).

For any scenario resulting in less harvest than CBAU in a given year, we apply a *leakage* factor to represent an assumed increase in out-of-state harvest activity compensating for the decrease in harvesting in-state. We apply a leakage factor of 84.4% (Wear and Murray 2004), meaning that 84.4% of reduced harvest relative to CBAU is assumed to leak out-of-state and the remaining 15.6% of reduced harvest relative to CBAU is subject to additional emissions from product substitution from using other emissions-intensive materials instead of wood. In all cases, we assume leakage only results from reduced in-state harvest; we assume any additional in-state harvest relative to CBAU results in increased in-state wood use and disposal (e.g., pile burning, recycling, or landfilling) rather than reductions in out-of-state harvest.

In cases where HWP substitute for alternative, more emissions-intensive products (e.g., concrete or steel), the difference in embodied emissions associated with those commodities relative to CBAU is associated with *displaced emissions*, also referred to as *substitution benefits*. When additional wood products are manufactured relative to CBAU, we assume those additional products will be used in place of alternative emissions-intensive materials and credit those scenarios with the corresponding substitution benefits, representing a reduction of atmospheric GHG emissions. Likewise, a decrease in harvest and commodity production may be associated with increased emissions (or negative substitution benefits) in cases where more emissions-intensive products are assumed to replace the less emissions-intensive wood products. Substitution benefits are applied only to saw log, composite panel, and mass timber products. Note that substitution benefits are only included for the assessment of scenario and policy alternatives. For the purpose of reporting GHG emissions and removals in the land sector, substitution benefits are not attributed to the forest sector; instead, they appear as emissions reductions in other sectors when wood products have reduced the use of other products. Those actual emission reductions will also reflect any actual leakage that may have occurred. See **Appendix** for more details on leakage and substitution benefit calculation methods.

To parameterize the CBM-HWP-OR model, we use state-specific harvest, commodity, and trade data from USDA Forest Service (Simmons et al. 2016; Dillon and Morgan 2023), University of Montana Bureau of Business and Economic Research (BBER 2022), US International Trade Commission trade database (USITC 2024), and Howard & Liang (2019). We rely on the FAOSTAT statistical database (FAO 2023) to determine the commodity distributions of exported roundwood. Softwood and hardwood products are parameterized and modeled separately, as the two wood types differ in exports and commodities produced, as well as their associated product half-lives and displacement factors. We incorporate commodity manufacturing efficiency data from Row & Phelps (1996), Franklin Associates (1998), and Skog & Nicholson (2000). We use end-use product half-lives from Row & Phelps (1996), Skog & Nicholson (1998, 2000), and Smith et al. (2006) and product use data from Marcille et al. (2020) to calculate weighted softwood- and hardwood-specific half-lives for all commodities currently produced in Oregon and default IPCC half-lives for international wood, fuel, and paper (Pingoud et al. 2006). We calculate a half-life for mass timber, differentiated for softwood and hardwood material, by assuming all mass timber material goes to construction end uses and applying the appropriate half-life from the above sources. We assume a biochar half-life of 100, on the conservative (i.e., low) end of literature ranges (Zhang et al. 2022; Li and Tasnady 2023), based on state partner input and recommendations that biochar persistence is lower in temperate soils such as those in Oregon (IPCC

2023). Displacement factors associated with wood product substitution come from Smyth et al. (2017) and Cabiyo et al. (2021) and include emissions from harvest, transport, and production but do not factor in building operational emissions. Landfill carbon dioxide and methane emissions calculations rely on IPCC defaults for methane generation (k) and landfill half-lives from Morgan et al. (2019). See **Table 3** in the **Developing Modeling Scenarios** section for BAU HWP parameters and **Appendix** for more details on data and assumptions used in model parameterization.

Identifying Forest Management Priorities

Through a series of meetings with ODF, Oregon Department of Environmental Quality (DEQ), and US Forest Service (USFS) staff, academics, and forestry practitioners in the state, we identified several management priorities and concerns for forests in Oregon. Discussions were focused on how these priorities and concerns would relate to influences on forest carbon stocks, and therefore did not cover an exhaustive list of forest management issues within the state. Likewise, not all priorities discussed were possible to model using CBM-CFS3, such as juniper encroachment into sagebrush and other non-forest landscapes (Rowland et al. 2011). As much as possible, we also integrated and aligned with priorities highlighted in other statewide efforts, including ODF's 20-Year Landscape Resiliency Strategy (Oregon Department of Forestry 2023c) and the Oregon Climate Action Commission's (OCAC, then the Oregon Global Warming Commission) 2021 Natural and Working Lands Proposal (Institute for Natural Resources 2023; Oregon Global Warming Commission 2021a). We used information and recommendations provided in these documents to construct various scenarios for our model, both for a forward-looking BAU scenario and alternative management scenarios representing a departure from BAU practices and climate conditions. Priorities indicated for Oregon include:

- **Understanding impacts from climate change.** Climate change impacts are already apparent in Oregon's forests, driving successive drought, insect mortality events, and escalating wildfires (Fleishman 2023). These drivers, and other changes like extreme temperatures, precipitation events, and declining forest productivity are projected to worsen as climate change intensifies, threatening forest carbon stability and watershed health (Domke et al. 2023; Galik and Jackson 2009; Clifton et al. 2018). CSF in Oregon will have to be centered on adapting to and mitigating future climate impacts and understanding those impacts is critical to success.

- **Land use and land cover.** Each city within Oregon designates an urban growth boundary (UGB), the area in which a city expects to grow over a 20-year period. Development of land outside the UGB for urban uses (e.g., housing, industrial facilities, businesses, or public facilities such as utilities) is strongly restricted, effectively limiting the potential for suburban sprawl into forest and farmland. With respect to forest land specifically, Oregon's Statewide Land Use Planning Goal 4 (OAR 660-015-0000(4)) seeks to maintain the state's forest land base by requiring local governments to inventory forest land and to apply zoning provisions that limit uses which may adversely impact forest land or forestry operations. However, Oregon has experienced a net rate of forest loss from land-use change trends, based on our analysis of changes between forest and non-forest land uses (water, developed land, barren land, herbaceous grasslands, pasture, cultivated crops, and herbaceous wetlands) in NLCD (Dewitz and USGS 2021) between 2001 and 2019. This reduction in forest area may have occurred as previously forested lands were cleared for agriculture, or as municipalities revised and expanded their UGBs. Preventing conversion of forests to non-forest land uses is a fundamental tenet of the OCAC 2021 Natural and Working Lands Proposal (Institute for Natural Resources 2023), which recommends activities aimed at forest land conservation and preservation through payments and tax incentives to compensate land owners for lost revenue from development. In addition, afforestation practices in riparian areas or on marginal agricultural lands can slow or counteract rates of forest loss to land-use change and positively benefit forest land use and land cover (Graves et al. 2020; Janowiak et al.

2017). Silvopasture (the low-density planting of trees in active pasture without disrupting its pastureland use), can also be a viable afforestation option, improving the quality and density of livestock forage and providing shade-relief during hot drought events, while also counteracting trends of conversion of forest to farmland (Angima 2009).

- **Harvesting practices and rotations**. Oregon has 29.7 million acres of forest land, of which 79.8% (23.7 million acres) is classified as timberland, containing an estimated 110,863 million cubic feet (ft^3) of wood, and representing the fourth largest timber volume of any US state (Kuusela et al. 2019). As such, timber harvests in Oregon exert a large influence on forest carbon dynamics, leading to increasing interest in investigating altered harvest practices or schedules (Institute for Natural Resources 2023). Many NCS assessments identify carbon benefits from practices such as extending rotations or reducing harvest intensities (Graves et al. 2020, 2022), which are both allowed practices under numerous Improved Forest Management (IFM) carbon offset protocols (Fargione et al. 2018; Kaarakka et al. 2021). The aim of these management practices is to increase forest carbon stocks on the landscape, either by allowing for trees to grow for longer, or by employing harvest practices such as variable retention cuts or uneven-aged management.

  While these practices may sequester more carbon in the forest, there is a risk of increased emissions from disturbances especially in fire-prone landscapes (Badgley et al. 2022). In addition, altering harvest rotations may have a financial cost due to reduced short term revenues from timberlands, and may face logistical hurdles as mills may lack the tools necessary to process large-diameter logs (Anderson 2023). Variable retention cuts or uneven-aged management practices may also not be feasible in all ecoregions or forest types, especially the highly productive Douglas-fir and true fir forest systems in Oregon's Coast Range (Harrington et al. 2022). Nonetheless, exploring the carbon implications of altered management and rotation length is of great interest in Oregon (Oregon Global Warming Commission 2021b) given the high carbon storage potential of its forests (Fain et al. 2018), and the central role that timber harvest plays in its economy (Kuusela et al. 2019).

- **Forest resilience to wildfire and pests.** Natural disturbances are a major source of forest carbon released to the atmosphere, especially in Oregon which has seen a marked increase in the frequency and intensity of disturbance events in the 21st century (Fleishman 2023). Much of this increased disturbance risk can be attributed to fire exclusion policies and loss of traditional ecological practices (Haugo et al. 2019). These altered management dynamics have caused substantial structural and compositional changes in forests, such as higher stand densities and a larger volume of coarse woody debris which can act as a ladder fuel or harbor pests and pathogens (Hagmann et al. 2021; Gougherty et al. 2024). Collectively, these forces have led to what some term a "carbon debt" (Serra-Diaz et al. 2018) in which forests at a high risk for disturbance contain 25-50% more carbon than more resilient analogues (Knight et al. 2022; Bernal et al. 2022). Restoring forest resilience may require an active and comprehensive approach, including reducing wildfire risk by reducing stand densities far below current conditions, ensuring successful forest regeneration using innovative techniques, restoring variable stand structures on existing and regenerating forest land, reintroducing beneficial fire including cultural burning, considering climate-adapted species selection and genetics for reforestation efforts, and treating within areas that are not typically treated (North et al. 2019; Larson and Churchill 2012; Young et al. 2017; Cansler et al. 2022; Ott et al. 2023; Stevens-Rumann et al. 2018; Meyer et al. 2021).

  Fire resilience treatments in forests are generally considered to include combinations of thinning and prescribed fire (Ott et al. 2023), while pest resilience treatments typically include thinning or replacement of affected stands, with special considerations for slash disposal to prevent cut

material from becoming a further vector for pest outbreaks (Shaw et al. 2011; MacLean 2019). Comprehensive studies of fire resilience treatment effectiveness are newly emerging, and so far show a strong link between treatments and reductions in future wildfire severity (Davis et al. 2024; Ott, Kilkenny, and Jain 2023). Studies of pest resilience treatments are less conclusive, suggesting that selective thinning can be effective for reducing pest prevalence, though spillover from adjacent stands remains a risk (Hicke et al. 2016; Coops et al. 2008; Whitehead et al. 2003). Further studies are needed to elucidate the long-term relationships between treatments and risk reduction (Safford et al. 2012; Cansler et al. 2022; Dodge et al. 2019; MacLean 2019) and to quantify the carbon tradeoffs of these activities over the short and long term (Safford et al. 2012; Cansler et al. 2022; Dodge et al. 2019; MacLean 2019). Understanding the carbon dynamics related to wildfire and pest risks and associated resilience treatments is a high priority for state policy and planning efforts, especially given the scale of the issue.

- **Forest regeneration and reforestation.** Forests across the western US are experiencing high rates of regeneration failure after high-severity wildfire, as burned acres in large patches are too far from natural seed sources and increasingly transition to shrub-based vegetation (i.e., non-forest) without active intervention (Davis et al. 2023b; Stevens-Rumann and Morgan 2019; Donato et al. 2009). With wildfire occurrence and severity projected to increase due to climate change acting on degraded forest conditions (North et al. 2019) and increases in soil temperature likely to reduce seedling survival (Holden et al. 2024), acres of post-fire regeneration failure are likely to increase, especially if high-severity patches grow in size and leave more forestland isolated from a viable seed source (Davis et al. 2023b). Already, fires in Oregon from 2017-2021 have resulted in 73,747 acres of high-severity fire patches larger than 25 acres (Parks et al. 2016) and with limited natural seed source (Potapov et al. 2021), these areas will likely enter a state of post-fire regeneration failure, and add to the growing reforestation backlog across the state (McCarley et al. 2025).

  Our analysis of data from Davis et al. (2023a) projects that an average of 72% of forests in Oregon could fail to regenerate following high-severity wildfire under future climate conditions in a high-emissions pathway (RCP 8.5). As such, addressing the current reforestation backlog and reducing the probability of future regeneration failure must be a critical forest carbon priority for Oregon (Dobrowski et al. 2024; Graves et al. 2020). This can be achieved through resilience treatments that moderate fire severity and through active reforestation of future high-severity fire areas, including salvage to prepare the landscape for safe planting efforts and to reduce future fuel hazards to planted stands. Though not specifically modeled here, climate-informed reforestation techniques like planting climate-adapted species in variable and low-density stand structures will be key to success (Meyer et al. 2021; North et al. 2019).

- **Wood use and efficiency.** The forest products sector can also play a leading role in helping to increase forest carbon storage. The residency time (the time spent in-use or in-landfill) and ultimate fate of carbon which enters the forest products sector varies considerably based on its use and product end of life (EPA 2024). Timber utilization in long-lived products such as construction lumber or mass timber can retain carbon for decades or longer, and in some cases this material may be recycled or repurposed beyond its original intended use (Johnston and Radeloff 2019). In addition, allocating wood toward products which can replace more emissions intensive materials like concrete and steel have additional benefits by displacing some of these emissions through product substitution (Smyth et al. 2017; Cabiyo et al. 2021). Increased or novel wood utilization provides another opportunity for the forest products sector to assist in long term carbon storage or product substitution. Finding a use and a market for small-diameter and residual materials removed from the forest during resilience treatments will be essential in ensuring that these treatments have a net carbon benefit. In the absence of this market and

product pathway, material is often left on site with the intention of subsequent pile burning or chipped and left to decay, and both of these strategies have large potential for biogenic carbon emissions. Increased efficiency in the utilization of bark or mill residues may also yield carbon benefits, as under current practices roughly 16% of mill and 92% of bark residues are combusted as industrial fuel. If a fraction of these residues are diverted for use in alternative products such as wood fiber insulation, wood product sector emissions could be reduced as a portion of the carbon in these products will end up inert in landfills. Finding ways to increase HWP efficiency and to sustain a market for novel products along with diverting wood products from landfills to permanent storage alternatives will be critical for reducing Oregon's forest products sector emissions but will need to balance ecological needs and urgency with long-term procurement contracts, technology development, and infrastructure siting constraints, among other considerations.

These priorities align well with the principles of CSF: balancing adaptation, mitigation, and ecosystem services like water and wood products while focusing on long-term forest health and resilience in the face of climate change. In the case of Oregon's forests, CSF may in part require practices that reduce overall carbon storage or sequestration but minimize losses to wildfire and insect and disease outbreaks. The close alignment between our state partners' priorities and CSF goals makes CSF a useful framework for evaluating performance of the scenarios modeled in this analysis.

Developing Modeling Scenarios

From these stated priorities and policy targets, we developed 23 scenarios to forecast potential CSF pathways represented by a broad range of forest management and wood utilization practices as described below. See **Appendix** for details on data and assumptions used in scenario development, and the **Uncertainties and Limitations** section for a discussion of how these assumptions affect model results

Business-as-Usual Scenario

A core objective of this project is to estimate the differential carbon impacts of various forest management and wood utilization practices in Oregon. This requires the construction of a business-as-usual (BAU) scenario to provide the basis for comparison to potential alternatives. The BAU represents a continuation of current management practices (i.e., harvests, thinnings, prescribed burns, reforestation, wood utilization), land-use changes (afforestation and deforestation), and natural disturbances (i.e., wildfires, insect and disease outbreaks, and abiotic events) at historical average levels, which allows for quantification and projection of current practices into the future. Due to data limitations at the time of our analysis, we assumed reforestation would occur after all stand-replacing events (both harvest and wildfire) in our BAU scenario, though data now exist to demonstrate that post-fire reforestation is not keeping pace (USDA Forest Service 2024; Dobrowski et al. 2024). Though this scenario construction does not account for changes in policies, climate, practices, or economics, it is a useful exercise to explore how the continuation of current behaviors and disturbances may affect future forest dynamics and carbon cycling.

This analysis covers the period from 2000-2100, capturing historical management and disturbance events from 2000-2021 and proceeding with BAU projections through the end of century (**Table 2**). Projected BAU activities are based on annual averages of management and disturbance acres binned into different severity classes and management types. This approach assumes the same acreage and intensity of disturbance each year, which does not allow for interannual variability (i.e., stochastic application of large fires, pest outbreaks, or harvests). BAU wood utilization, discard and decay parameters (including landfill methane) are based on historical averages from 2000-2019 (**Table 3**). See the **Systems-Based Forest Carbon Modeling** section for data sources and **Appendix** for

methodology and additional scenario details. It should be noted here that while modeling efforts often project to end of century, as simulations progress further into the future, uncertainties surrounding climate, policy, and market dynamics increase (Monier et al. 2015; Fyfe et al. 2021). Our modeling approach does not allow for quantification of these uncertainties and can only provide a single "best estimate" for each scenario projecting forward the average of historical data. However, even with these uncertainties, we can reasonably have confidence in the trends and directionality indicated by the results.

Climate-Adjusted Business-As-Usual

In recognition of the current and growing influence of climate change in Oregon's forests and our state partners' stated priority of understanding future climate impacts, we developed a climate-adjusted business-as-usual (CBAU) scenario. This CBAU scenario uses the same management, land-use change and wood utilization parameters from BAU and incorporates some projected climate change impacts on forests under Representative Concentration Pathway (RCP) 8.5 from 2022-2100. RCP 8.5 is representative of the upper range of the current high trajectory of global emissions and was used to represent business-as-usual increases in greenhouse gas emissions in the Sixth Oregon Climate Assessment (Fleishman, 2023).

The CBAU scenario includes modified frequency and severity of natural disturbance events, post-fire regeneration probability, and declines in productivity due to climate mismatch. We project substantial changes in future high-severity wildfire (+191,486 acres per year by 2100) among other natural disturbance changes (**Table 2**) based on state-specific and regional analyses using a range of climate models (Barbero et al. 2014; Chegwidden et al. 2021; Parks et al. 2016; Anderegg et al. 2022). Our analysis of data from Davis et al. (2023b), which determines the likelihood of conifer regeneration within 10 years of a high-severity wildfire, projects that an average of 73% of forest could fail to regenerate following high-severity wildfire events, though this rate varies by ecoregion and forest type group. We assumed that each high-severity wildfire acre in our model would incur this amount of regeneration failure (i.e., 0.73 acres out of 1 acre burned would not regenerate) and applied this to all high-severity burns modeled from 2022-2100. This is an impactful and somewhat uncertain assumption, as not enough is known about high-severity disturbance recovery to completely discount the possibility of regeneration occurring 10+ years post-disturbance (Tepley et al. 2014), but it allows us to illustrate the potential impacts on Oregon's forest landscape given a high-emissions future with increasingly severe wildfires. This assumption does not account for the possibility of vegetation type transitions after disturbance (Stevens-Rumann and Morgan 2019), or differential recovery rates or successional trajectories based on local climate conditions like elevation, heat load, or soil moisture availability (Larson and Franklin 2005; Dodson and Root 2013). To incorporate future declines in productivity, we analyzed data from the Climate-Adapted Seed Tool (Stewart and Wright 2023) and found a statewide average of -57% productivity by 2100 due to future climate mismatch. We modeled this as a percentage reduction in growth (based on forest type group) each decade from 2022-2100.

The CBAU scenario is used as the basis of comparison for all alternative scenarios so that we can examine the influence of those scenarios within the context of potential future climate conditions and quantify the extent to which our scenarios help to mitigate projected future climate impacts. See **Table 2** for CBAU parameters, including changes from BAU, and **Appendix** for methodology and additional CBAU impact details.

Alternative Management and Disturbance Scenarios

We developed 10 of our 21 remaining scenarios by changing CBAU parameters at the beginning of our 79-year projection period (i.e., starting in 2022), representing potential changes in future management decisions or disturbance events. These scenarios apply to one specific practice or objective, where one

CBAU practice is changed and the rest of CBAU remains the same. This allows us to examine the specific influences of a proposed altered management practice on forest carbon dynamics in isolation and evaluate its relative power as a CSF and NCS action. These 10 alternative scenarios cover a broad range of forest management and resilience practices as discussed in the **Identifying Forest Management Priorities** section above and are grouped into three categories representing similar management concerns or objectives: 1) landscape resilience and post-fire landscape restoration; 2) land use and land cover; and 3) altered harvest management. See **Table 4** for scenario parameters, including changes from CBAU, and **Appendix** for additional scenario development details.

General concerns about forest resilience and landscape restoration are represented by three scenarios. In the Wildfire Resilience scenario, wildfire resilience treatments (641,858 ac yr^{-1} on average) are implemented in areas identified by the 2023 Pacific Northwest Quantitative Wildfire Risk Assessment as having high or very high wildfire hazard potential (McEvoy et al. 2024). In the Pest Resilience scenario, pest resilience treatments (272,193 ac yr^{-1} on average) are implemented in areas which, according to our analysis of the National Insect and Disease Risk Map (USDA Forest Service 2018b), may be at risk of increased future moderate or high-severity insect outbreaks. In the Landscape Restoration scenario, site preparation and post-fire landscape restoration treatments are implemented in areas which, according to our analysis (McCarley et al. 2025), have experienced high-severity wildfire between 2000 and 2021 and have limited access to a natural seed source (16,969 ac yr^{-1} on average), as well as the areas which burn and fail to regenerate from 2022-2100 (95,089 ac yr^{-1} on average) in our CBAU simulation. In keeping with the 2021 Natural & Working Lands Proposal's goal of sequestering and storing at least an additional 9 $TgCO_2e$ by 2050 (Oregon Global Warming Commission 2021a), and ODF's 20-year Landscape Resiliency Strategy (Oregon Department of Forestry 2023c), initial treatments in these three restoration and resilience scenarios were modeled over a 29-year timeframe (from 2022-2050) before transitioning into maintenance of treated areas (i.e., repetition of earlier treatment on the same land area) from 2051-2100.

An additional four scenarios relate to land use and land cover change. Of these, there are two scenarios in which net zero forest loss is achieved, either through increased statewide afforestation (the Net Zero Forest Loss Via Increased Afforestation scenario, or NZA Scenario for short, +32,252 ac yr^{-1} afforestation), or through decreased statewide deforestation (the Net Zero Forest Loss Via Decreased Deforestation scenario, or NZD scenario for short, -32,252 ac yr^{-1} deforestation). We also constructed the No Deforestation Outside of the Urban Growth Boundary scenario (the UGB scenario for short) which was designed to curtail all temporary or permanent deforestation outside of the states 2023 UGB (State of Oregon 2023). Because the rate of afforestation outpaces the rate of deforestation in the UGB scenario, net forest area increases over time (+31,300 ac yr^{-1}). The final scenario in this category, the Silvopasture scenario, implements a statewide silvopastoral tree planting program (+24,928 ac yr^{-1}) on all lands identified as eligible by the Reforestation Hub (Cook-Patton et al. 2020). Eligible lands are those which are currently used for livestock grazing or the production of grass or hay crops and are underlain by "marginal" soil types that constrain productivity. For the former three scenarios, changes in land use are modeled from 2022-2100, while for the Silvopasture scenario, plantings are implemented from 2022-2050.

Altered harvest management practices are represented by a further three scenarios, two of which relate to altered harvest rotations. In the 80-Year Rotations scenario, the minimum age for harvest is increased from 40 (private industrial), 50 (public), or 60 years (private non-industrial) to 80 years for all forest types and ownerships. In the CMAI-Based Rotations scenario, minimum harvest age is set as the age at which each forest type group reaches culmination of mean annual increment (CMAI) (Kerr 2020). In the Uneven-Aged Management scenario, group selection (an uneven-aged management type) replaces high harvest (an even-aged management type) for all land ownerships in ecoregions east

of the Cascades. As with the NZA, NZD, and UGB scenarios, all three altered harvest management scenarios were modeled to start immediately in 2022 and continue until 2100.

While each individual scenario represents a potential CSF management tactic, these practices would rarely be implemented alone across the state. To better represent comprehensive forest climate action, our next three scenarios were constructed as *portfolios* – ensembles of scenarios or practices that could be concurrently implemented throughout the state – to visualize the cumulative potential of Oregon's forests to provide climate mitigation benefits. These were: 1) the Combined Resilience and Restoration portfolio (the CRR portfolio for short, a combination of the Wildfire Resilience, Pest Resilience, and Landscape Restoration scenarios), 2) the Maximum Forest Area and Carbon portfolio (the Max FAC portfolio for short, a combination of the Silvopasture, 80-Year Rotations, and UGB scenarios), and 3) the Maximum Forests as Natural Climate Solutions portfolio (the Max NCS portfolio for short, a combination of the CRR and the Max FAC portfolios). The CRR portfolio can be thought of as a group of climate adaptation strategies, that is, strategies which alter forest management to adapt with the effects of climate change. The Max FAC portfolio focuses more on climate mitigation, with management practices aimed at preserving or increasing forest cover and forest carbon density. When combined as in the Max NCS portfolio, these practices should theoretically provide the best potential combination of CSF management strategies examined in this analysis.

Alternative Wood Utilization Scenarios

In addition to the 15 ecosystem scenarios outlined above, we developed two additional wood utilization scenarios focused on improving the carbon storage or avoided emissions potential of the forest products sector. We developed the Innovative Wood Utilization scenario to explore the carbon outcomes of innovative uses for the material removed during resilience (wildfire and pest) treatments. Under the BAU HWP assumptions, this material, which represents all wood cut during pest resilience treatments as well as wood cut on non-reserved private and public lands west of the Cascades during wildfire resilience treatments, is treated like any other harvested material (see **Table 3** and the **Appendix** for further details on the BAU HWP assumptions, and management prescriptions for the Pest and Wildfire resilience scenarios). In this scenario, material from thinning is prioritized for use as lumber (50%) and biochar (up to 5% of total by 2100), with the remainder being combusted for bioenergy.

The Increased HWP Efficiency scenario focuses on increasing the efficiency and storage potential of the current product streams in Oregon's forest products sector, in line with legislation and grant programs gaining popularity in the state (e.g., Oregon DEQ's Materials Management program and the City of Portland's Deconstruction program). This scenario increases the lifespan and recycling rate of lumber used in residential and commercial construction (via a 50% increase in the in-use half-life and a 25% increase in the commodity recycling rate). It also expands the production of wood fiber insulation from mill residues (25% of total), and adds production of mass timber and plywood as new products streams (up to 5% each of total domestic roundwood commodity production by 2100).

We combined each of these alternative wood utilization scenarios with various ecosystem scenarios or portfolios, for a total of eight additional scenarios modeled. As the Innovative Wood Products scenario relates directly to the additional woody material cut during resilience treatments, we chose to only apply this scenario with the Wildfire Resilience and Pest Resilience scenarios, and the CRR and Max NCS portfolios. Similarly, while the Increased HWP Efficiency scenario could be paired with any of the ecosystem scenarios, for simplicity we chose only to pair it with the CBAU scenario, and the CRR, Max FAC, and Max NCS portfolios. All ecosystem scenarios were also modeled with BAU wood utilization assumptions, for a total of 23 unique combinations of ecosystem and HWP scenarios. Once modeled, we compared and evaluated all scenarios and portfolios for their alignment with CSF principles and their climate mitigation potential. Results are discussed in the following section.

Table 2. Oregon BAU and CBAU ecosystem disturbance parameters. BAU values are based on historical average rates from 2000-2021. CBAU values are based on decadal projections under RCP 8.5 from 2022-2100, reported here as the mean from 2022-2100. See **Appendix** *for assumptions and data sources.*

Land-use change (same for BAU and CBAU)

Practice	Biomass Impact	Total (ac yr^{-1})	USFS (ac yr^{-1})	Other Federal (ac yr^{-1})	State / Local (ac yr^{-1})	Private / Native American (ac yr^{-1})
Forest loss	-	-62,620	-30,596	-2,375	-1,218	-28,431
Forest gain	-	31,364	2,870	957	649	26,889
Net trend	**-**	**-31,256**	-27,726	-1,418	-569	-1,542

Forest management practices (same for BAU and CBAU)

Practice	Biomass Impact	Total (ac yr^{-1})	USFS (ac yr^{-1})	Other Federal (ac yr^{-1})	State / Local (ac yr^{-1})	Private / Native American (ac yr^{-1})
High harvest	90% cut, 85% removed	260,589	10,855	3,616	15,538	230,580
Intermediate harvest	50% cut, 45% removed	77,792	20,321	3,280	1,946	52,246
Group selection	50% cut, 45% removed	2,335	2,330	-	-	5
Commercial thin	30% cut, 25% removed	193,085	56,986	15,428	4,100	116,570
Hazardous fuels thin	30% cut, no removal	39,551	4,787	3,135	719	30,908
Precommercial thin	10% cut, no removal	127,818	33,203	2,484	4,007	88,125
Rx fire	5% burned	104,469	47,315	3,994	2,497	50,663
Pile burn	50-90% consumption of pile	18,942	16,555	-	-	2,387
Salvage	90% cut, 90% removed	98,001	9,640	16,278	2,953	69,130
Total	**-**	**922,582**	201,992	48,215	31,760	640,615

Natural disturbances

Disturbance	Severity	BAU (ac yr^{-1})	CBAU mean 2022-2100 (ac yr^{-1})	Difference (ac yr^{-1})	Historical Range (ac yr^{-1})
Wildfire	High	38,800	245,231	+206,431	649 - 349,070
	Moderate	28,526	180,497	+151,970	282 - 250,009
	Low	37,461	37,461	-	748 - 300,190
Insects	High, mortality	25	20	-5	0 - 680
	Moderate, mortality	351,022	338,673	-12,349	45,856 - 634,514
	Low, mortality	42,552	38,171	-4,382	0 - 409,491
	High, defoliation	21,080	21,080	-	269 - 136,292
	Moderate, defoliation	3,074	3,074	-	0 - 43,251
	Low, defoliation	96,745	96,745	-	117 - 377,143
Disease	High, mortality	-	-	-	0 - 6
	Moderate, mortality	4,636	3,153	-1,483	92 - 10,535
	Low, mortality	198	126	-73	0 - 2,043
	High, no mortality	18,817	18,817	-	0 - 348,539
	Moderate, no mortality	2,972	2,972	-	0 - 48,088
	Low, no mortality	22,758	22,758	-	130 - 22,5037
Abiotics	High, mortality	44	36	-7	0 - 1,117
	Moderate, mortality	1,524	1,288	-236	25 - 23,398
	Low, mortality	7	6	-1	0 - 333
	High, no mortality	209	209	-	0 - 2,493
	Moderate, no mortality	512	512	-	0 - 4,694
	Low, no mortality	354	354	-	0 - 3,077

Additional climate impacts (statewide weighted average)

Post-fire regeneration failure on 72.7% of high-severity wildfire acres	57.2% decline in forest productivity (annual growth rates) by 2100

Table 3. Oregon BAU HWP parameters. Values are based on most recent available data from 2000-2019. Percentages may not sum to 100% due to independent rounding. See **Appendix** *for assumptions and data sources.*

Removals distribution (proportion of carbon inputs distributed to various modeling streams)			
Softwood removals		**Hardwood removals**	
Industrial roundwood	90% of harvest removals	Industrial roundwood	90.39% of harvest removals
Utilized biomass	0.01% of harvest removals	Utilized biomass	0% of harvest removals
Bark residue	9.99% of harvest removals	Bark residue	9.61% of harvest removals
Roundwood exports			
Softwood exports	16.79% of industrial roundwood	Hardwood exports	0.02% of industrial roundwood
Commodity distribution (proportion of carbon distributed to various commodities)			
Softwood commodities		**Hardwood commodities**	
Lumber	31.57%	Lumber	24.62%
Composite panels	9.59%	Composite panels	7.48%
Posts, poles, pilings	0.85%	Posts, poles, pilings	0%
Paper	4.37%	Paper	28.40%
Composite panels from mill residue	11.69%	Composite panels from mill residue	19.53%%
Other industrial uses from mill residue	0.51%	Other industrial uses from mill residue	0.43%
Paper from mill residue	22.98%	Paper from mill residue	18.38%
Mulch from bark residue	1.07%	Mulch from bark residue	1.12%
Fuel from exported roundwood	8.95%	Fuel from exported roundwood	0.02%
Paper from exported roundwood	5.21%	Paper from exported roundwood	0.01%
Wood from exported roundwood	3.21%	Wood from exported roundwood	0.02%
Product half-lives			
Domestic use			
Softwood lumber	35.39 years	Softwood mass timber	85.5 years
Hardwood lumber	27.07 years	Hardwood mass timber	73.3 years
Softwood composite panels	42.68 years	Mass plywood	81.4 years
Hardwood composite panels	22.53 years	Biochar	100 years
Posts, other industrial uses	12 years	Bioenergy	0 years
Pulp	2.6 years	Transportation fuel	0 years
International use			
Wood, composite panels, other industrial uses, poles	30 years	Fuel	0 years
		Paper	2 years
Product retirement (100% to landfill unless specified)			
Softwood lumber	91.09% landfill 8.91% recycled	Paper	26% landfill 68% recycled 6% burned
Hardwood lumber	90.74% landfill 9.26% recycled		
Landfills			
Decomposable materials	Paper: 56% Wood: 23%	Landfilled product half-lives	Paper: 14.5 years Wood: 29 years
Methane generation rate *k*	Paper: 0.06 m^3 yr^{-1} Wood: 0.03 m^3 yr^{-1}	Exported landfilled product half-lives	Paper: 14.5 years Wood: 29 years
Methane release	37.2% flared/burned for energy 62.8% unrecovered		

Table 4. Ecosystem and wood utilization scenario parameters for Oregon. Unless otherwise noted, scenario changes from CBAU are immediate and last for the entire simulation period (2022-2100). Scenario impacts are activity acres (not footprint acres), meaning some scenario treatments can occur or repeat on the same physical acre of forest, though not within the same model year. Scenarios that are components of one or more portfolios are marked with the symbol for the appropriate portfolio. See **Appendix** *for assumptions and data sources.*

Forest management scenarios

Landscape resilience

Scenario name	Objective	Change from CBAU	Scenario impact, 2022-2100
Wildfire Resilience*^	Address current wildfire resilience treatment needs within 29 years (by 2050), then continue maintenance treatments	+149,214 ac yr^{-1} mechanical thin (no product removals) to reduce fuels from 2022-2050, with follow up thins every 10-15 years	21,096,115 acres thinned
		+14,615 ac yr^{-1} mechanical thin (with product removals) to reduce fuels from 2022-2050, no follow up thinning	
		+72,989 ac yr^{-1} Rx fire (burn only, no follow-up after thinning), with follow-up burns every 15-20 years	29,610,710 acres of Rx fire and pile burn
		+14,615 ac yr^{-1} Rx fire (follow-up 1-5 years after thinning with removal)	
		+149,214 ac yr^{-1} pile burn (follow-up 1-5 years after thin with no product removals)	
	Decrease wildfire severity in response to treatments	240,682 ac yr^{-1} moderate-severity wildfire instead of high-severity wildfire	28,868,427 acres of fire at lower severity
		165,916 ac yr^{-1} low-severity wildfire instead of moderate-severity wildfire	
Pest Resilience*^	Address current pest resilience treatment needs within 29 years (by 2050), then continue maintenance treatments	+199,588 ac yr^{-1} mechanical thin (with product removals) to reduce insect risk from 2022-2050, with follow up thins every 20 years	21,156,272 acres thinned
	In the Coast Range ecoregion, treat 100% of area impacted by disease –no mortality (high and moderate-severity) in the year following disturbance	+4,449 ac yr^{-1} diseased tree removal and replanting with healthy trees at the same density	347,005 acres cut and replanted due to Swiss needle cast infection
	Decrease insect-mortality severity in response to treatments	22 ac yr^{-1} moderate-severity insect-mortality instead of high-severity insect-mortality	19,985,790 acres of insect-mortality at lower severity
		281,468 ac yr^{-1} low-severity insect-mortality instead of moderate-severity insect-mortality	
	Decrease insect-defoliation severity in response to treatments	14,546 ac yr^{-1} moderate-severity insect-defoliation instead of high-severity insect-defoliation	1,172,849 acres of insect-defoliation at lower severity
		1,973 ac yr^{-1} low-severity insect-defoliation instead of moderate-severity insect-defoliation	

Post-fire landscape restoration

Scenario name	Objective	Change from CBAU	Scenario impact, 2022-2100
Landscape Restoration*^	Address current post-fire reforestation needs within 29 years (by 2050)	+16,969 ac yr^{-1} post-fire site prep and low-density reforestation from 2022-2050	492,095 post-fire acres reforested at low density
	Address future post-fire reforestation needs within 3-5 years of high-severity wildfire	+105,803 ac yr^{-1} post-fire salvage/site prep and low-density reforestation	7,512,013 post-fire acres reforested at low density

Table 4, cont. *Ecosystem and wood utilization scenario parameters for Oregon. Unless otherwise noted, scenario changes from CBAU are immediate and last for the entire simulation period (2022-2100). Scenario impacts are activity acres (not footprint acres), meaning some scenario treatments can occur or repeat on the same physical acre of forest, though not within the same model year. Scenarios that are components of one or more portfolios are marked with the symbol for the appropriate portfolio. See* ***Appendix*** *for assumptions and data sources.*

Land use and land cover

Scenario name	Objective	Change from CBAU	Scenario impact, 2022-2100
Net Zero Forest Loss via Increased Afforestation (NZA)	Reduce net permanent forest loss from land-use change to zero	+32,252 ac yr^{-1} of afforestation (203% of BAU/CBAU afforestation rate)	2,547,908 forest acres added
Net Zero Forest Loss via Decreased Deforestation (NZD)	Reduce net permanent forest loss from land-use change to zero	-32,252 ac yr^{-1} of deforestation (43.9% of BAU/CBAU deforestation rate)	2,547,908 forest acres conserved
No Deforestation Outside of the Urban Growth Boundary (UGB)‡^	Prevent all permanent forest loss from land-use change outside of 2023 UGB	-62,556 ac yr^{-1} of deforestation (99.2% of BAU/CBAU deforestation rate)	4,941,924 forest acres conserved
Silvopasture‡^	Maximum silvopasture implementation by 2050	+24,928 ac yr^{-1} planted in silvopasture system from 2022-2050	722,920 acres planted in silvopasture system

Altered harvest management

Scenario name	Objective	Change from CBAU	Scenario impact, 2022-2100
80-Year Rotations‡^	Increase harvest age for all forest owners to 80 years	Increase minimum harvest age from 40 (private industrial), 50 (public), or 60 (private non-industrial) years to 80 years for all ownerships	30,118,024 acres eligible for extended rotation lengths
CMAI Based Rotations	Change harvest age for all forest owners to the forest type group specific CMAI	Change minimum harvest age from 40 (private industrial), 50 (public), or 60 (private non-industrial) years to the age at CMAI for all ownerships	30,118,024 acres eligible for modified rotation lengths
Uneven-Aged Management	Increase the use of uneven-aged management practices in east side forests	+23,961 ac yr^{-1} of group selection - 23,961 ac yr^{-1} of high harvest	1,701,285 acres managed with group selection in place of high-intensity harvest

Forest management portfolios

Portfolio symbol and name	Objective	Change from CBAU	Scenario impact, 2022-2100
* Combined Resilience and Restoration (CRR)	Fully implement proposed post-fire landscape restoration, wildfire resilience, and pest resilience treatments by 2050, then continue maintenance of resilience treatments and post-fire landscape restoration for any forest area which enters regeneration failure	This portfolio combines the Landscape Restoration, Wildfire Resilience, and Pest Resilience scenarios with CBAU management and natural disturbance not affected by other component scenarios	2,461,213 post-fire acres reforested 50,706,825 acres treated for wildfire resilience 21,503,277 acres treated for pest resilience
‡ Max Forest Area and Carbon (Max FAC)	Maximize forest area and forest carbon storage through altered management, reduced forest loss to conversion and novel afforestation pathways	This portfolio combines the UGB, Silvopasture, and 80-Year Rotations scenarios with CBAU management and natural disturbance not affected by other component scenarios	4,441,486 forest acres conserved 722,920 acres planted in silvopasture system 30,118,024 acres eligible for extended rotation lengths
^ Max Forests as Natural Climate Solutions (Max NCS)	Maximize natural climate solutions action statewide (based on the scenarios included in this analysis, not all possible natural climate solutions in Oregon)	This portfolio combines Landscape Restoration, Wildfire Resilience, Pest Resilience, UGB, Silvopasture, and 80-Year Rotations scenarios with CBAU management and natural disturbance not affected by other component scenarios	2,461,213 post-fire acres reforested 50,706,825 acres treated for wildfire resilience 21,503,277 acres treated for pest resilience 4,441,486 forest acres conserved 722,920 acres planted in silvopasture system 30,118,024 acres eligible for extended rotation lengths

Table 4, cont. *Ecosystem and wood utilization scenario parameters for Oregon. Unless otherwise noted, scenario changes from CBAU are immediate and last for the entire simulation period (2022-2100). Scenario impacts are activity acres (not footprint acres), meaning some scenario treatments can occur or repeat on the same physical acre of forest, though not within the same model year. Scenarios that are components of one or more portfolios are marked with the symbol for the appropriate portfolio. See* ***Appendix*** *for assumptions and data sources.*

Alternate wood utilization scenarios				
Scenario name	**Objective**	**Change from HWP BAU**	**Scenario impact, 2022-2100**	**Paired Ecosystem Scenarios**
Innovative Wood Utilization	Allocate harvested wood from fire and/or pest resilience treatments to innovative wood products which more accurately reflect their potential use	50% of additional harvested material to lumber 0.07% of additional harvested material to biochar, increasing to 5% by 2100 Remaining additional harvested material combusted for bioenergy	Altered wood product allocations for materials from resilience treatments Longer half-life for biochar than biomass left or burned on site	Wildfire Resilience, Pest Resilience, CRR, Max NCS
Increased HWP Efficiency	Improve the efficiency and storage potential of the state's forest products sector by increasing product half-lives and recycling Increase production of longer-lived wood products from roundwood and mill residue.	50% increase in the half-life of lumber used in construction (62.02 years SW, 29.24 HW) 25% increase in the recycling rate of lumber used in construction (10.50% SW, 9.55% HW) 25% of mill residue used in wood fiber products (composite panels) 5% of roundwood commodity production is mass timber by 2100 5% of roundwood commodity production is mass plywood by 2100	Longer half-life and increased recycling rate for lumber Longer half-life for wood fiber than default mill residue products (paper and other industrial) Substitution benefits from using mass timber and mass plywood in construction	CBAU, CRR, Max FAC, Max NCS

Results and Discussion

Results of our analysis show that from 2000-2021, the forest ecosystem in Oregon has fluctuated between being a net source and a net sink of carbon. However, in the future forests are projected to be a more consistent net source, with forecasted losses of carbon substantially increased due to climate change. Further, while the forest products sector provides consistent net carbon storage for the state, it is not strong enough to counteract ecosystem trends. Our results suggest that there are several opportunities to dampen future forest carbon losses, especially through practices focused on addressing loss of forest area to deforestation and post-fire regeneration failure, the latter of which is projected to increase substantially as climate change intensifies. Management practices which promote maintenance of existing forest carbon stocks, such as lengthened harvest rotations, can be effective at sequestering more carbon in the forest in the near term. However, intensifying disturbance losses and climate change related declines in productivity mean that in the long term, these practices may see diminishing or even negative returns. Further, wildfire resilience treatments reduce the risk of high-severity wildfire and associated direct emissions of carbon. Nevertheless, due to this major reduction in stand-replacing disturbance, wildfire resilience treatments cause a substantial increase in average forest age, with an associated decline in productivity and long-term carbon sequestration capacity. As discussed in the **Forest Carbon** section above, forest climate mitigation potential can be influenced by both carbon sequestration and carbon storage dynamics across the landscape, and climate-smart practices strive to balance both factors while supporting long-term forest health. Our results indicate that focusing on landscape-level restoration and afforestation treatments, coupled with increased HWP efficiency, is a leading strategy for minimizing forest carbon losses now, while also maximizing forest carbon sequestration potential into the future.

Influence of Future Climate

During the period from 2000-2021, when both the BAU and CBAU scenarios are using the same parameters, Oregon's forests fluctuate between being a net carbon source, represented by a net

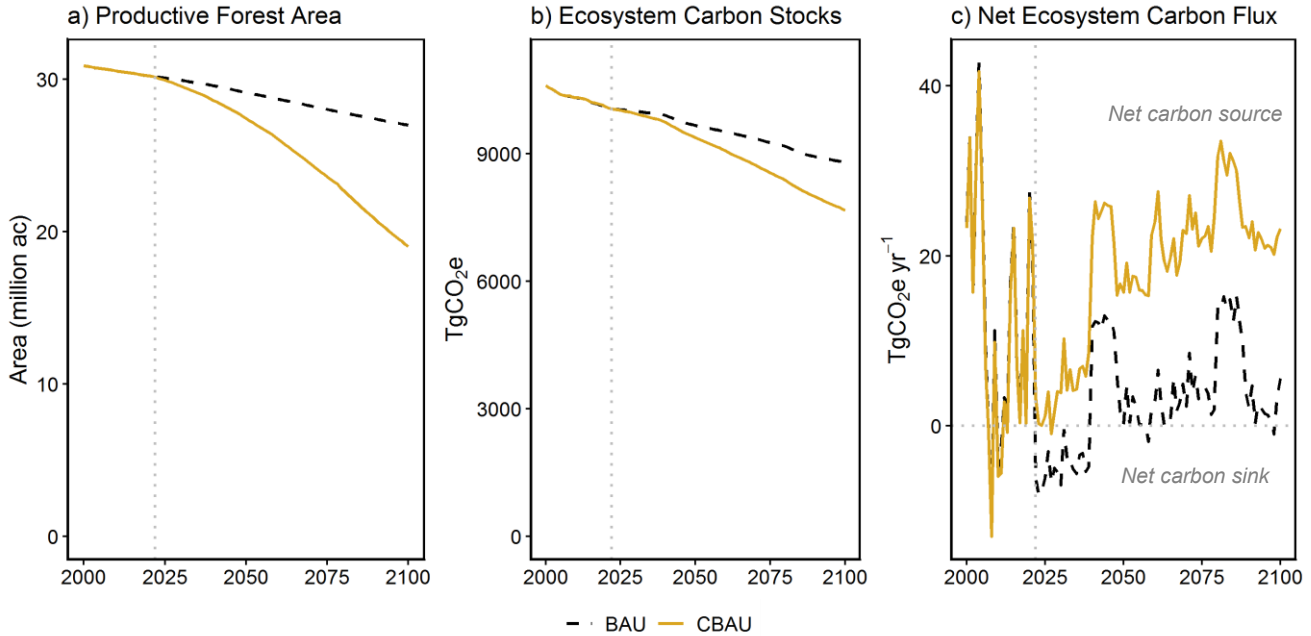


Figure 5. BAU and CBAU scenario results showing a) productive forest area (million acres), b) ecosystem carbon stocks ($TgCO_2e$), and c) annual net ecosystem carbon flux ($TgCO_2e\ yr^{-1}$) from 2000-2100. Productive forest area refers to the amount of forest which is not in a state of post-fire regeneration failure. Net ecosystem carbon flux refers to the net yearly sequestration of carbon by forests across all 14 ecosystem carbon pools, after accounting for decomposition, natural disturbance emissions, and wood product transfers. In Panel c), negative numbers for net ecosystem carbon flux represent a net carbon sink and positive numbers represent a net carbon source.

ecosystem carbon flux above zero, and a net carbon sink, represented by a net ecosystem carbon flux below zero (**Figure 5c**). *Net ecosystem carbon flux* refers to the net yearly sequestration of carbon by forests across all 14 ecosystem carbon pools, after accounting for decomposition, natural disturbance emissions, and wood product transfers. Net ecosystem carbon flux is presented from the atmospheric perspective, where negative numbers represent a net carbon sink (less carbon in the atmosphere) and positive numbers represent a net carbon source (more carbon in the atmosphere).

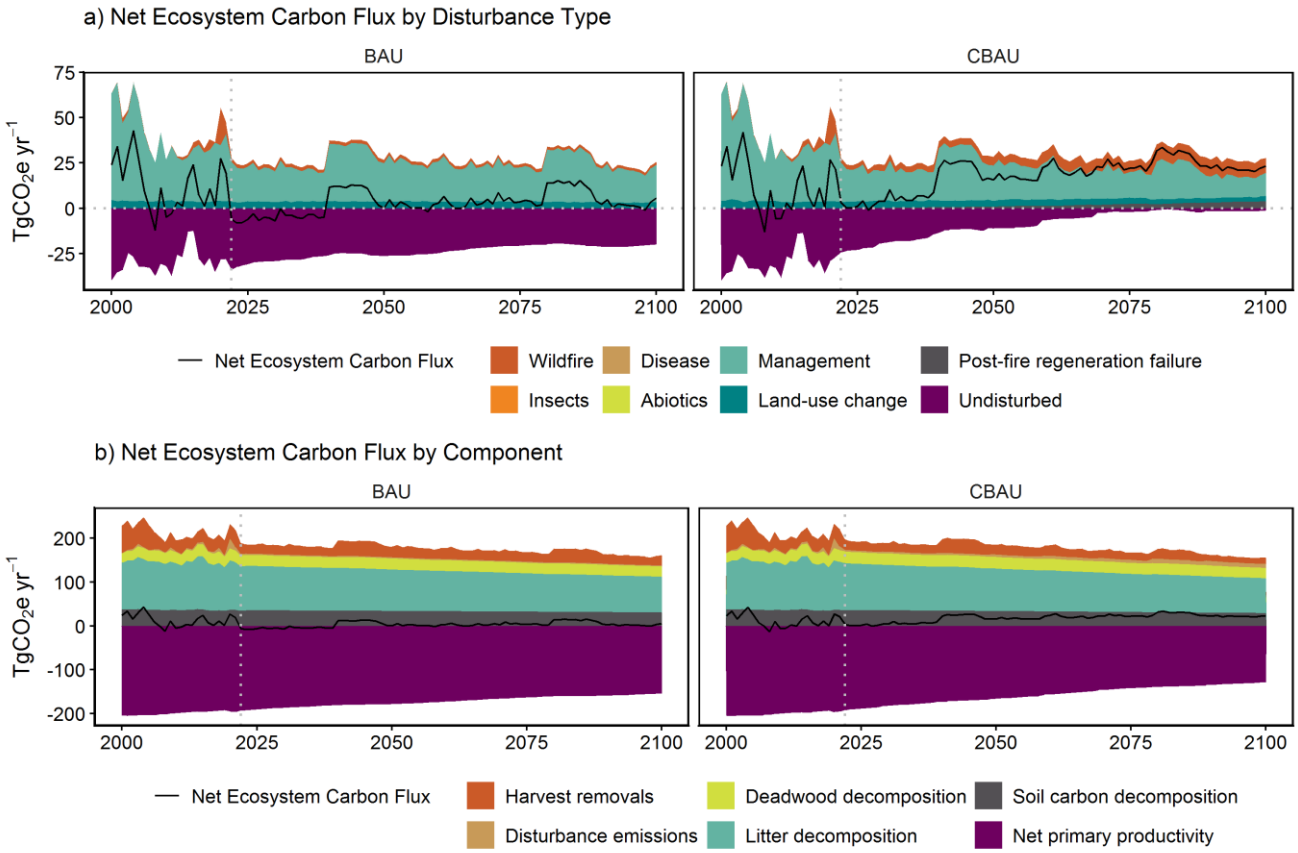


Figure 6. BAU and CBAU scenario results showing annual net ecosystem carbon flux ($TgCO_2e\ yr^{-1}$) from 2000-2100, a) broken out by disturbance type and b) broken out into its component parts. Net ecosystem carbon flux refers to the net yearly sequestration of carbon by forests across all 14 ecosystem carbon pools, after accounting for decomposition, natural disturbance emissions, and wood product transfers. Negative numbers for net ecosystem carbon flux represent a net carbon sink and positive numbers represent a net carbon source.

The major dynamics fueling the transition of forests between net carbon sink and net carbon source from 2000-2021 are *harvest removals*, and to a lesser degree emissions from *disturbance* (**Figure 6**). While harvest removals are not a direct emission of carbon to the atmosphere like decomposition or disturbance emissions, they none-the-less lower forest ecosystem carbon stocks as wood is transferred to the forest products sector, which appears as a loss of carbon when viewed in terms of net ecosystem carbon flux. Over this same period, annual *net primary productivity* (NPP), the measure of net sequestration of carbon in forests from growth, is relatively stable but becomes slightly less negative through time, ranging from -205.7 $TgCO_2e\ yr^{-1}$ in 2001 to -192.4 $TgCO_2e\ yr^{-1}$ in 2019 (**Figure 6b**). Emissions from *decomposition*, the measure of carbon emitted from dead wood, litter, and soil, are also quite stable, and range from 157.3 $TgCO_2e\ yr^{-1}$ in 2019 to 184.6 $TgCO_2e\ yr^{-1}$ in 2016. Harvest removals range from 23.8 $TgCO_2e\ yr^{-1}$ in 2008 to 68.0 $TgCO_2e\ yr^{-1}$ in 2004 while emissions from disturbance (e.g. carbon released from wildfires) range from 0.8 $TgCO_2e\ yr^{-1}$ in 2005 to 23.1 $TgCO_2e\ yr^{-1}$ in 2020, both having much larger relative rates of variation than decomposition or NPP.

Quantifying the exact role of harvests and disturbance events on long-term net ecosystem carbon sequestration is difficult, as their impacts extend beyond just the immediate loss of carbon from forests (direct emissions and harvest removals). These dynamics can decrease live tree sequestration rates, increase emissions from deadwood and litter decomposition, and lead to larger dead organic matter (DOM) carbon pools, which may lead to elevated emissions from wildfires in subsequent years. However, the immediate effect of harvest and disturbance on net ecosystem carbon flux are clear, as the two years in which the forest was the strongest net carbon sink, 2008 and 2010, had the lowest combined loss of carbon from disturbance and harvest, while the two years in which the forest was the strongest net carbon source, 2001 and 2004, had the highest combined loss of carbon from disturbance and harvest (**Figure 6a**). It is also important to note that net ecosystem carbon flux is not a complete picture of full forest sector *Net Carbon Balance*, as carbon removed during harvest is transferred to the forest products sector where it may be stored in durable wood products or the landfill. In such cases, this carbon remains in storage, contributing to overall mitigation and, in cases where inputs outpace emissions, potentially keeping the whole forest sector a net carbon sink. For a complete analysis of net carbon balance, including the influence of leakage and product substitution, see the section **Net Carbon Balance in Forests and the Forest Products Sector**.

Interestingly, our model results for the period from 2000-2021 differ substantially from previous estimates of forest carbon flux for Oregon (Christensen et al. 2019). The data from Christensen et al. (2019), which are based on growth, removals, and mortality (GRM) of remeasured trees in FIA plots, indicate that from 2001-2016, Oregon forests were a net carbon sink, with an average forest carbon flux of -31.4 $TgCO_2e\ yr^{-1}$. Over the same period, our BAU scenario suggests that forests were a net carbon source, with an average net ecosystem carbon flux of 12.7 $TgCO_2e\ yr^{-1}$. While it is not unexpected that two different methodologies would lead to different outcomes, the magnitude of the difference is noteworthy.

To compare the results between our BAU scenario and the GRM approach from Christensen et al. (2019), we calculated gross tree growth, equivalent to change in woody biomass for the aboveground live component, and removals or mortality by causal agent for our BAU scenario for 2001-2016 and

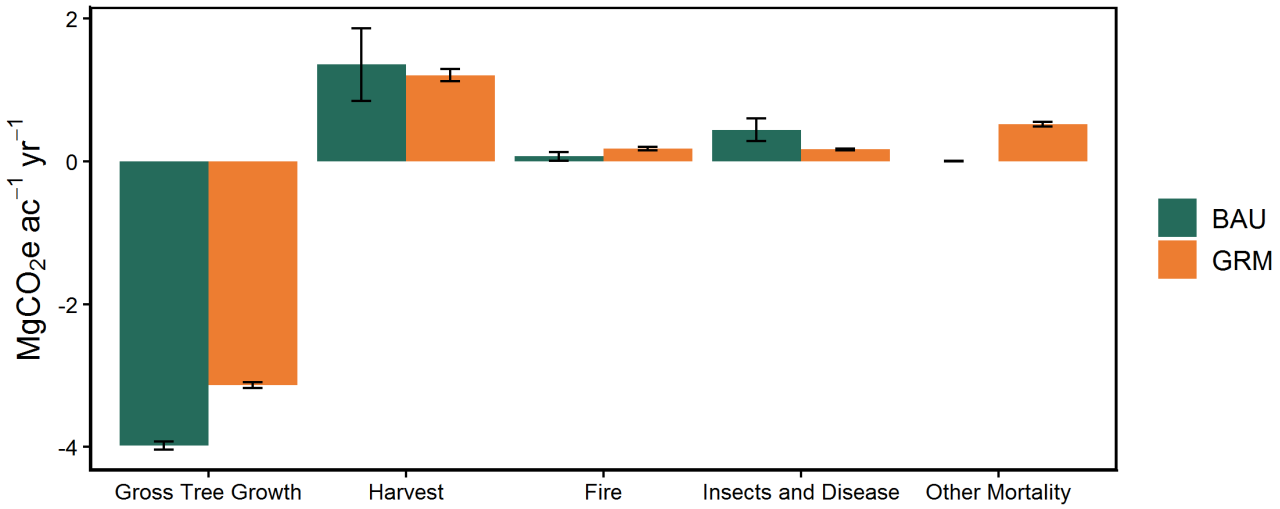


Figure 7. Comparison of per-acre changes in aboveground woody biomass ($MgCO_2e\ ac^{-1}\ yr^{-1}$) from our BAU scenario and the Growth Removal and Mortality (GRM) measurement approach as reported in Christensen et al. (2019). Both methodologies cover the period from 2001-2016. BAU scenario results were grouped into similar categories as in the GRM approach. Error bars for the BAU scenario represent the standard deviation of the annual (2001-2016) estimate for each category. Error bars for the GRM methodology represent the standard error as reported in Table B10 in Christensen et al. (2019). Data are presented from the atmospheric perspective where negative values represent carbon accrual in woody biomass while positive values represent carbon loss from woody biomass.

compared these data to those presented in Table 4.4 from Christensen et al. (2019) (**Figure 7**). Based on this comparison, our estimates for gross tree growth (GRM = -3.14 megagrams of carbon dioxide equivalent ($MgCO_2e$) ac^{-1} yr^{-1}, BAU = -3.99 $MgCO_2e$ ac^{-1} yr^{-1}) and harvest removals (GRM = 1.21 $MgCO_2e$ ac^{-1} yr^{-1}, BAU = 1.36 $MgCO_2e$ ac^{-1} yr^{-1}) align quite well with those from the GRM method (**Figure 7**), suggesting that both methods are estimating similar per-acre growth and harvest patterns, at least for the aboveground biomass component. We observed larger deviations in estimates of mortality from fire (GRM = 0.18 $MgCO_2e$ ac^{-1} yr^{-1}, BAU = 0.07 $MgCO_2e$ ac^{-1} yr^{-1}) mortality from insects and disease (GRM = 0.17 $MgCO_2e$ ac^{-1} yr^{-1}, BAU = 0.44 $MgCO_2e$ ac^{-1} yr^{-1}), and other mortality (GRM = 0.52 $MgCO_2e$ ac^{-1} yr^{-1}, BAU = <0.01 $MgCO_2e$ ac^{-1} yr^{-1}; **Figure 7**), which is likely due to differences in how each methodology categorizes disturbance agents. In our BAU scenario, only a single disturbance type can impact each inventory record in a single year, whereas in the GRM method remeasurement of trees in FIA plots means that some plots will have had multiple unique disturbances during the resampling interval, or the disturbance agent may not be known. When we sum mortality across all causal agents (GRM = 0.88 $MgCO_2e$ ac^{-1} yr^{-1}, BAU = 0.51 $MgCO_2e$ ac^{-1} yr^{-1}), the methods align more closely.

Given this, the differences in forest carbon flux between our BAU estimates and the GRM method are more likely due to differences in DOM and soil carbon dynamics, rather than an inherent error or misestimation of forest carbon dynamics in our CBM-CFS3 based modeling approach. Both our BAU scenario and the GRM approach utilize FIA data to estimate starting carbon stocks; however, the method of estimation, the relative starting size of each pool, and the permanence or lability of these stocks can have a large influence on annual forest carbon flux. In addition, contrasting trends in land-use change and differences in the area of management and disturbances may also contribute to differences in total forest carbon flux, even if the per-acre fluxes are in alignment (**Figure 7**). Although our results are different from those presented in Christensen et al. (2019), we have full confidence in the validity of our modeling approach, especially for scenario comparisons like this study. A more detailed comparison of the similarities and differences between the BAU scenario and the GRM methodology can be found in the **Appendix** section **Comparison of BAU Scenario and Growth Removals and Mortality Methodology**.

Future projections of net ecosystem carbon flux indicate that in the BAU scenario forests return to a net carbon sink status from 2022-2039 (**Figure 5c**), driven by a reduced rate of harvest during this period (**Figure 6b**). From 2040-2047 harvest levels are again elevated, pushing the forest back to a net carbon source. From 2048 onward, small declines in the level of NPP mean that annual carbon sequestration is not enough to offset carbon losses from harvest, disturbance, and decomposition, and therefore the forest remains a net carbon source again for most of the rest of the century (**Figure 6b**).

By contrast, forests in the CBAU scenario act as a net carbon source in all years from 2022-2100 (except 2029), with a trend toward increasing source strength as the simulation progresses (**Figure 6a**). In addition to increased natural disturbance and post-fire regeneration failure, which each increase ecosystem emissions, forests in the CBAU scenario also experience declining productivity each decade from 2022-2100. These declines in productivity, meant to represent mismatches in climate adaptation between the current climate and the climate which the trees are adapted to, cause forests to accumulate biomass more slowly or experience higher rates of mortality (Stewart and Wright 2023). Across Oregon, forest productivity is projected to decline by about 57% by 2100 (based on our analysis of data from Stewart and Wright 2023), further depressing carbon accumulation and NPP rates (**Figure 6b**) and contributing to the forest's net carbon source status into the future (**Figure 5c**). The combination of lower productivity and increased emissions from tree mortality also contributes to a higher (less negative, meaning more emissions) net ecosystem carbon flux even on otherwise undisturbed lands (**Figure 6a**). These declines in NPP, coupled with increasing emissions from wildfires and post-fire regeneration failures and elevated decomposition rates from higher mean annual temperatures (**Figure**

6), mean that cumulative net ecosystem carbon flux for the CBAU scenario is approximately 3 times higher (12.0 $TgCO_2e\ yr^{-1}$) than the BAU simulation, leading to higher emissions under projected future climate conditions (**Figure 5c**).

Next, looking at both the BAU and CBAU, productive forest area and ecosystem carbon stocks decline in tandem throughout both simulations (**Figure 5a, b**). We distinguish here between total forest area, including forests in a state of post-fire regeneration failure, and productive forest area, which only includes forests actively growing and with the capacity to sequester carbon (but does not imply that all forests are equally productive in terms of net primary productivity or productivity class). CBAU results show a much stronger trend of loss with -37% forest area (a loss of about 11.1 million acres) and -24% carbon stocks (a loss of 2.4 petagrams of carbon dioxide equivalent; $PgCO_2e$) from 2022-2100, compared with BAU scenario losses of -11% forest area (3.2 million acres) and -14% carbon stocks (0.6 $PgCO_2e$; **Figure 5a, b**). In the BAU simulation, these losses in productive forest area are mainly due to a rate of deforestation which is nearly double the rate of afforestation, leading to a modeled annual net loss of 31,256 acres of forest land each year (**Table 2**). For the CBAU scenario, this net rate of forest loss, in combination with more frequent high-severity wildfire and regeneration failure following roughly 73% of those high-severity fires, means that by 2100, 8 million acres (30%) of the remaining forest land is projected to be in a state of post-fire regeneration failure, leaving just 19 million acres (70%) of total forest area as productive (**Figure 5a**).

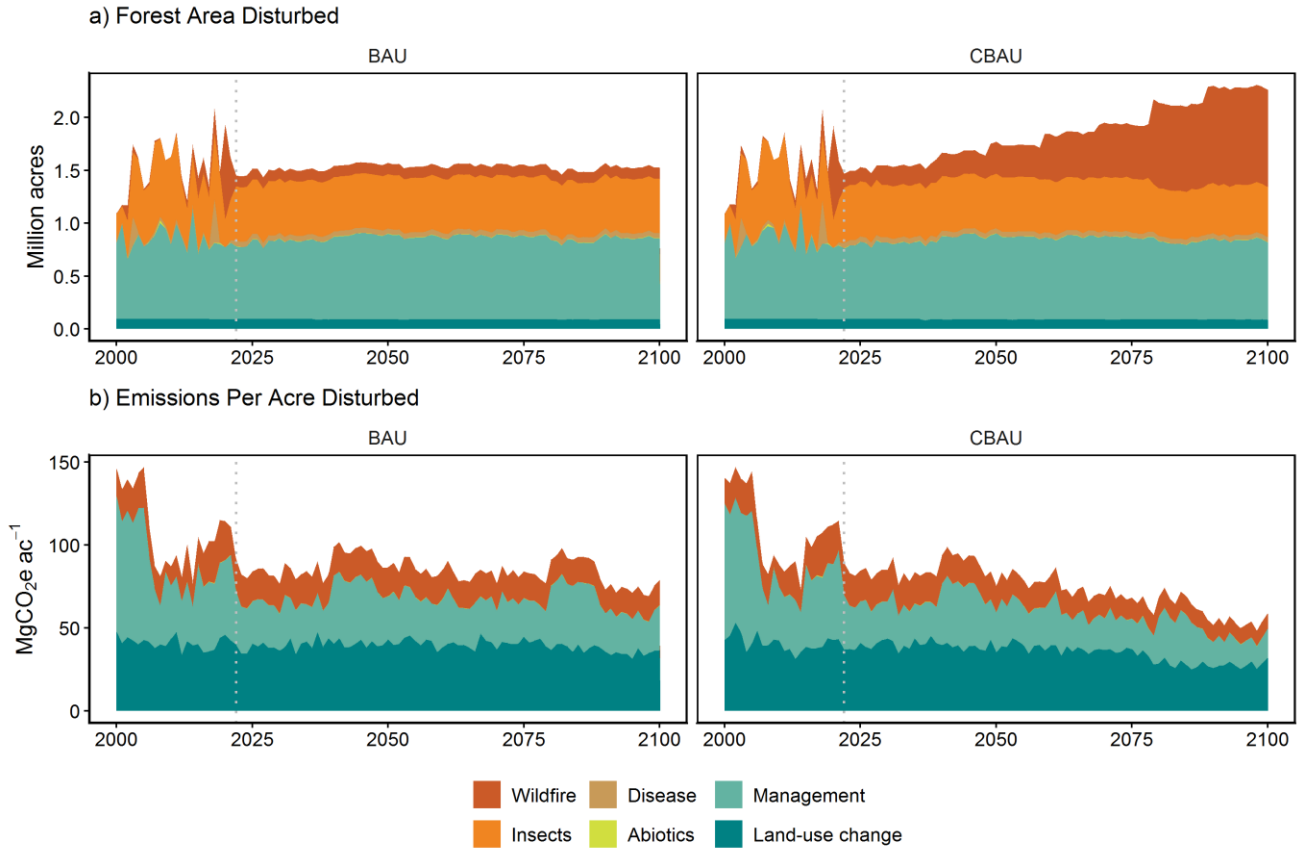


Figure 8. BAU and CBAU scenario results showing a) disturbance area (million acres) and b) carbon emissions per area disturbed ($MgCO_2e\ ac^{-1}$) by disturbance type. Carbon emissions depicted are direct (e.g., carbon to the atmosphere from wildfire, carbon removed for use in HWPs) rather than all the emissions which may be attributed to a disturbance event over time (e.g., biomass to DOM which eventually decays).

The increased frequency of natural disturbance events and regeneration failure in the CBAU scenario also has implications for ecosystem carbon stocks, both in terms of carbon directly emitted during a disturbance (e.g., wildfire emissions), but also carbon emitted from snags and other DOM left on site after a disturbance. In the CBAU scenario, wildfire acres are projected to increase by about 6 times from 2022-2100 (**Figure 8a**), leading to an additional (relative to BAU) 322 $TgCO_2e$ of direct wildfire emissions over this period (**Figure 6a**). Interestingly, direct disturbance emissions per acre are projected to decline over time for both BAU and CBAU simulations, with a larger projected decline for CBAU than for BAU (**Figure 8b**). For example, emissions per acre for wildfire drop from 19.2 $MgCO_2e$ ac^{-1} yr^{-1} (BAU) and 19.1 $MgCO_2e$ ac^{-1} yr^{-1} (CBAU) in 2022 to 15.1 $MgCO_2e$ ac^{-1} yr^{-1} (BAU) and 9.0 $MgCO_2e$ ac^{-1} yr^{-1} (CBAU) in 2100 (**Figure 8b**). These within-scenario declines are the result of loss of biomass and DOM stock densities during successive disturbances. Due to aggressive contemporary fire suppression coupled with loss of traditional ecological practices (e.g., cultural burning), forests in some ecoregions in Oregon are largely overstocked relative to their historical densities (Serra-Diaz et al. 2018; Knight et al. 2022; Bernal et al. 2022), meaning there is more carbon per acre available to be combusted early in the simulation. Differences in wildfire emissions per acre between BAU and CBAU are due in part to reburns, which, under the CBAU assumptions, largely occur on the portions of the landscape which have previously burned and failed to regenerate, and thus have substantially lower carbon stocks in biomass and DOM. It is important to note that reburns are not a prescribed model behavior, rather they are the consequence of the model's stochastic application of wildfire disturbance to all eligible inventory records, regardless of whether or not that forest area is in a state of post-fire regeneration failure. Areas with higher annual wildfire disturbance tend to have a proportionally higher amount of post-fire regeneration failure, meaning that reburns in these regeneration failure areas are proportionally more likely.

Carbon in wood products increases throughout the model period, though at a slower rate under CBAU due to decreased harvest as a result of declining forest area and productivity (**Figure 9**). Still, the projected transfer of carbon from the forest to the forest products sector outweighs emissions from historical products (those produced prior to 2000 and either still in use or in landfills) and current wood products in use or in landfills. As such, HWP and the forest products sector are a growing carbon storage pool for Oregon (**Figure 9**). Much of this growth in HWP carbon stocks can be attributed to the

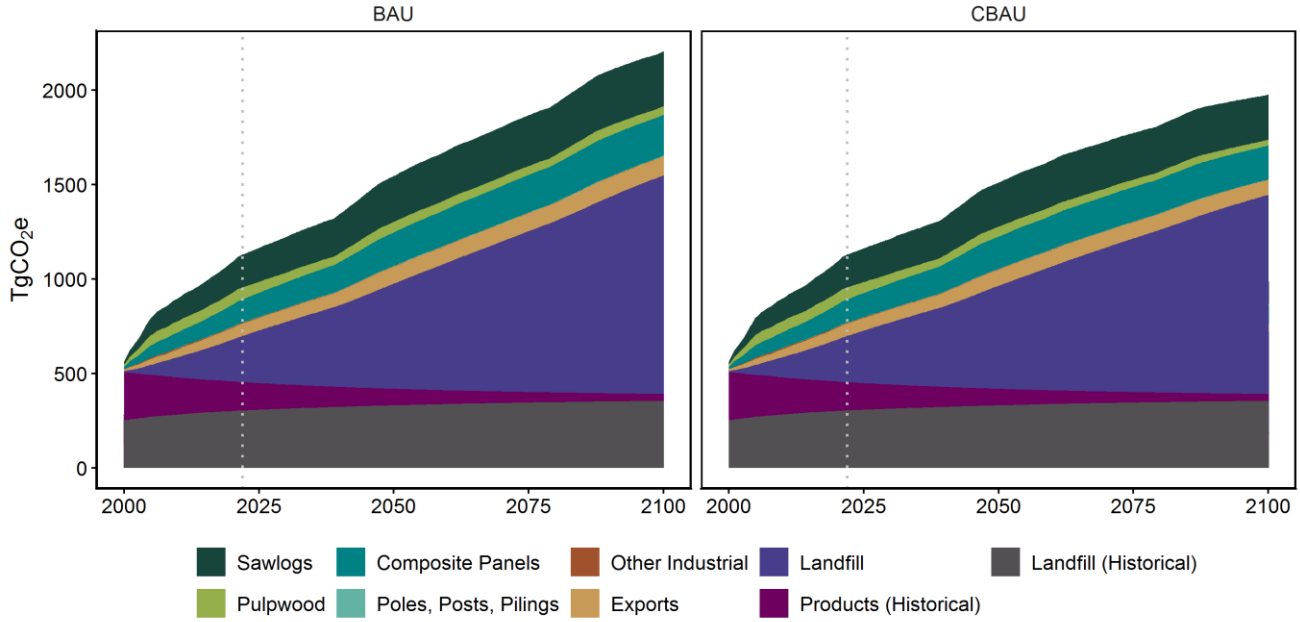


Figure 9. BAU and CBAU scenario HWP carbon stocks ($TgCO_2e$) by primary product, 2000-2100. Positive numbers denote accruing carbon stocks.

production and use of long-lived products such as lumber and composite panels (**Table 3**) and the relative stability of carbon in landfilled HWP, with only 23% of wood and 56% of paper assumed to be decomposable (Morgan et al. 2019).

In both the BAU and CBAU scenarios, softwood and hardwood removal volumes vary widely, with softwoods comprising 90% of annual removals from 2000-2100 on average. The majority of harvested softwood (85.6%) and hardwood (83.7%) goes into industrial roundwood products (**Figure 10**). Of this volume, 16% of total softwood roundwood and just 0.02% of total hardwood roundwood is exported as raw roundwood. The remainder of the roundwood volume stays domestic and is used in commodities such as lumber, composite panels, paper products, poles, posts, or pilings (**Table 3**), some of which may be later exported as finished products. Utilized biomass, representing the small volume of tops and limbs which are harvested and subsequently combusted at the mill for industrial bioenergy, accounts for <0.01% of harvested softwood material and 0% of harvested hardwood material. Bark residue makes up 10% of harvested softwood material and 9% of harvested hardwood material, and, regardless of wood type, is used for bioenergy (92%) and mulch (8%), with the remainder (0.01%) going unused. Though total harvest volume under CBAU is 89% of BAU volume, the relative distribution of harvested wood to different streams (**Table 3**) does not change between scenarios.

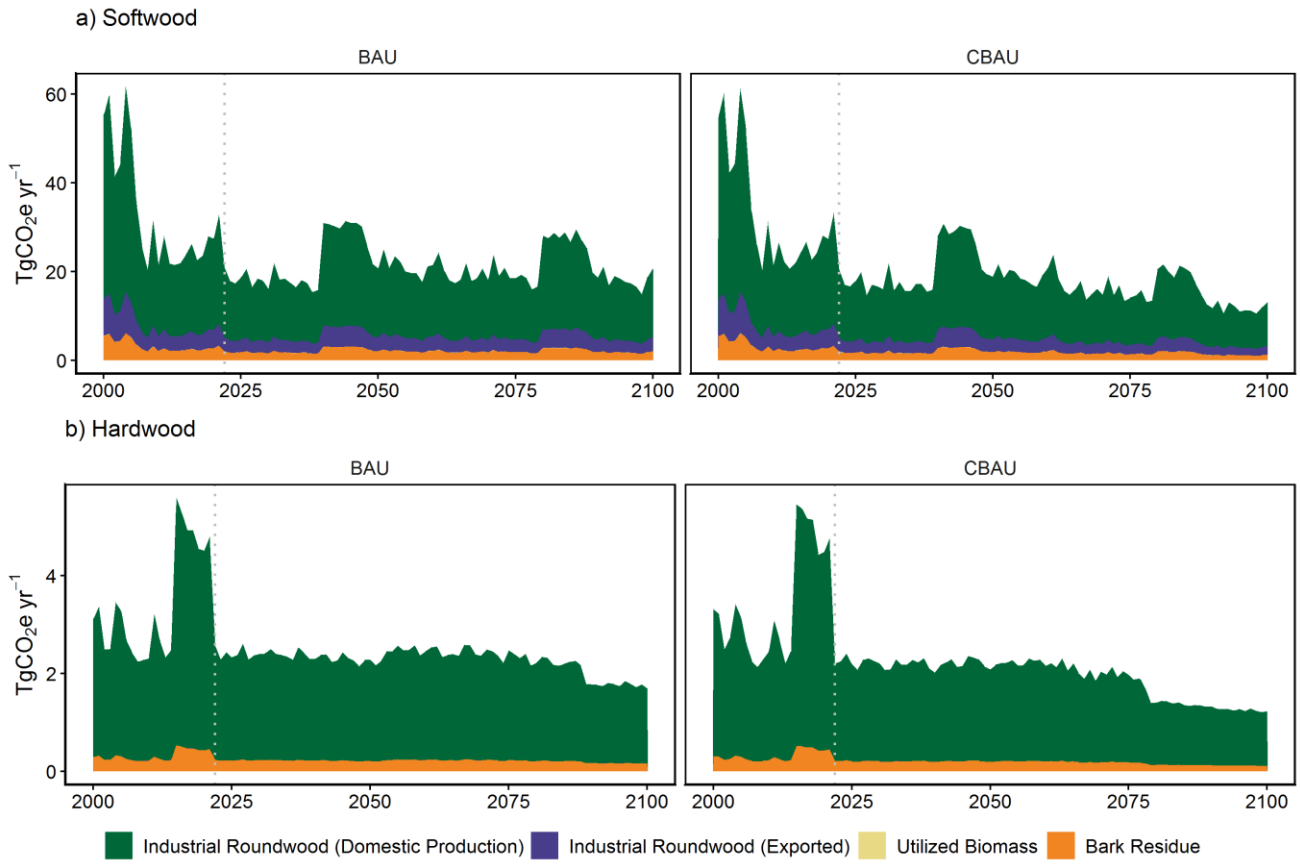


Figure 10. BAU and CBAU scenario results showing annual HWP removal distribution ($TgCO_2e\ yr^{-1}$) for a) softwoods and b) hardwoods from 2000-2100. Removals are comprised of woody material that is cut and removed from the forest and does not include any residues or other materials left on site.

In 2000 at the start of the simulation, 81% (25.3 million acres) of the forestland in Oregon was younger than 140 years old, distributed among 18 forest type groups according to FIA (**Figure 11a**; USDA Forest Service 2021a). This means 19% (5.6 million acres) of the landscape is already older than our modeled

maximum harvest age of 140 years, a proportion that decreases slightly to 16% (5 million acres) in 2022 and increases to 47% (9.3 million acres) by the end of the CBAU scenario in 2100 (**Figure 11b, c**). This modeled maximum harvest age, determined from analysis of FIA removals data (USDA Forest Service 2021a), sets an upper limitation on forest eligible to harvest in our model, meaning any forest reaching 141+ years of age can no longer be targeted by harvest in our simulation and will continue to grow unless affected by a natural disturbance or land-use change event. Forests aging out of harvest eligibility, an overall net loss of total forest area in the BAU and CBAU scenarios (**Table 2**), declines in productivity, and loss of productive forest area to regeneration failure in the CBAU scenario all contribute to the lower rates of projected (2022-2100) harvest removals when compared with historical (2000-2021) trends (**Figure 10**). Similarly, we imposed a minimum harvest age of 40 (private industrial), 50 (public), or 60 years (private non-industrial) at the recommendation of state partners, which further restricts the forest area eligible for harvest. The effects of this minimum age limitation can be clearly seen in the elevated softwood harvest removals from 2040-2047, and again from 2080-2087, date ranges which correspond to when the stands harvested at the start of the simulation (2000-2007) return to harvest eligibility (**Figure 10**).

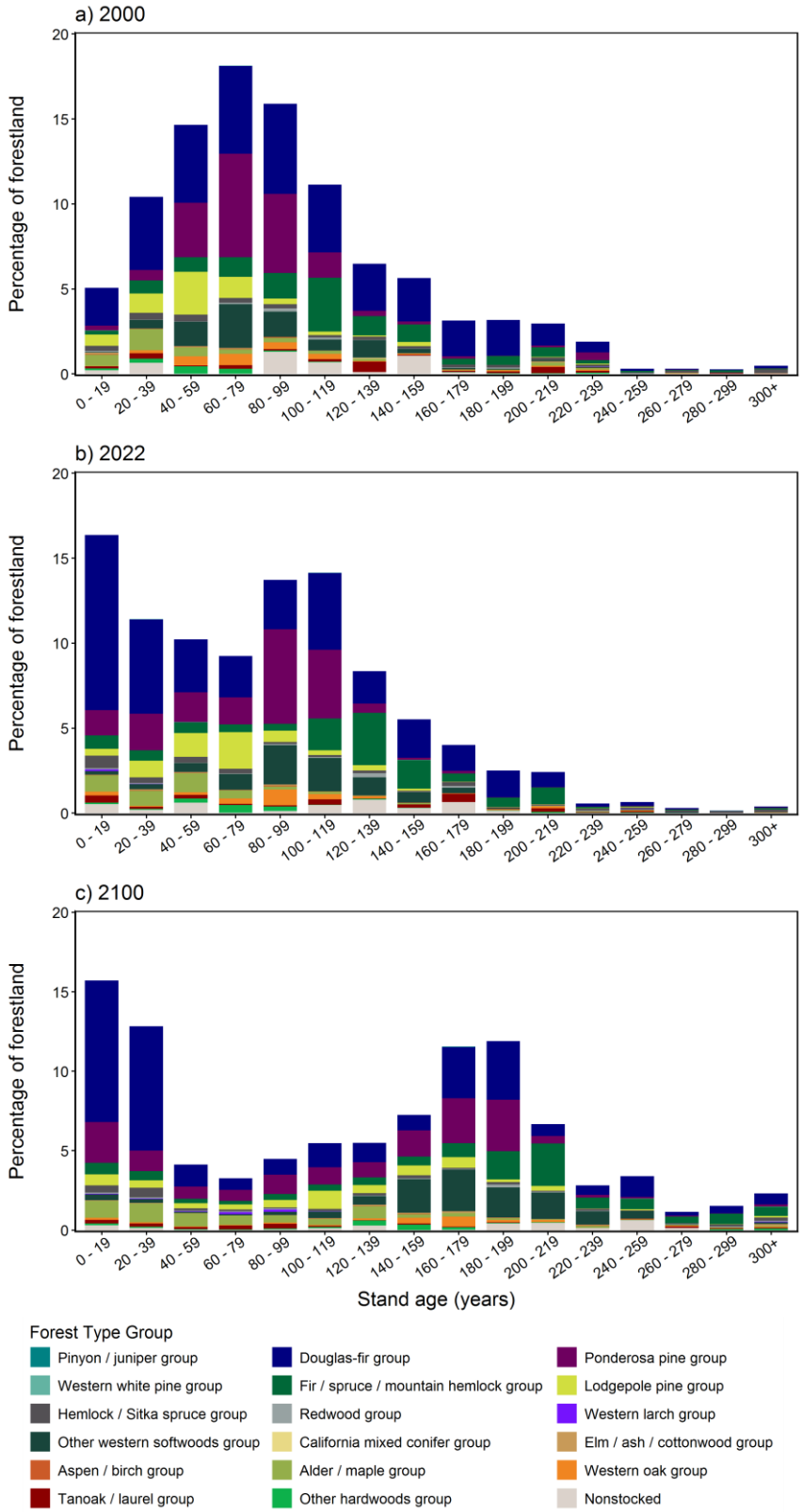


Figure 11. Age class distribution for the CBAU scenario by forest type group a) at the beginning of the simulation (2000), b) at the start of forward projections (2022), and c) at the end of the simulation (2100). Percentages calculated excluding post-fire regeneration failure.

Excluding areas of post-fire regeneration failure (which have a stand age of zero because they have not regenerated), by 2100 the age distribution of forest land in Oregon becomes increasingly bimodal (**Figure 11**). Two cohorts emerge, one which continues to age due to lack of harvest or disturbance, and a second younger cohort of forest which is regularly harvested or subjected to stand-replacing disturbance. While mature and old growth stands are a critical component of a resilient forest landscape due to the ecosystem services they provide (Davis et al. 2022; Pelz et al. 2023) and large amounts of carbon they store (DellaSala et al. 2022; Mildrexler et al. 2020), they may become more vulnerable to climate impacts and natural disturbances like wildfire and insect events without management to preserve resilience (Anderson et al. 2024), and because of an increase in per-acre decomposition emissions and biomass accumulation rates, experience an overall decline in stand-level forest carbon sequestration capacity (Gray et al. 2016; Vangi et al. 2024). Likewise, while a forest landscape heavily skewed toward younger stand ages will be more productive (i.e., higher per-acre NPP; Robinson et al. 2025) and may have a greater capacity to adapt to current conditions (Quetin et al. 2023), young forests store substantially less carbon per acre, are known to have lower water use efficiency (Farinacci et al. 2024) and may have lower resilience to future climate conditions (Giebink et al. 2022). These projected trends in forest age distribution underscore the importance of active forest management, across all age cohorts, to ensure a diverse (and therefore more resilient) age distribution for all forest types, ownerships, and regions. Future updates of regional forest management programs like the Northwest Forest Plan and Oregon's 20-Year Landscape Resiliency Strategy will need to keep these goals in mind, while also attempting to balance other ecological, social, economic, and carbon sequestration goals with the realities of changing forest demographics, climate change impacts and projected losses in productive forest area due to post-fire regeneration failure.

Climate Change Impacts by Ownership Class

Results from the CBAU scenario vary greatly by ownership (see **Figure 3** for reference map), mainly due to the relative number of acres in each ownership category, the amount of projected harvest for each ownership, and the influences of increasing wildfire, natural regeneration failure, and declines in productivity on those acres. Forests owned and managed by the USDA Forest Service (USFS, within the National Forest System), which make up 46% of forest land and 51% of the ecosystem carbon stocks in 2022, are projected to be most vulnerable to and affected by future climate conditions and natural disturbances. In the CBAU scenario, these forests are projected to lose 48% of their productive area from 2022-2100 (decreasing from 14.0 to 7.2 million acres) and 29% of their carbon stocks (decreasing from 5.1 to 3.6 $PgCO_2e$) over the same period (**Figure 12**). USFS lands are also projected to accumulate 4.7 million acres of post-fire regeneration failure area by 2100, which is 66% of the area of productive USFS forests in the same year. This drives cumulative (2022-2100) net carbon emissions on USFS lands to be on average +5.2 $TgCO_2e\ yr^{-1}$ (+124%) higher under CBAU than under BAU.

Private and Native American lands, which make up 37% of forest land and 32% of the ecosystem carbon stocks in 2022, also experience significant impacts under the CBAU scenario. These forests lose 30% of their productive forest area (decreasing from 11.1 to 7.8 million acres) and 22% of their carbon stocks (decreasing from 3.2 to 2.5 $PgCO_2e$) from 2022-2100 (**Figure 12**). By 2100, these forests are projected to accumulate 2.5 million acres of post-fire regeneration failure and emit on average +4.5 $TgCO_2e\ yr^{-1}$ (+612%) more carbon under the CBAU scenario than under BAU (**Figure 12**), switching from a cumulative net carbon sink to a cumulative net carbon source.

State and locally managed forests (4% of forest area and 5% of ecosystem carbon stocks in 2022) and forests managed by non-USFS federal agencies (13% of forest area and 13% of ecosystem carbon stocks in 2022), each see smaller, though still negative, changes through the CBAU simulation. From 2022-2100, state/local forests lose 8% of their productive forest area (decreasing from 1.2 to 1.1 million acres), 12% of their carbon stocks (decreasing from 0.48 to 0.41 $PgCO_2e$; **Figure 12**), and end the simulation

in 2100 with just 44 thousand acres of post-fire regeneration failure, yet have net carbon emissions that are on average +0.6 $TgCO_2e\ yr^{-1}$ (+249%) higher than BAU. Non-USFS managed federal forests experience losses of 23% of productive forest area (decreasing from 3.8 to 2.9 million acres) and 10% of carbon stocks (decreasing from 1.3 to 1.2 $PgCO_2e$) from 2022-2100 (**Figure 12**), with 0.77 million acres of forest failing to regenerate post-fire and an average of +1.7 $TgCO_2e\ yr^{-1}$ (+198%) higher net carbon emissions than BAU. Forests under both ownership types switch from a net carbon sink under BAU to a net carbon source under CBAU.

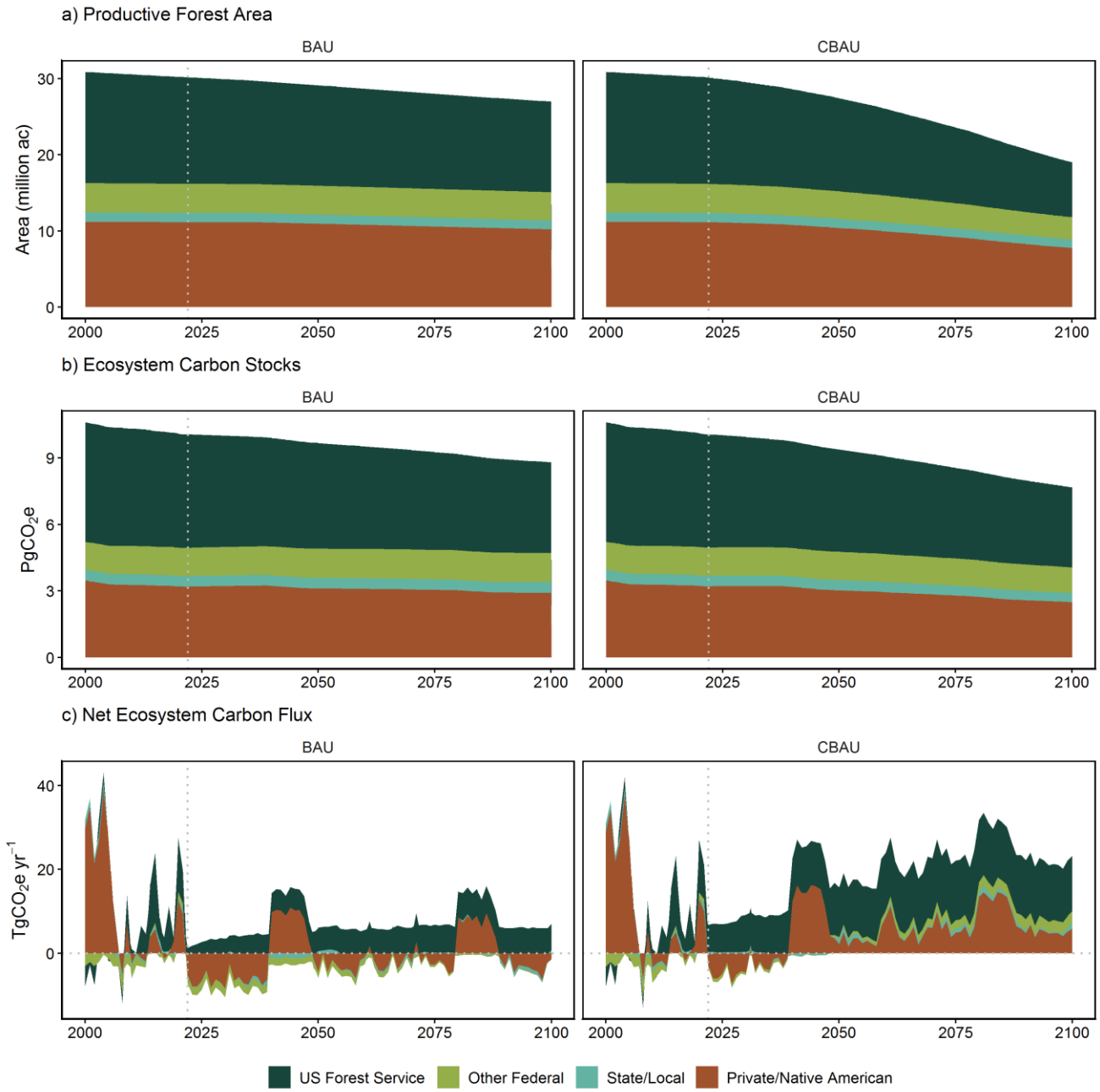


Figure 12. BAU and CBAU scenario results showing a) total productive forest area (million acres), b) ecosystem carbon stocks ($PgCO_2e$), and c) annual net ecosystem carbon flux ($TgCO_2e\ yr^{-1}$) by ownership class from 2000-2100. Net ecosystem carbon flux refers to the net yearly sequestration of carbon by forests across all 14 ecosystem carbon pools, after accounting for decomposition, natural disturbance emissions, and wood product transfers. In Panel c), negative numbers for net ecosystem carbon flux represent a net carbon sink and positive numbers represent a net carbon source.

Overall, of the productive forest area lost in the CBAU scenario from 2022-2100, 61% is on USFS managed lands, 30% is on private and Native American lands, 8% is on non-USFS managed federal lands, and just 1% is on state or locally managed lands. Of the carbon stocks lost under the CBAU scenario, 63% of the carbon lost is from USFS managed lands, 30% from private and Native American lands, 5% from non-USFS managed federal lands, and 2% from state or locally managed lands. Finally, of the additional 1212.3 $TgCO_2e$ emitted under the CBAU scenario, 44% of these emissions are projected to originate from USFS managed lands, 38% from private and Native American lands, 14% from non-USFS managed federal lands, and 5% from state or locally managed lands.

Climate Change Impacts by Ecoregion

CBAU results also vary by ecoregion (see **Figure 3** for reference map). Ecoregions east of the Cascade crest include the East Cascades & Modoc, Blue Mountains, and Eastern Oregon ecoregions, while those west of the Cascade crest include the Coast Range, Willamette Valley, Klamath Mountains, and West Cascades ecoregions. Of these, the West Cascades, Klamath Mountains, and East Cascades & Modoc ecoregions are projected to experience the greatest changes in forest area and carbon stocks (**Figure 13**). These three ecoregions experienced the highest amounts of high-severity wildfire during our historical period (2000-2021), so our model assumes they will continue experiencing higher rates of wildfire and associated post-fire regeneration failure, driving changes in forest area and carbon. Consequently, by the end of the simulation, the area of post-fire regeneration failure is greater than the area of productive forest for the West Cascades and East Cascades & Modoc ecoregions and is 47% of the total forest area for the Klamath Mountains ecoregion.

The West Cascades ecoregion, which makes up 16% of forest area and 21% of carbon stocks in 2022, loses 68% of its productive forest area (decreasing from 4.8 to 1.6 million acres) and 24% of its carbon stocks (decreasing from 2.1 to 1.6 $PgCO_2e$) from 2022-2100 under CBAU (**Figure 13**), accumulating 2.8 million acres of land that have failed to regenerate post-fire. This large loss of productive forest area, combined with a 55% decline in productivity by 2090, means that from 2022-2100 the West Cascades ecoregion is projected to switch from being a net carbon sink to a net carbon source and emit on average 4.7 $TgCO_2e\ yr^{-1}$ more carbon than under BAU assumptions, accounting for 30% of the total additional net carbon emissions across the entire state.

Similarly, the Klamath Mountains ecoregion, which makes up 13% of forest area and 16% of carbon stocks in 2022, loses 61% of its productive forest area (decreasing from 4.0 to 1.6 million acres) and 36% of its carbon stocks (decreasing from 1.6 to 1.0 $PgCO_2e$) in the CBAU scenario, with 1.4 million acres of post-fire regeneration failure accumulating by 2100. As in the West Cascades ecoregion, substantial losses of productive forest area to post-fire regeneration failure and a 54% decline in productivity by 2090 mean that from 2022-2100 the Klamath Mountains ecoregion, which is a very slight net carbon source under BAU assumptions (0.02 $TgCO_2e\ yr^{-1}$), will emit on average 2.8 $TgCO_2e\ yr^{-1}$ more carbon under CBAU assumptions. These additional emissions account for 19% of the total additional net carbon emissions across the state.

The East Cascades & Modoc ecoregion, which makes up 21% of forest area and 17% of carbon stocks in 2022, loses 57% of its productive forest area (decreasing from 6.5 to 2.8 million acres) and 34% of its carbon stocks (decreasing from 1.7 to 1.1 $PgCO_2e$) under CBAU, with 2.9 million acres of post-fire regeneration failure accumulating from 2022-2100. Interestingly, despite this large loss of productive forest area, and an above average (60% vs 57%) decline in productivity, the East Cascades & Modoc ecoregion only accounts for 9% (+1.3 $TgCO_2e\ yr^{-1}$) of the total additional net carbon emissions under CBAU. This relatively small change in emissions is due to the fact that under the BAU scenario, the East Cascades & Modoc ecoregion is the largest net carbon source, emitting an average of 3.8 $TgCO_2e\ yr^{-1}$ (**Figure 13**), and thus has limited capacity for increased emissions from more frequent disturbance.

In addition, for much of the forest area in this ecoregion which burns but does not fail to regenerate (primarily Ponderosa pine and Western white pine forest type groups), carbon stocks and productivity increase post-fire, indicating that under the BAU scenario these forests have reached an age-related asymptote in net growth and productivity (mean stand age of 109 years old in 2022 vs the statewide average of 87 years old).

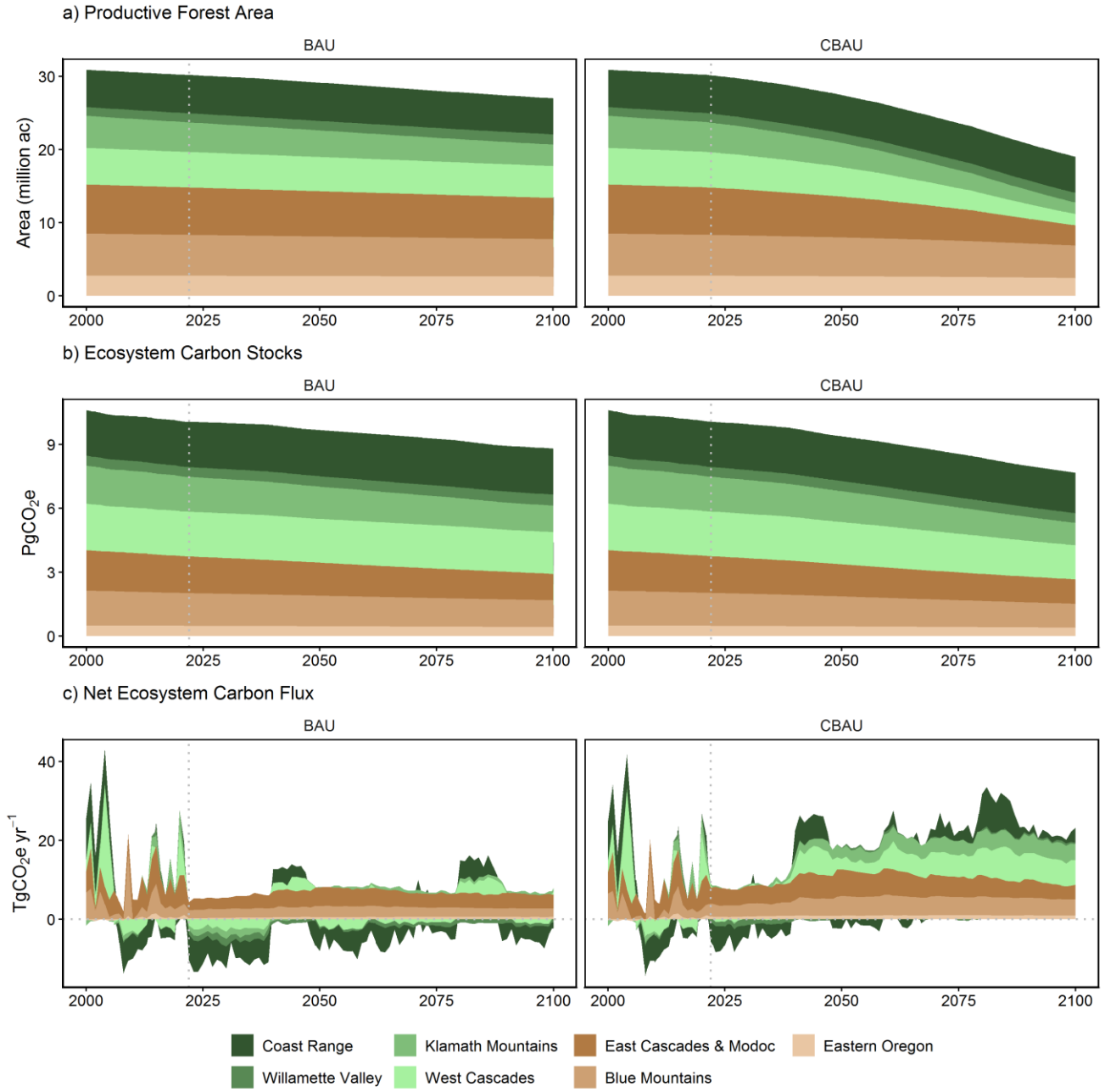


Figure 13. BAU and CBAU scenario results showing a) total productive forest area (million acres), b) ecosystem carbon stocks ($PgCO_2e$), and c) annual net ecosystem carbon flux ($TgCO_2e\ yr^{-1}$) by ecoregion from 2000-2100. Net ecosystem carbon flux refers to the net yearly sequestration of carbon by forests across all 14 ecosystem carbon pools, after accounting for decomposition, natural disturbance emissions, and wood product transfers. In Panel c), negative numbers for net ecosystem carbon flux represent a net carbon sink and positive numbers represent a net carbon source. Ecoregions are color coded; those which are west of the Cascade crest are depicted in shades of green, while those that are east of the Cascade crest are shown in shades of brown.

The four other ecoregions in our model experience more moderate losses of productive forest area and carbon stocks under the CBAU scenario, and of these, the Blue Mountains ecoregion exhibits the largest changes. In this ecoregion, which makes up 19% of forest area and 15% of carbon stocks in 2022, productive forest area declines by 20% (decreasing from 5.6 to 4.5 million acres) and carbon stocks decline by 27% (decreasing from 1.5 to 1.1 $PgCO_2e$) from 2022-2100 (**Figure 13**), with 0.7 million acres of land in a state of post-fire regeneration failure by the end of century. The combined effect of this loss in productive forest area and a 60% decline in productivity by 2090 is an increase in net carbon source strength for the Blue Mountains ecoregion. On average, this ecoregion emits 1.9 $TgCO_2e\ yr^{-1}$ more carbon under CBAU than under BAU, which corresponds to 12% of the total additional net carbon emissions across the state.

In the Eastern Oregon ecoregion, which makes up 9% of forest area and 5% of carbon stocks in 2022, productive forest area declines by 11% (decreasing from 2.7 to 2.4 million acres) and carbon stocks decline by 18% (decreasing from 0.5 to 0.4 $PgCO_2e$) in the CBAU scenario from 2022-2100, over which time this ecoregion accumulates 0.2 million acres of post-fire regeneration failure. These losses of productive forest area and a 62% decline in productivity by 2090 (the largest of any ecoregion) mean that under CBAU, forests in Eastern Oregon become a stronger source emitting on average 0.4 $TgCO_2e\ yr^{-1}$ more carbon than under BAU, making up 3% of the total additional statewide net carbon emissions.

In the Coast Range ecoregion, which makes up 17% of forest area and 21% of carbon stocks in 2022, productive forest area declines by 6% (decreasing from 5.2 to 4.9 million acres) and carbon stocks decline by 10% (decreasing from 2.1 to 1.9 $PgCO_2e$) under the CBAU scenario from 2022-2100. This ecoregion did not experience any historical (2000-2021) high-severity wildfire, and this disturbance is therefore not included in our CBAU assumptions, so none of the Coast Range forest area is projected to enter a state of post-fire regeneration failure by 2100. Despite this lack of post-fire regeneration failure and the relatively small loss of forest area to deforestation, forests in the Coast Range are expected to experience a 53% decline in productivity by 2090, which causes the Coast Range to switch from net carbon sink to net carbon source and emit an average of 3.4 $TgCO_2e\ yr^{-1}$ more carbon than under BAU, accounting for 22 % of the total additional statewide net emissions under CBAU.

Finally, from 2022-2100, the Willamette Valley ecoregion, which makes up 4% of forest area and 5% of carbon stocks in 2022, experiences a net increase of productive forest area due to a trend of afforestation outpacing deforestation (+7.5%, increasing from 1.2 to 1.3 million acres). However, over this period the Willamette Valley still experiences a modest 0.6% net loss of carbon stocks (decreasing from 0.459 to 0.456 $PgCO_2e$) and accumulates 0.07 million acres of post-fire regeneration failure. Like the Coast Range, these small losses and a 53% decline in productivity by 2090 mean that under the CBAU the Willamette Valley ecoregion is projected to emit more carbon (0.8 $TgCO_2e\ yr^{-1}$; 6% of total statewide net carbon emissions) than under BAU. Despite this, it is the only ecoregion which remains a net carbon sink from 2022-2100.

Overall, the ecoregions east of the Cascade crest (East Cascades & Modoc, Blue Mountains, Eastern Oregon), which make up 49% of forest area and 37% of carbon stocks in 2022, account for 41% of the loss of productive forest area and 45% of the loss of carbon stocks from 2022-2100 (**Figure 13**). Of the additional 1212.3 $TgCO_2e$ emitted under the CBAU scenario from 2022-2100, just 23% (282.0 $TgCO_2e$) comes from these three ecoregions, each of which are a net carbon source under both BAU and CBAU. By contrast, the four west side ecoregions (Coast Range, Willamette Valley, Klamath Mountains, and West Cascades) contribute 77% of the additional carbon emissions, with two of four ecoregions (Klamath Mountains and West Cascades) switching from a net carbon sink to a net carbon source.

Effects of Alternative Management Scenarios

Net Carbon Balance in Forests and the Forest Products Sector

From a systems perspective, Oregon forests and forest products collectively remain a net carbon source from 2034-2100 under all scenarios modeled in this analysis, indicated by a net carbon balance greater than zero (**Figure 14a**). *Net carbon balance* here includes net ecosystem carbon flux in the forest, transfers of HWP from the forest to in use or in landfill pools, emissions from HWP in use and in landfills, substitution benefits (which can be positive or negative) in years where harvest is different than CBAU, and leakage in years where harvest is less than CBAU. Net carbon balance is presented from the atmospheric perspective, where negative values indicate CO_2 sequestered from the atmosphere and captured as carbon in forests and wood products (a net carbon sink) and positive values indicate CO_2 emitted to the atmosphere from forests and wood products (a net carbon source).

Prior to 2034, several scenarios exhibited annual rates of carbon sequestration and storage which surpassed their annual emissions; however, by 2034 and beyond, climate related declines in NPP and growth reduce annual sequestration levels below annual emissions levels in all scenarios tested, switching the forest and forest products sector from net carbon sink to net carbon source. Despite this systems-level trajectory of increasing net carbon balance (i.e. lower carbon sequestration and storage), several scenarios illustrate potential pathways to slow or reverse the influences of future climate on forest ecosystems, and when combined with alternate wood utilization, these pathways may offer progress toward climate-smart forestry objectives – balancing carbon sequestration and storage while improving the stability and resilience of forests in the state. We explore these dynamics in various sections below, starting here with the overall net carbon balance for each ecosystem scenario, then moving to examine our alternative HWP scenarios in the **Wood Products Carbon Dynamics** section. Finally, we delve into the ecosystem condition and age class dynamics at play in each scenario in the **Ecosystem Carbon Trends** and **Impacts of Age Class Distribution on Ecosystem Carbon Stocks and Productivity** sections.

To better compare each scenario's performance against the CBAU scenario, we can assess net carbon balance in *cumulative standardized* terms, where CBAU values are subtracted from each scenario (essentially setting CBAU to 0) and net ecosystem carbon flux or net carbon balance values are summed over the 101-year simulation period to quantify the cumulative carbon sequestered and stored or emitted for each scenario relative to CBAU (**Figure 14b**). This allows for a more direct comparison of the relative impacts of each alternative management practice on projected future carbon trends. We can also disaggregate these cumulative standardized metrics into their component parts to illustrate the influence of each scenario on each element of net carbon balance (**Figure 15**).

Of the 13 alternative scenarios with BAU HWP parameters tested in this analysis, six yielded lower cumulative net carbon balance (i.e. higher carbon sequestration and storage) (**Figure 14b**) relative to the CBAU scenario. For the scenarios focused on resilience to future natural disturbance, the Wildfire Resilience scenario had the highest cumulative net carbon balance (+562.3 $TgCO_2e$, +53% relative to CBAU; **Figure 14b**), while the Pest Resilience scenario had the second lowest cumulative net carbon balance (-232.6 $TgCO_2e$, -22% relative to CBAU; **Figure 14b**).

Both resilience scenarios include additional thinning treatments to reduce the severity of future natural disturbances, and the Wildfire Resilience scenario also includes prescribed burning (pile burn and Rx burn) treatments (**Table 4**). The Wildfire Resilience scenario reduces the cumulative area of high and moderate-severity wildfire from 2022-2100 by 16,799,589 and 11,570,138 acres respectively, while subsequently increasing the area of low-severity wildfire by 18,397,570 acres. The Pest Resilience scenario reduces the area of high and moderate-severity insect disturbance (defoliation and mortality)

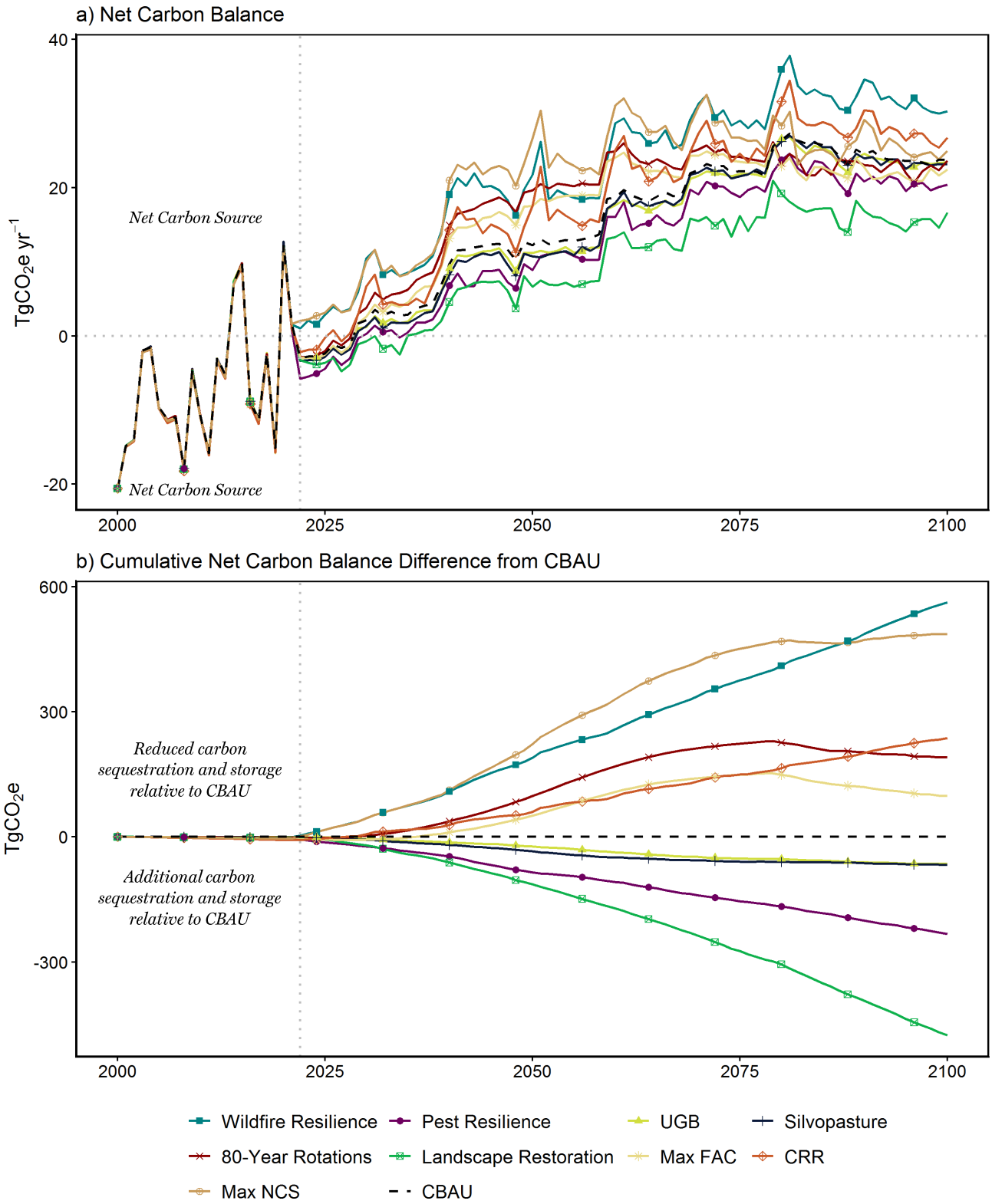


Figure 14. Net carbon balance for selected scenarios (2000-2100) depicted in a) annual terms and b) cumulative terms, standardized to CBAU. Net carbon balance includes net ecosystem carbon flux in the forest, transfers to HWP, emissions from wood products in use and in landfills, substitution benefits in years where harvest is different than CBAU, and leakage in years where harvest is less than CBAU. Negative values denote carbon sequestration (a net carbon sink). Positive values denote carbon emissions (a net carbon source). Scenario abbreviations are as follows: UGB = No Deforestation outside of the Urban Growth Boundaries, CRR = Combined Resilience and Restoration, Max FAC = Maximum Forest Area and Carbon, Max NCS = Maximum Forests as Natural Climate Solutions. Scenarios not depicted are the CMAI Based Rotations, Uneven-Aged Management, Net Zero Forest Loss via Decreased Deforestation (NZD), and Net Zero Forest Loss via Increased Afforestation (NZA) scenarios.

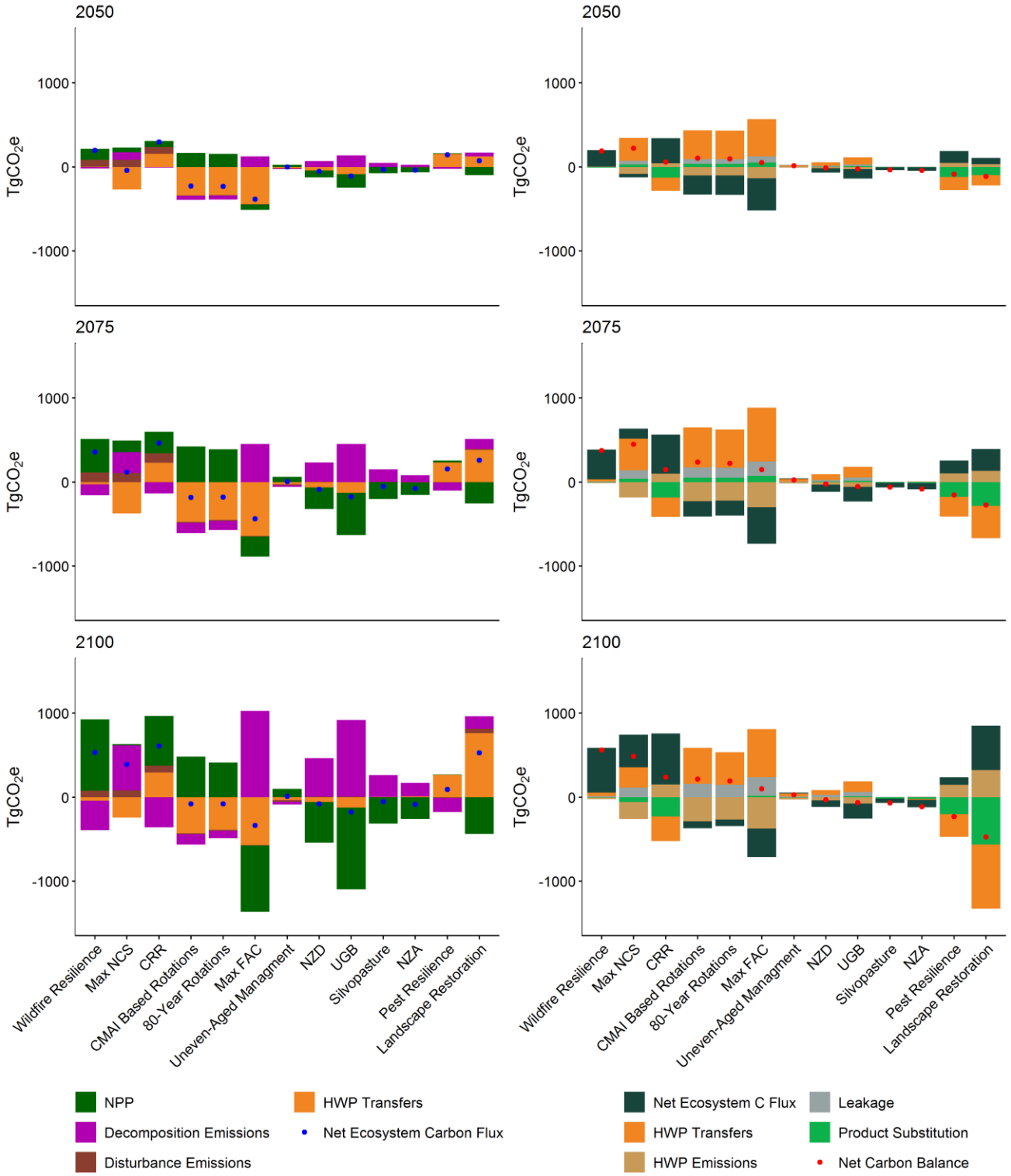


Figure 15. Snapshot of cumulative standardized net ecosystem carbon flux (left column) and cumulative standardized net carbon balance (right column) and their component parts for all scenarios with BAU HWP parameters in 2050, 2075, and 2100. Scenarios are listed from left to right in descending order of net carbon balance in 2100 (from higher emissions to lower emissions). Negative values denote additional carbon sequestration and storage relative to CBAU. Positive values denote reduced carbon sequestration and storage relative to CBAU. HWP transfers are depicted as a net loss from the perspective of the forest (left column), and as gross storage from the system-level perspective (right column). To calculate net storage of carbon in in-use and in-landfill HWP pools, sum HWP transfers and HWP emissions values in the left column. Scenario abbreviations are as follows: NZA = Net Zero Forest Loss via Increased Afforestation, NZD = Net Zero Forest Loss via Decreased Deforestation, UGB = No Deforestation Outside of the Urban Growth Boundary, CRR = Combined Resilience and Restoration, Max FAC = Maximum Forest Area and Carbon, Max NCS = Maximum Forests as Natural Climate Solutions.

from 2022-2100 by 1,034,362 and 20,112,022 acres respectively, while subsequently increasing the area of low-severity insect disturbance (defoliation and mortality) by 21,155,041 acres. As a result of these treatments, cumulative decomposition emissions are substantially reduced relative to CBAU (-351.4 $TgCO_2e$, -2% for Wildfire Resilience; -170.7 $TgCO_2e$, -1% for Pest Resilience; **Figure 15a**) due to more material either being removed for HWP during thinning treatments (which occurs in both the Wildfire Resilience and the Pest Resilience scenario; **Table 4**) or combusted in pile or Rx burn treatments (which only occur in the Wildfire Resilience scenario; **Table 4**). These treatments also reduce the transfer of carbon to DOM pools relative to CBAU by shifting high and moderate-severity disturbance to low-severity disturbance (both insect and fire), leading to lower tree mortality and subsequent decomposition emissions (**Figure 15a**). In the Wildfire Resilience scenario, 7,166,472 (60%) fewer acres of forest enter a state of post-fire regeneration failure from 2022-2100, meaning that decomposition emissions for this landscape type will be reduced. Despite these decreased decomposition emissions, cumulative disturbance emissions are higher than CBAU in the Wildfire Resilience scenario (+76.6 $TgCO_2e$, +13%; **Figure 15a**), due in part to the additional 3,358,856 acres of Rx fire and pile burns associated with wildfire resilience treatments, which shift carbon emissions from larger, less frequent wildfire events to smaller, more frequent treatment events. For the Pest Resilience scenario, cumulative disturbance emissions are slightly lower than CBAU (-7.6 $TgCO_2e$, -1%; **Figure 15a**), which can mainly be attributed to fewer emissions from wildfire due to reduced carbon stocks in areas which have received treatment.

An additional side effect of the wildfire resilience treatments is an increased average stand age across the state. High-severity wildfire acts as a stand-replacing disturbance, so reducing the area of high-severity wildfire reduces the rate of stand replacement across the landscape and leads to an increase in mean stand age (+18 years relative to CBAU in 2100). In general, older stands have lower rates of biomass accumulation (explored more in the **Impacts of Age Class Distribution on Ecosystem Carbon Stocks and Productivity** section below) and this effect leads to substantially reduced (less negative) cumulative NPP for the Wildfire Resilience scenario (+849.6 $TgCO_2e$, -5% relative to CBAU; **Figure 15a**). The Pest Resilience scenario also reduces the area of stand-replacing high-severity insect mortality (-1,548 acres relative to CBAU), but this rather small effect does not meaningfully impact stand age. The very small cumulative decrease in NPP (+2.5 $TgCO_2e$, -0.01% relative to CBAU; **Figure 15a**) observed in the Pest Resilience scenario is likely the result of model stochasticity in disturbance events, rather than a real effect of the scenario altering forest productivity.

HWP transfers also differ between these two resilience scenarios. The Wildfire Resilience scenario has a lower cumulative transfer of carbon from the forest to the forest products sector than CBAU (-43.1 $TgCO_2e$, -2%; **Figure 16**), while the Pest Resilience scenario has a higher cumulative amount of HWP transfer relative to CBAU (+266.3 $TgCO_2e$, +11%; **Figure 16**). In the case of the Wildfire Resilience scenario, this reduced transfer is occurring for two reasons. First, since the wildfire resilience treatments are helping to reduce the area of high-severity wildfire, the cumulative volume of material removed via salvage harvest in the Wildfire Resilience scenario is reduced (-69.1 $TgCO_2e$ relative to CBAU). Although this reduction in salvage harvest means more merchantable biomass remains in the forest, facilitating an increase in cumulative high and intermediate harvest for the Wildfire Resilience scenario (+22.8 $TgCO_2e$ relative to CBAU), the net effect from the loss of this salvage is lower cumulative HWP transfers (**Figure 16**). The second effect is a reduction in the volume of material removed during commercial thinning treatments (-6.6 $TgCO_2e$ relative to CBAU). This occurs primarily in the latter half of the simulation, as aggressive resilience treatments from 2022-2050 successfully lower carbon and biomass, reducing the yield of subsequent commercial thinning treatments. This latter effect is more likely to occur east of the Cascades, where removals during thinning treatments were not modeled. Wood utilization from thinning treatments is substantially less common in these ecoregions, due in part to lack of mill infrastructure and market demand for HWPs produced from small diameter material

(see **Appendix Table S8** for additional details of wildfire resilience treatments). In contrast to the Wildfire Resilience scenario, all of the Pest Resilience treatments include HWP removals. This represents guidance that to effectively reduce the risk of insect and disease spread, slash must be appropriately treated (typically burnt, masticated, or otherwise disposed of offsite). Since this material is removed from the forest, we chose to divert this carbon into the forest products sector, thus treating it as any other harvested wood. Implications of this modeling decision and other alternative wood products modeling scenarios are explored in more detail in the **Harvested Wood Products Carbon Dynamics** section.

Relative to differences in the ecosystem components, differences in the forest products sector between CBAU and the resilience scenarios are small. The Wildfire Resilience scenario has lower cumulative HWP emissions (-20.1 $TgCO_2e$, -1%; **Figure 15b**) relative to CBAU, about 57% of which (11.6 $TgCO_2e$) is offset by leakage (in years when harvest is less than CBAU), and a small (-3.9 $TgCO_2e$) amount of product substitution as the result of years where additional material was removed from thinning treatments and was converted into commodities such as lumber and composite panels. However, since cumulative HWP transfers are lower than CBAU for the Wildfire Resilience scenario, carbon stocks in the in-use and in-landfill pools of the forest products sector (calculated as HWP transfers minus HWP emissions) are 23.0 $TgCO_2e$ (-3%) lower than under CBAU by 2100. The Pest Resilience scenario has higher HWP emissions (+147.1 $TgCO_2e$, +8%; **Figure 15b**) than CBAU, no leakage (as annual harvest levels are higher than CBAU in all years), and a much larger amount of product substitution (-203.9 $TgCO_2e$; **Figure 15b**) from additional harvested material being used in products which displace more emissions-intensive alternatives. In addition, more carbon is stored in the in-use and in-landfill pools of the forest products sector (+119.2 $TgCO_2e$, +18% relative to CBAU). Overall, from a systems perspective, the net reductions in emissions from the forest products sector are too small to make up for the reduced NPP and additional prescribed fire emissions associated with the Wildfire Resilience scenario, causing it to have the highest cumulative net carbon balance (meaning reduced carbon sequestration and storage relative to CBAU) of any scenario tested (**Figure 14b**). Conversely, the reduced ecosystem emissions, large amount of HWP carbon storage, and substantial amount of product substitution associated with the Pest Resilience scenario mean that its cumulative net carbon balance is the second lowest (meaning higher carbon sequestration and storage than CBAU) of the 13 alternative scenarios examined (**Figure 14b**).

All three of the altered harvest management scenarios (CMAI Based Rotations, 80-Year Rotations, and Uneven-Aged Management) experience similar ecosystem and HWP dynamics, scaled in proportion to the forest area affected by each scenario (**Figure 15**). The CMAI Based Rotations and 80-Year Rotations scenario each allow for extended rotations on 30,118,024 acres, whereas the Uneven-Aged Management scenario switches 1,701,285 acres east of the Cascade crest from management with clearcut to a group selection harvest rotation (**Table 4**). All three scenarios have cumulative net carbon balance values which are greater (meaning lower carbon sequestration and storage) than CBAU: +214.7 $TgCO_2e$ (+20%) for the CMAI Based Rotations scenario, +190.7 $TgCO_2e$ (+18%) for the 80-Year Rotations Scenario, and +28.4 $TgCO_2e$ (+3%) for the Uneven-Aged Management scenario (**Figure 14b**). These scenarios have lower cumulative ecosystem emissions than CBAU: -137.2 $TgCO_2e$ (-0.9%) for the CMAI Based Rotations scenario, -101.5 $TgCO_2e$ (-0.6%) for the 80-Year Rotations scenario, and -52.3 $TgCO_2e$ (-0.3%) for the Uneven-Aged Management scenario (**Figure 15a**), mainly driven by reductions in decomposition emissions from logging residue, as less frequent but larger harvests lead to less overall logging residue production. However, the altered harvest dynamics associated with each of these scenarios increase mean stand age relative to CBAU. For the CMAI Based Rotations and 80-Year Rotations scenarios, difference in stand age initially grows to a maximum of +6.1 and +5.4 years (respectively) in 2065, before declining down to +1.9 and -0.7 years (respectively) in 2100, after the first round of deferred harvests are completed. Because harvest levels are more constant (though lower) in

the Uneven-Aged Management scenario, difference in stand age slowly increases throughout the simulation (+0.04 yrs yr^{-1}) to a maximum difference of +3.1 years in 2099. As with the Wildfire Resilience scenario, these increases in stand age cause a reduction (less negative value) in cumulative NPP relative to CBAU of +484.3 $TgCO_2e$ (-3%) for the CMAI Based Rotations scenario, +410.5 $TgCO_2e$ (-2%) for the 80-Year Rotations scenario, and +98.1 $TgCO_2e$ (-0.6%) for the Uneven-Aged Management scenario (**Figure 15a**). This outweighs the carbon gains from reduced ecosystem emissions.

Looking at forest product sector dynamics for the CMAI Based Rotations, 80-Year Rotations, and Uneven-Aged Management scenarios, cumulative transfers of carbon from the forest to the forest products sector are lower than CBAU for all three scenarios (-428.4 $TgCO_2e$, -17% for the CMAI Based Rotations scenario; -387.5 $TgCO_2e$, -16% for the 80-Year Rotations scenario; and -34.9 $TgCO_2e$, -1% for the Uneven-Aged Management scenario; **Figure 15**). In turn, these reductions in cumulative HWP transfers mean lower cumulative HWP emissions (-286.7 $TgCO_2e$, -16% for the CMAI Based Rotations scenario; -265.3 $TgCO_2e$, -15% for the 80-Year Rotations scenario; and -27.1 $TgCO_2e$, -1% for the Uneven-Aged Management scenario; **Figure 15b**) and less carbon storage in the in-use or in-landfill pools (-141.7 $TgCO_2e$, -21% for the CMAI Based Rotations scenario; -122.2 $TgCO_2e$, -18% for the 80-Year Rotations scenario; and -13.2 $TgCO_2e$, -2% for the Uneven-Aged Management scenario; **Figure 15b**). Leakage is applied to each of the scenarios in years where harvest volumes are less than CBAU, further increasing emissions by 157.2 $TgCO_2e$ for the CMAI Based Rotation scenario, 146.8 $TgCO_2e$ for the 80-Year Rotations scenario, and 10.1 $TgCO_2e$ for the Uneven-Aged Management scenario (**Figure 15b**). The impact of product substitution is relatively small for each scenario, reducing cumulative emissions by -2.9 $TgCO_2e$ and -5.8 $TgCO_2e$ for the CMAI Based Rotations and Uneven-Aged Management scenarios (because of higher levels of annual harvest and thus product production after the deferral period), while increasing emissions by 0.2 $TgCO_2e$ for the 80-Year Rotations scenario (because of lower annual harvest levels in most years of the simulation; **Figure 15b**). Overall, despite a cumulative net ecosystem carbon flux less than CBAU (meaning greater ecosystem carbon sequestration and storage) for the CMAI Based Rotations and 80-Year Rotations scenarios (-81.3 $TgCO_2e$, -5%; and -78.5 $TgCO_2e$, -5%, respectively; **Figure 15a**), when accounting for the systems-level impacts of less carbon storage in in-use or in-landfill HWP pools and leakage of some harvest outside of Oregon, our results suggests that net carbon balance will be increased (meaning less carbon sequestration and storage) relative to CBAU if rotation lengths are increased or if uneven-aged management is adopted in place of traditional even-aged management on the east side of the Cascades (**Figure 14b**).

All four of the altered land use and land cover scenarios (Net Zero Forest Loss via Decreased Deforestation (NZD), No Deforestation Outside of the Urban Growth Boundary (UGB), Silvopasture, and Net Zero Forest Loss via Increased Afforestation (NZA)) have cumulative net carbon balance values which were less than CBAU (meaning more carbon sequestration and storage; -33.2 $TgCO_2e$, -3% for the NZD scenario; -64.8 $TgCO_2e$, -6% for the UGB scenario; -67.1 $TgCO_2e$, -6% for the Silvopasture scenario; and -113.8 $TgCO_2e$, -11% for the NZA scenario; **Figure 14b**). Like the altered harvest management scenarios, these net carbon balance effects are proportional to the amount of net forest area change (**Figure 15**). The NZD and UGB scenarios each decrease the amount of total deforestation from 2022-2100 (-2,487,301 and -4,914,436 acres relative to CBAU, respectively), while the Silvopasture and NZA scenarios each add forest area via low density tree planting in pastures (+722,921 acres relative to CBAU) or afforestation (+2,474,327 acres relative to CBAU). As a result, all four scenarios end the simulation with a greater amount of forest area than CBAU. These increases in forest area relative to CBAU mean that cumulative NPP is increased (more negative) relative to CBAU for all four scenarios (-483.0 $TgCO_2e$, +3% for the NZD scenario; -973.6 $TgCO_2e$, +6% for the UGB scenario; -314.4 $TgCO_2e$, +2% for the Silvopasture scenario; and -258.4 $TgCO_2e$, +2% for the NZA scenario;

Figure 15a). Concurrently, cumulative ecosystem emissions from decomposition and disturbance are also increased (+462.8 $TgCO_2e$, +3% for the NZD scenario; +920.5 $TgCO_2e$, +6% for the UGB scenario; +260.1 $TgCO_2e$, +2% for the Silvopasture scenario; and +161.2 $TgCO_2e$, +1% for the NZA scenario; **Figure 15a**). The NZD and UGB scenarios each decrease the cumulative amount of carbon transferred to the forest products sector relative to CBAU (-58.7 $TgCO_2e$, -2%; and -125.2 $TgCO_2e$, -5%, respectively; **Figure 15a**), because of reduced HWP inputs from deforestation. In the Silvopasture and NZA scenarios, cumulative HWP transfers are greater than CBAU (+1.8 $TgCO_2e$, +0.1%; and +8.4 $TgCO_2e$, +0.3%, respectively; **Figure14a**) because some of the newly forested landscape is eligible for later harvest. The net result of these differences in NPP, ecosystem emissions, and HWP transfers is that all four scenarios have lower cumulative net ecosystem carbon flux (meaning more carbon sequestration and storage) than CBAU: -78.8 $TgCO_2e$, -5% for NZD; -178.3 $TgCO_2e$, -10% for UGB; -52.5 $TgCO_2e$, -3% for Silvopasture; and -88.8 $TgCO_2e$, -5% for NZA (**Figure 15a**).

From the forest products sector side of the equation, the scenarios with decreased deforestation (NZD and UGB) had lower cumulative emissions from the forest products sector (-37.0 $TgCO_2e$, -2% for the NZD scenario and -75.2 $TgCO_2e$, -4% for the UGB scenario, relative to CBAU; **Figure 15b**). However, because of reduced HWP transfers, less carbon is cumulatively stored in the in-use and in-landfill pools than under CBAU (-21.7 $TgCO_2e$, -3% for the NZD scenario and -50.0 $TgCO_2e$, -8% for the UGB scenario), and some leakage (+26.4 $TgCO_2e$ for the NZD scenario and +53.7 $TgCO_2e$ for the UGB scenario; **Figure 15b**) occurs in years where harvest is less than CBAU. Cumulative product substitution values are more dynamic, reflecting the fact that substitution is first calculated on an annual basis and can either lead to displaced or additional economy-wide emissions. This means that a small number of years with a large surplus in product production relative to CBAU can skew the cumulative substitution value toward displaced emissions, even if overall HWP transfers (and thus product production) is reduced relative to CBAU. We see this in the NZD scenario, where even though commutative HWP transfers are lower than CBAU, substitution still leads to cumulative emissions reductions (-2.4 $TgCO_2e$; **Figure 15b**). However, in the UGB scenario substitution leads to a cumulative increase in emissions (+9.9 $TgCO_2e$; **Figure 15b**). Overall, these two scenarios emit more carbon from the forest products sector than CBAU (+8.6 $TgCO_2e$ for the NZD scenario and +38.4 $TgCO_2e$ for the UGB scenario), but from a net carbon balance perspective, their increase in ecosystem carbon sequestration more than offsets this effect (**Figure 15b**). For the scenarios with tree planting (Silvopasture and NZA), differences in HWP emissions from CBAU are smaller (-0.1 $TgCO_2e$, <0.05% for the Silvopasture scenario and +2.4 $TgCO_2e$, +0.1% for the NZA scenario), and more carbon is stored in in-use and in-landfill pools (1.9 $TgCO_2e$, +0.3% for the Silvopasture scenario and 6.1 $TgCO_2e$, +0.9% for the NZA scenario) relative to CBAU (**Figure 15b**). Despite the higher cumulative HWP transfers than CBAU, which lead to beneficial product substitution (i.e. reduced emissions from other products; -15.1 $TgCO_2e$ for the Silvopasture scenario and -21.8 $TgCO_2e$ for the NZA scenario), a small amount of leakage (+2.3 $TgCO_2e$ for the Silvopasture scenario and +2.9 $TgCO_2e$ for the NZA scenario) still occurs in years where harvest is less than CBAU (**Figure 15b**). Overall, the tree planting scenarios cumulatively emit less carbon than CBAU from the forest products sector (-14.7 $TgCO_2e$ for the Silvopasture scenario and -22.7 $TgCO_2e$ for the NZA scenario), and when combined with their moderate increases in ecosystem carbon sequestration, their cumulative net carbon balance is lower than CBAU (**Figure 14a**).

The Landscape Restoration scenario is the final solo scenario to be assessed, and it has the lowest net carbon balance of all scenarios modeled, emitting 475.7 $TgCO_2e$ (-45%) less carbon than the CBAU over the course of the 101 years of simulation (**Figure 14b**). This scenario includes restoration treatments to address the current post-fire reforestation backlog (modeled as afforestation; 436,772 acres) as well as contemporary treatments, including site prep, salvage where legally permissible, and low-density tree planting, which restart growth for forest areas in a state of post-fire regeneration failure (14,509,713 acres). The most apparent consequence of these treatments is the increase in both total forest area and

productive (not in a state of post-fire regeneration failure) forest area relative to CBAU (+265,088 and +7,777,113 acres, respectively). Due to this increase in forest area, cumulative NPP is increased (more negative) by -437.2 $TgCO_2e$ (+3%) relative to CBAU, while cumulative emissions are also increased by +201.3 $TgCO_2e$ (+1%) relative to CBAU (**Figure 15a**). This increase in emissions comes mainly from increased decomposition across the larger productive forest area (+150.8 $TgCO_2e$, +1% relative to CBAU), and partly from increased disturbance emissions (+50.5 $TgCO_2e$, +8% relative to CBAU) due to reburn of restored forests in fire prone areas (**Figure 15a**). In addition, ~84% of the contemporary landscape restoration treatments include salvage logging during site preparation, which contributes to the increase in carbon transferred from the forest to the forest products sector (+763.9 $TgCO_2e$, +31% relative to CBAU; **Figure 15**). As a result of this increased HWP transfer, HWP emissions are +323.8 $TgCO_2e$ (+18%) greater than CBAU and carbon storage in the HWP in-use or in-landfill pools is +440.0 $TgCO_2e$ (+66%) higher than CBAU (**Figure 15b**). Further, product substitution occurs because this material is used in products like lumber and composite panels which displace more emissions-intensive alternative products (-563.7 $TgCO_2e$), offsetting more than the amount of these increased emissions from both the forest ecosystem and the HWP sector. Therefore, even though cumulative net ecosystem carbon flux is +528.0 $TgCO_2e$ (+31%) greater than CBAU, the Landscape Restoration scenario has a net carbon balance almost half the amount of the CBAU scenario (meaning more sequestration and storage), the best of any single ecosystem scenario.

In addition to the ten ecosystem scenarios examined above, we also ran three *portfolios* with BAU HWP assumptions. These portfolios are ensembles of multiple scenarios which could be implemented concurrently to provide a combination of climate change mitigation benefits. These include the Maximum Forest Area and Carbon portfolio (Max FAC; a combination of the Silvopasture, 80-Year Rotations, and UGB scenarios), the Combined Resilience and Restoration portfolio (CRR; a combination of the Wildfire Resilience, Pest Resilience, and Landscape Restoration scenarios), and the Maximum Forests as Natural Climate Solutions portfolio (Max NCS; a combination of the CRR and Max FAC portfolios).

All three portfolios have cumulative net carbon balances greater than CBAU, with the Max FAC portfolio emitting the least carbon (+97.9 $TgCO_2e$, +9%), the CRR portfolio emitting the next most carbon (+236.5 $TgCO_2e$, +22%) and the Max NCS portfolio emitting the most carbon (+486.9 $TgCO_2e$, +46%) relative to CBAU (**Figure 14b**). Beginning with the Max FAC portfolio and looking at the contribution of ecosystem and forest product sector dynamics to its net carbon balance (**Figure 15**), we see that both cumulative NPP (-789.0 $TgCO_2e$, +5%) and cumulative decomposition emissions (+1028.0 $TgCO_2e$, +7%) are increased relative to CBAU, which mirrors the effects of the UGB and Silvopasture scenarios, which each increase the total forest area (**Figure 15a**). However, these effects are somewhat tempered by the inclusion of the 80-Year Rotations scenario in this portfolio. As examined above, deferring harvests reduces cumulative decomposition emissions due to less frequent but larger harvests producing less overall logging residue, and causes an increase in stand age thereby reducing (making less negative) NPP. The combination of the three scenarios in this portfolio also reduces cumulative HWP transfers (-571.5 $TgCO_2e$, -23%, relative to CBAU), through deferred harvest and less material from deforestation entering the forest products sector (**Figure 15**). This reduced cumulative HWP transfer leads to lower HWP emissions (-374.7 $TgCO_2e$, -20%, relative to CBAU), but this also means there is leakage (+220.1 $TgCO_2e$) and negative product substitution leading to an increase (+18.6 $TgCO_2e$) in economy-wide emissions from the use of more emissions-intensive alternative materials instead of wood in years when harvest is deferred (**Figure 15b**). The Max FAC portfolio also has less carbon storage in in-use and in-landfill HWP pools than CBAU (-196.8 $TgCO_2e$, -30%; **Figure 15b**). Even though the Max FAC portfolio has a lower cumulative net ecosystem carbon flux (greater ecosystem carbon sequestration and storage) than CBAU (-337.7 $TgCO_2e$, -20%; **Figure**

15a), increased emissions and decreased HWP carbon storage than CBAU means that its cumulative net carbon balance is higher relative to the CBAU scenario (+97.9 $TgCO_2e$, +9%; **Figure 14b**).

The CRR portfolio has the next highest cumulative net carbon balance of the three portfolios, with additional emissions of +236.5 $TgCO_2e$ (+22%) relative to CBAU. Here the synergistic effects of this portfolio's components become clear, containing scenarios which independently sequester and store the most carbon (Landscape Restoration), second most carbon (Pest Resilience), and least carbon (Wildfire Resilience) through 2100 (**Figure 14b**). This is especially apparent when looking at mean stand age and its effect on NPP. As examined above, mean stand age increases significantly in the Wildfire Resilience scenario due to a substantial reduction in the amount of stand-replacing high-severity wildfire, leading to a decrease in NPP compared with CBAU. In the Landscape Restoration scenario, mean stand age is reduced relative to CBAU, as the result of restoration treatments which restart growth in areas with post-fire regeneration failure, thereby increasing (making more negative) NPP. Both of these effects are present in the CRR portfolio. However, in order for landscape restoration treatments to be necessary, the forest must first enter a state of post-fire regeneration failure, and since the wildfire resilience treatments significantly reduce the amount of high-severity fire and thus post-fire regeneration failure, the landscape restoration treatment effect is more muted (-12,743,710 acres (-87.7%) of treatment area relative to the Landscape Restoration scenario). The mean stand age in 2100 for the CRR portfolio is slightly lower than the Wildfire Resilience scenario, though still greater than CBAU, and much greater than the Landscape Restoration scenario (-5 years relative to Wildfire Resilience, +13 years relative to CBAU, +43 years relative to Landscape Restoration). As a result, cumulative NPP is +592.1 $TgCO_2e$ (-3.5%) greater (less negative) than CBAU for the CRR portfolio (**Figure 15a**).

Looking at other components in the CRR portfolio less impacted by synergistic effects, cumulative decomposition emissions are lower than CBAU (-360.3 $TgCO_2e$, -2.3%), mainly driven by material either being removed or combusted during resilience treatments, though somewhat offset by increased decomposition on restored landscapes (**Figure 15a**). Cumulative disturbance emissions are higher than CBAU (+83.6 $TgCO_2e$, +13.9%) partially because of Rx fire and pile burns associated with wildfire treatments, and due to reburn of landscapes which have undergone restoration treatments (**Figure 15a**). Cumulative HWP removals are greater than CBAU (+292.6 $TgCO_2e$, +11.8%) due to material removed during resilience treatments, as well as material salvaged during restoration treatments (**Figure 15**). Due to this increased cumulative volume of HWP transfers, cumulative HWP emissions (+ 150.7 $TgCO_2e$, +8.3%) and storage of carbon in in-use and in-landfill pools (+141.9 $TgCO_2e$, +21.4%) are also higher than CBAU (**Figure 15b**). The CRR portfolio also sees substantial positive product substitution (-299.7 $TgCO_2e$) from an increase in available wood products which displace more emissions-intensive alternatives, more than offsetting the increase in cumulative HWP emissions. However, due to substantially reduced ecosystem sequestration, which is the result of the age effect of wildfire resilience treatments, cumulative net carbon balance for the CRR portfolio remains above CBAU (e.g., less carbon storage and sequestration; **Figure 14a**).

The Max NCS portfolio, which contains all the scenarios in both the Max FAC and CRR portfolios, has the highest cumulative net carbon balance of all three portfolios and the second highest overall net carbon balance, +483.9 $TgCO_2e$ (+46%) relative to CBAU (**Figure 14b**). In this portfolio, the effects of the Wildfire Resilience and 80-Year Rotations scenarios, which decrease cumulative NPP, are offset by the effects of the UGB, Silvopasture, and Landscape Restoration scenarios, which increase cumulative NPP. As a result, cumulative NPP is just +15.3 $TgCO_2e$ (-0.1%) greater (less negative) than CBAU (**Figure 15a**). Emissions differences are less balanced, which leads the Max NCS portfolio to have higher cumulative decomposition (+533.8 $TgCO_2e$, +4%) and disturbance emissions (+81.7 $TgCO_2e$, +14%) than CBAU (**Figure 15a**). Increased decomposition is mainly the result of a larger amount of productive

forest area associated with the reduced deforestation, silvopasture, and landscape restoration treatments in this portfolio, though this is also offset somewhat by the decreased decomposition in existing forests associated with resilience treatments. Increased disturbance emissions come solely from Rx fire, pile burns, and reburn of landscapes which have undergone restoration treatments, as none of the scenarios associated with the Max FAC portfolio substantially alter disturbance emissions. Cumulative HWP transfers are also lower than CBAU for this portfolio (-242.3 $TgCO_2e$, -9.7%), mainly due to the substantial reduction in harvest removals associated with deferred harvest and decreased deforestation, though offset somewhat by material removed in pest resilience treatments and during salvage after landscape restoration (**Figure 15**). As a result of these reduced HWP transfers, cumulative HWP emissions in the Max NCS portfolio are lower than CBAU (-202.0 $TgCO_2e$, -11%), less carbon is stored in in-use and in-landfill pools (-40.2 $TgCO_2e$, -6%), and leakage occurs in years when harvest is less than CBAU (+114.5 $TgCO_2e$), offsetting some of these emissions reductions (**Figure 15b**). However, because HWP transfers exceed CBAU in some years, this portfolio also benefits from product substitution with cumulative substitution benefits of -56.3 $TgCO_2e$ (**Figure 15b**). Overall, despite net HWP carbon balance being lower than CBAU, the cumulative net carbon balance for the Max NCS portfolio is still greater (meaning less carbon sequestration and storage) than CBAU, driven mainly by increased ecosystem emissions without a reciprocal increase in productivity (**Figure 14b**).

Harvested Wood Products Carbon Dynamics

Oregon has a robust and complex forest products sector (**Table 3**), and with continued business as usual forest management, harvest, HWP dynamics, and wood utilization (as represented by the CBAU scenario with BAU HWP assumptions), the forest products sector is projected to have a cumulative *net HWP carbon balance* of -662.5 $TgCO_2e$ through 2100 (**Figure 16b**), making it a growing carbon storage pool. Net HWP carbon balance includes transfers of HWP from the forest to the forest products sector, emissions from wood products in use and in landfills, substitution benefits in years where harvest is different than CBAU, and leakage in years where harvest is less than CBAU. Negative values for net HWP carbon balance denote net carbon storage, whereas positive values denote net carbon emissions (a net carbon source).

The net HWP carbon storage for the CBAU scenario (which is not subject to leakage or substitution) is wholly the result of higher HWP inputs than annual HWP emissions, causing carbon stocks to increase throughout the simulation (**Figure 17**). This is evident when looking at annual dynamics from 2040-2049 and 2080-2087 (**Figure 16a**), both of which are periods of elevated harvest on the typical 40-year rotation (**Figure 10**), leading to a greater-than-average input of carbon to the forest products sector, and thus more storage relative to the somewhat stable level of annual emissions (**Figure 18**). Notably however, annual net HWP carbon balance values become positive (meaning net carbon emissions) in 2064 (0.03 $TgCO_2e\ yr^{-1}$), 2067 (1.1 $TgCO_2e\ yr^{-1}$) and at the end of the simulation (averaging +1.9 $TgCO_2e\ yr^{-1}$ during the period from 2089-2100; **Figure 16a**). This trailing off of net HWP carbon balance in the final decade is driven by reduced harvest yields, brought about by climate-related declines in forest productivity, and an increasing fraction of forest area which would otherwise be eligible for harvest in a state of post-fire regeneration failure. While cumulative net HWP carbon balance for the CBAU only increases slightly from 2089-2100 (**Figure 16b**), indicating that up to this point the forest products sector has provided consistent net carbon storage, a continuation of this depressed HWP inputs trend could lead to further growth in net emissions from the forest products sector. The forest products sector provides net carbon storage for all of the alternative ecosystem scenarios and portfolios, with cumulative net HWP carbon balance values ranging from -266.9 $TgCO_2e$ for the Max FAC portfolio to -1666.1 $TgCO_2e$ for the Landscape Restoration scenario (**Figure 16**). As with the CBAU scenario, much of the annual and cumulative trends in net HWP carbon balance mirror the relative level of HWP transfers, with scenarios with lower overall transfer having higher (less negative, meaning less carbon storage)

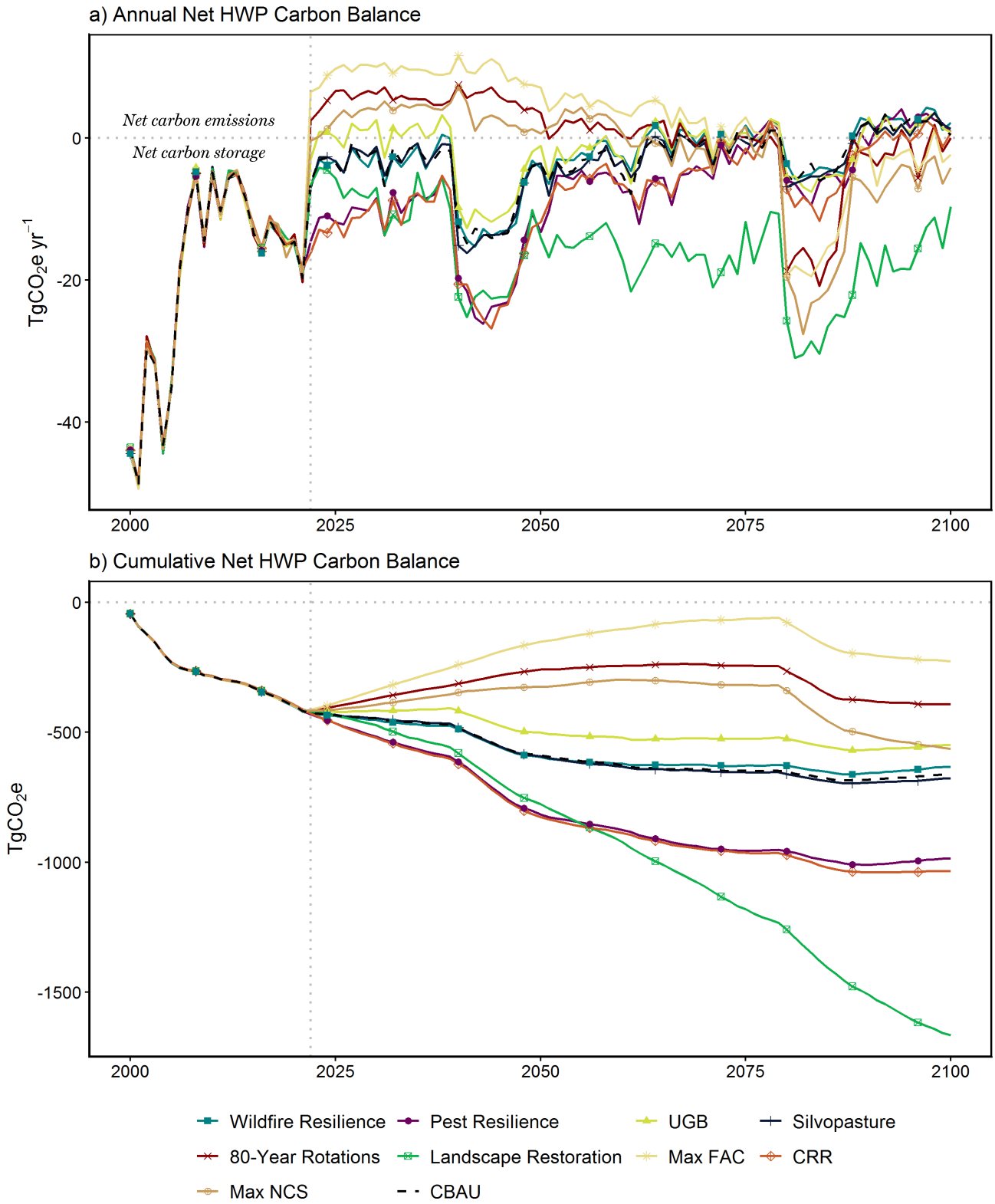


Figure 16. Net HWP carbon balance for selected scenarios (2000-2100) depicted in a) annual and b) cumulative terms. Net HWP carbon balance includes transfers of HWP from the forest to the forest products sector, emissions from wood products in use and in landfills, substitution benefits in years where harvest is different than CBAU, and leakage in years where harvest is less than CBAU. Negative values for net HWP carbon balance denote net carbon storage, whereas positive values denote net carbon emissions (a net carbon source). Scenario abbreviations are as follows: UGB = No Deforestation outside of the Urban Growth Boundary, CRR = Combined Resilience and Restoration, Max FAC = Maximum Forest Area and Carbon, Max NCS = Maximum Natural Climate Solutions. Scenarios not depicted are the CMAI Based Rotations, Uneven-Aged Management, Net Zero Forest Loss via Decreased Deforestation (NZD), and Net Zero Forest Loss via Increased Afforestation (NZA) scenarios.

cumulative net HWP carbon balances. Of particular note, the four scenarios or portfolios which implement deferred harvest (CMAI-Based Rotations, 80-Year Rotations, Max FAC, Max NCS) each have annual net HWP carbon balances above zero (indicating they are a net carbon source) from 2023-2070 (**Figure 16a**). This is the result of lower-than-CBAU harvest rates, which lead to leakage and negative product substitution (e.g., higher economy-wide emissions; **Figure 19**). In addition, during the deferral period, HWP emissions remain at a similar level to the period prior to harvest deferral, due to emissions from products produced before this period reaching end of life or already in landfills (**Figure 18**). Starting in 2080, once the majority of forests reach the age of harvest eligibility under the extended rotation plans and harvest levels return to (and in some cases exceed) CBAU levels, cumulative net HWP carbon balance for each of these scenarios and portfolios begins to trend downward (more storage), though in 2100 net HWP carbon balance still remains above CBAU (**Figure 16**).

By contrast, scenarios with increased HWP transfers store more carbon annually and cumulatively in the forest products sector than CBAU (**Figure 16**). For example, thinning treatments associated with reducing insect risk, which are included in the Pest Resilience scenario and the CRR portfolio, lead to more storage of carbon in HWP (**Figure 17**) as well as substantial product substitution leading to displaced emissions (**Figure 19**). This contributes to a more negative (i.e. lower emissions) net HWP carbon balance, especially from 2022-2050 during the initial treatment phase (**Figure 16a**). Insect thinning treatments are also included in the Max NCS portfolio, though their effects are somewhat masked by the overall reduction in harvest due to extended rotations. However, they can be seen in part when contrasting annual net HWP carbon balance between the Max NCS (includes pest thinning) and Max FAC (does not include pest thinning) portfolios (**Figure 16a**). Wildfire resilience treatments also contribute to a slight increase in the transfer of carbon from the forest during the initial treatment phase (2022-2050); however, a commensurate reduction in post-fire salvage material later in the simulation means that cumulative net HWP carbon balance is largely the same as CBAU (**Figure 16**).

An assumption inherent to all the scenarios run with BAU HWP assumptions is that all of the wood transferred to the wood products sector can be fully utilized according to Oregon's BAU commodity allocation (**Table 3**). Here we assume that regardless of variation in annual harvest levels, where the material originated, or its diameter, harvested wood can and will be utilized in exactly the same way as at present. In reality, wood utilization is a market driven process, and transporting timber over long distances or between millsheds to an appropriate processing facility may not be economically viable. Oregon may also lack the processing capacity for the small diameter material typically removed during resilience treatments, necessitating further investments in novel wood products in order to see full utilization of this material.

To address these another concerns, in addition to modeling each scenario with BAU HWP usage and dynamics, we developed two alternative HWP scenarios which we applied to a subset of ecosystem scenarios (**Table 4**). The Increased HWP Efficiency scenario includes four changes aimed at improving the efficiency and storage capacity of Oregon's forest products sector, in line with several proposed pieces of legislation and state-wide initiatives (e.g., Oregon DEQ's Materials Management program and the City of Portland's Deconstruction program). These changes include an increased product half-life and recycling rate for lumber products, diverting 25% of mill residue toward wood fiber products, and diverting an increasing amount (up to 5% each by 2100) of hardwood material normally used in lumber and composite panels toward mass timber and mass plywood, which are novel product streams not included in the BAU HWP model. We applied this HWP scenario to the CBAU scenario along with the CRR, Max FAC, and Max NCS portfolios in order to assess its impact alone (CBAU) and when implemented concurrently with a suite of possible CSF management practices as represented by our portfolios.

Our second HWP-specific scenario, the Innovative Wood Utilization scenario, is designed to incorporate new and different ways to use harvested wood. Under the BAU HWP assumptions, all of the wood removed during wildfire and pest treatments is treated identically to any other harvest of merchantable timber. However, while Oregon's forest products sector is robust, there are limited uses and markets for the small diameter material typically removed as part of resilience treatments, especially as the annual volume of this material is on average 1.25 times greater than the annual commercial removal and utilization of similar material at present. In addition, the existing mills with the capacity to process this wood (mainly in western Oregon) may be geographically isolated from where the majority of treatments are occurring (in central and eastern Oregon), increasing transportation costs and making use of this wood difficult to justify economically (BBER 2022). Therefore, a more realistic assumption would be that this wood is subject to a separate utilization scheme, encapsulated by the Innovative Wood Utilization scenario. Here, 100% of the material from wildfire and pest resilience treatments is separated from other roundwood inputs in our CBM-HWP-OR model. Of this wood, 50% is used in lumber products, an increasing amount (up to 5% by 2100) is used in biochar (a novel product stream), and the remaining material is combusted for bioenergy. This scenario is only applicable to the Wildfire Resilience and Pest Resilience scenarios along with the CRR and Max NCS portfolios.

These scenarios alter three of the four carbon dynamics for wood products: storage, emissions, and substitution benefits (see the **Harvested Wood Products Model** section for descriptions). Leakage is not affected by these alternate HWP scenarios, as the amount of leakage is based on the level of harvest (and thus HWP carbon inputs) which do not change between the BAU and alternate HWP scenarios. In addition, ecosystem dynamics (NPP, ecosystem emissions, and HWP transfers) are also not affected by the use of an alternate HWP scenario.

For all ecosystem scenarios and portfolios, the Increased HWP Efficiency scenario leads to more carbon stored in HWP stocks relative to BAU HWP assumptions. For the CBAU scenario, implementing the Increased HWP Efficiency scenario leads to +64.9 $TgCO_2e$ (+3%) more carbon stored in the forest products sector by 2100 (**Figure 17**). This includes +18.6 $TgCO_2e$ stored in mass timber and mass plywood, +38.0 $TgCO_2e$ stored in wood fiber, and +90.3 $TgCO_2e$ (+41%) stored in lumber (**Figure 17**). Pulpwood stocks decline by -6.0 $TgCO_2e$ (-20%) as the result of utilizing mill residues for wood fiber instead of for pulpwood products, and contemporary landfill stocks decline by -17.9 $TgCO_2e$ (-8%) due to a higher recycling rate for lumber. When applied to the CRR and Max NCS portfolios, the Increased HWP Efficiency scenario also increases carbon storage by +75.4 $TgCO_2e$ (+4%) for the CRR portfolio and +53.9 $TgCO_2e$ (+3%) for the Max NCS portfolio, relative to each scenario's BAU HWP assumptions (**Figure 17**). In both cases, product distributions are similar to the CBAU scenario.

Conversely, the Innovative Wood Products scenario leads to less carbon stored in HWP stocks by 2100 relative to the BAU HWP assumptions, -58.9 $TgCO_2e$ (-3%) for the CRR portfolio and -61.4 $TgCO_2e$ (-3%) for the Max NCS portfolio (**Figure 17**). This reduced storage comes from the fact that the Innovative Wood Products scenario allocates a substantial proportion (up to 44.9%) of wood coming from wildfire and pest resilience treatments to bioenergy, a product stream which does not accrue carbon stocks due to the assumption that wood used for bioenergy will be combusted in the same year it is harvested. Compared to the BAU HWP assumptions, by 2100 the CRR and Max NCS portfolios store -26.2 $TgCO_2e$ (-13%) and -27.4 $TgCO_2e$ (-16.5%) less carbon in composite panels, -3.5 $TgCO_2e$ (-10%) and -3.8 $TgCO_2e$ (-10%) less carbon in pulpwood, -0.11 $TgCO_2e$ (<-0.01%) and -0.13 $TgCO_2e$ (-0.1%) less carbon in lumber, and -32.4 $TgCO_2e$ (-3%) and -33.7 $TgCO_2e$ (-4%) less carbon in contemporary landfill stores (**Figure 17**). Because of the addition of biochar as a novel product stream for this scenario, the CRR and Max NCS portfolios store additional carbon (+3.3 $TgCO_2e$ and +3.4 $TgCO_2e$, respectively) in biochar.

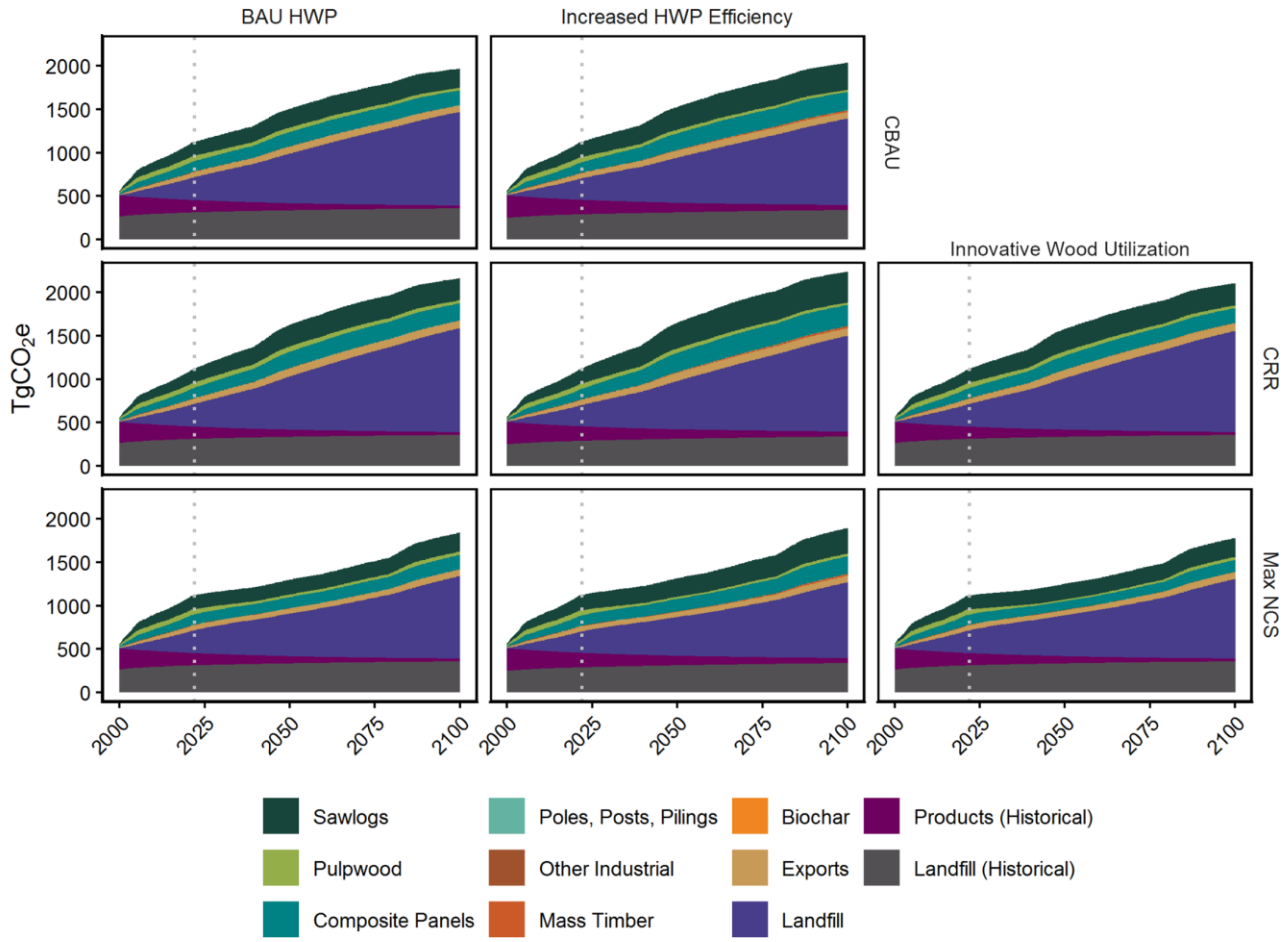


Figure 17. Cumulative HWP carbon stocks (2000-2100, $TgCO_2e$) by primary product for selected combinations of ecosystem (rows) and HWP (columns) scenarios. Positive numbers denote accruing carbon stocks.

The Increased HWP Efficiency scenario leads to lower cumulative HWP emissions relative to BAU HWP assumptions for all ecosystem scenarios and portfolios modeled. For the CBAU scenario, implementing the Increased HWP Efficiency scenario leads to -117.4 $TgCO_2e$ (-6%) less carbon emitted from the forest products sector by 2100 (**Figure 18**). This includes -15.4 $TgCO_2e$ (-5%) fewer emissions from industrial fuel produced from mill residue, -92.1 $TgCO_2e$ (-6%) fewer emissions from commodities in landfills, and -9.9 $TgCO_2e$ (-12%) fewer emissions from waste incineration (**Figure 18**). Declines in landfill emissions are primarily the result of increased half-lives and recycling of construction lumber, and to a lesser degree, shifting away from shorter half-life lumber and composite panel products toward mass timber and mass plywood. In addition, increasing wood fiber production from mill residues means that less pulpwood is produced from mill residues (which on average account for 30% of the annual pulpwood production), and therefore emissions from waste incineration (6% of all pulpwood retirement) decrease. However, the Increased HWP efficiency scenario does not affect bioenergy production, either internationally (from exported roundwood) or domestically (from utilized biomass). When applied to the CRR and Max NCS portfolios, the Increased HWP Efficiency scenario also decreases HWP carbon emissions by -135.7 $TgCO_2e$ (-7%) and -97.2 $TgCO_2e$ (-6%), respectively, relative to each scenario's BAU HWP assumptions (**Figure 18**).

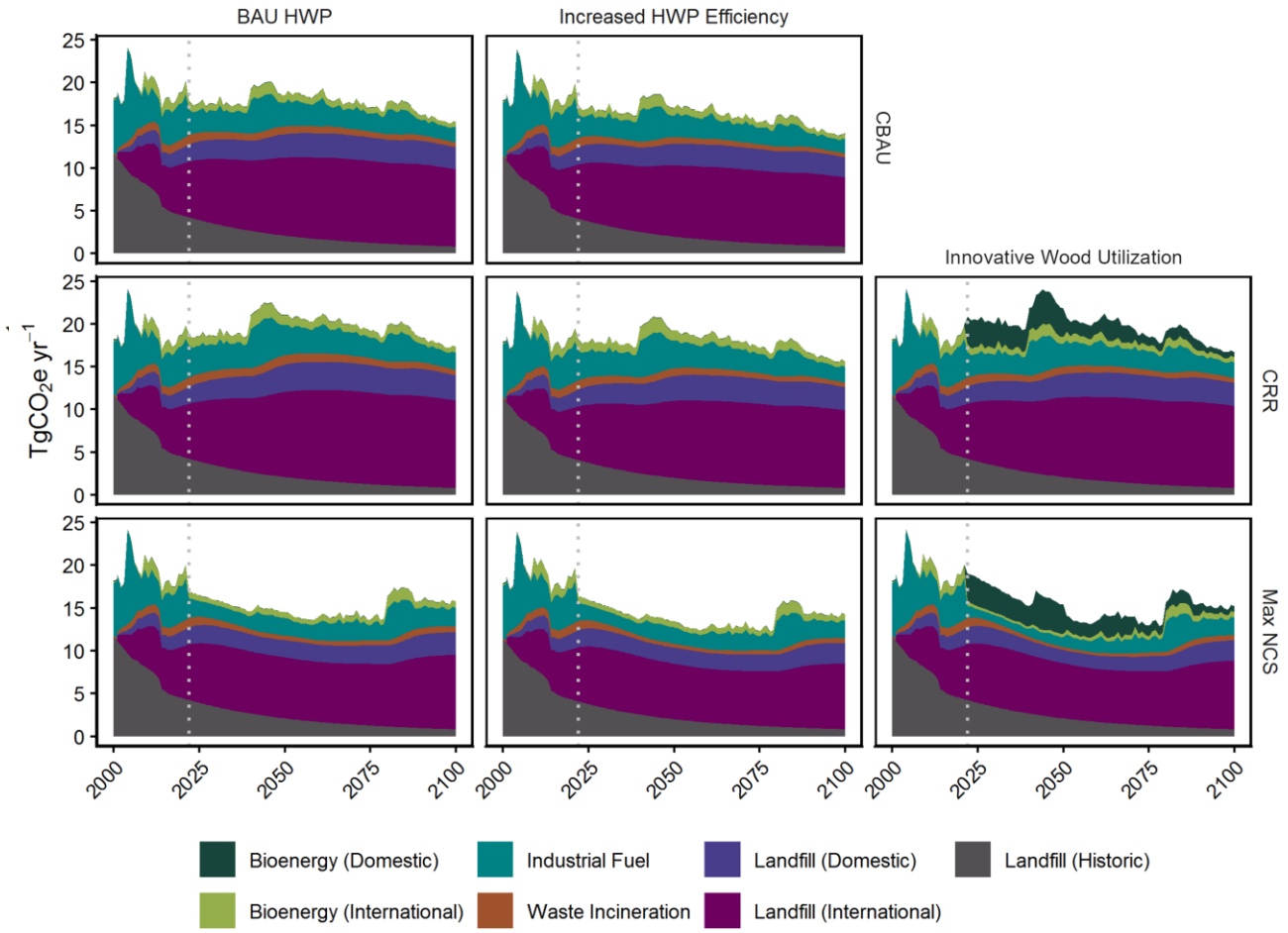


Figure 18. Annual HWP carbon emissions (2000-2100, $TgCO_2e\ yr^{-1}$) by emission source for selected combinations of ecosystem and HWP scenarios. Positive numbers denote emissions of carbon from the forest products sector to the atmosphere.

While the Increased HWP Efficiency scenario leads to lower cumulative HWP emissions, the Innovative Wood Utilization scenario leads to higher cumulative HWP carbon emissions. Relative to each scenario's BAU HWP assumptions, the CRR and Max NCS portfolios each cumulatively emit +16.7 $TgCO_2e$ (+0.8%) and +18.0 $TgCO_2e$ (+1.1%) more carbon, respectively, by 2100 (**Figure 18**). These increased emissions stem from substantial increases in domestic bioenergy emissions (+155.7 $TgCO_2e$ for CRR and +161.6 $TgCO_2e$ for Max NCS), as roughly half of the wood coming from wildfire and pest resilience treatments is allocated to bioenergy. Because of this increase in bioenergy, emissions from landfills (-72.3 $TgCO_2e$ for CRR and -74.9 $TgCO_2e$ for Max NCS), industrial fuel (-40.1 $TgCO_2e$ for CRR and -42.6 $TgCO_2e$ for Max NCS), and waste incineration (-10.4 $TgCO_2e$ for CRR and -10.7 $TgCO_2e$ for Max NCS) are all reduced compared to BAU HWP assumptions (**Figure 18**). However, these reductions do not make up for the increased bioenergy emissions, which are immediate (produced in the same year as the harvest), and complete (100% of the carbon mass is emitted).

Product substitution is also impacted by the alternative HWP scenarios. Relative to the CBAU with BAU HWP assumptions, which has no associated product substitution, the Increased HWP Efficiency scenario leads to a cumulative displacement (i.e. reduction) of -154.4 $TgCO_2e$ of emissions (**Figure 19**). These displaced emissions arise from increased production of wood fiber insulation (-145.9 $TgCO_2e$ of emissions), which receives the same displacement calculation as composite panels, as well as an increase

in the production of mass timber (-11.3 $TgCO_2e$ of emissions). Even though production of mass timber results in less lumber, and therefore an increase in emissions from products being substituted for lumber (+2.8 $TgCO_2e$ of emissions), this scenario still nets out to an overall emissions reduction (**Figure 19**). When the Increased HWP Efficiency scenario is applied to the CRR and Max NCS portfolios, they lead to an additional -167.0 $TgCO_2e$ (+72%) and -75.1 $TgCO_2e$ (+129%), respectively, of displaced emissions relative to each scenario's BAU HWP assumptions (**Figure 19**).

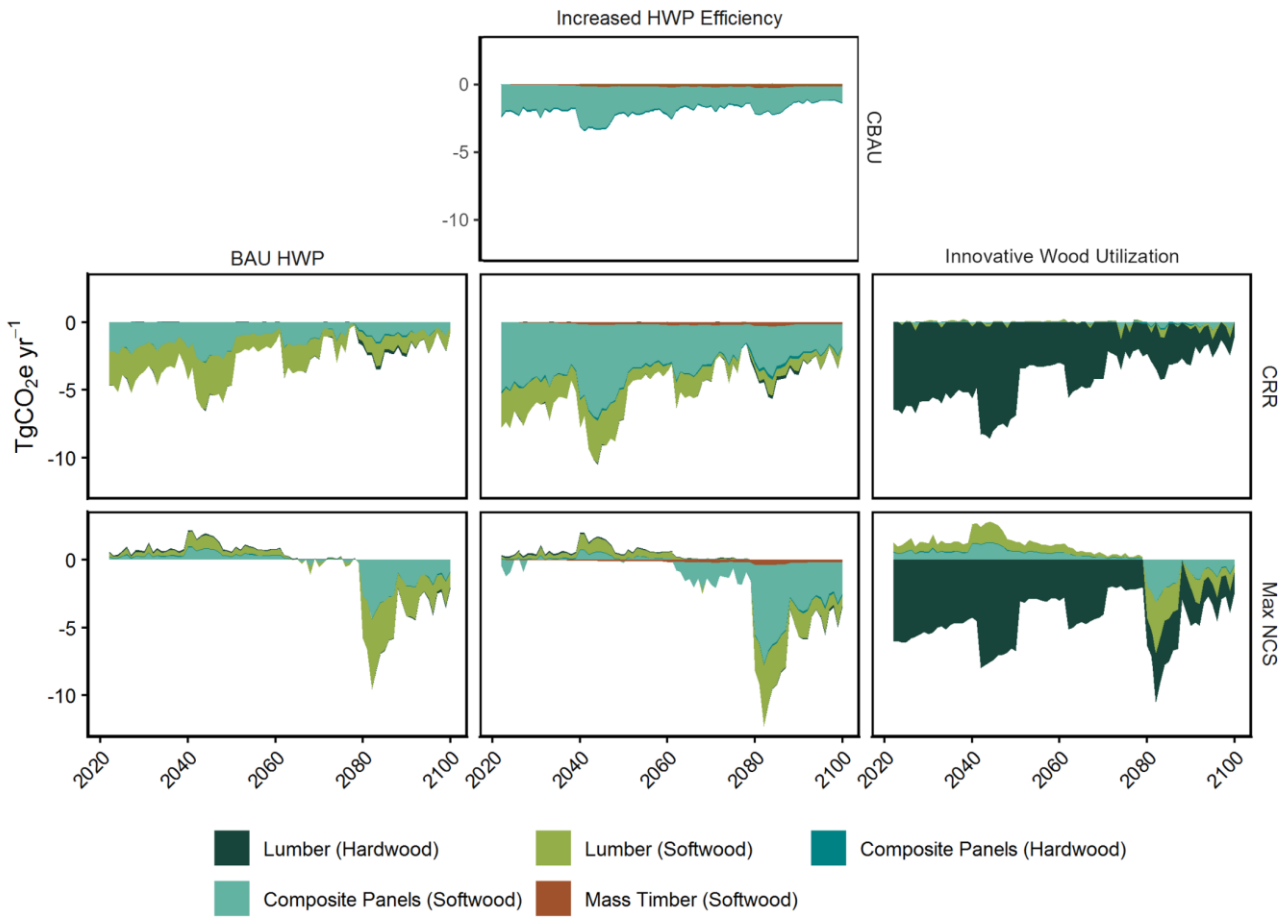


Figure 19. Annual HWP product substitution (2022-2100, $TgCO_2e\ yr^{-1}$) by product category for selected combinations of ecosystem and HWP scenarios. Positive numbers denote emissions from emissions-intensive materials being used in place of wood products. Negative numbers denote HWPs being used in place of for more emissions-intensive materials.

The Innovative Wood Products scenario further alters timber product production, and thus substitution (**Figure 19**). When paired with the CRR and Max NCS portfolios, an additional -102.8 $TgCO_2e$ (+44%) and -241.4 $TgCO_2e$ (+414%) of emissions are displaced relative to each scenario's BAU HWP assumptions. In both cases, increased production of hardwood lumber products leads to substantial product displacement (-321 $TgCO_2e$ for CRR and -311.8 $TgCO_2e$ for Max NCS; **Figure 19**). This is somewhat balanced out by a reduction in the production of composite panels (+100.5 $TgCO_2e$ for CRR and +32.8 $TgCO_2e$ for Max NCS) and softwood lumber (+117.6 $TgCO_2e$ for CRR and +37.8 $TgCO_2e$ for Max NCS).

When taken together, cumulative net HWP carbon balance is lower (meaning lower emissions) than the BAU HWP assumptions for both alternative HWP scenarios across all ecosystem scenarios tested (**Figure 20**). In particular, implementing the Increased HWP Efficiency scenario reduces net HWP carbon balance by -256.8 $TgCO_2e$ (-39%) for CBAU, -303.6 $TgCO_2e$ (-29%) for CRR, -159.0 $TgCO_2e$ (-28%) for Max NCS, and -118.8 $TgCO_2e$ (-52%) for Max FAC. Likewise, the Innovative Wood Products

scenario reduces net HWP carbon balance by -64.6 $TgCO_2e$ (-6%) for CRR, -11.6 $TgCO_2e$ (-2%) for Max NCS, -61.3 $TgCO_2e$ (-6%) for Pest Resilience, and -3.3 $TgCO_2e$ (-0.5%) for Wildfire Resilience.

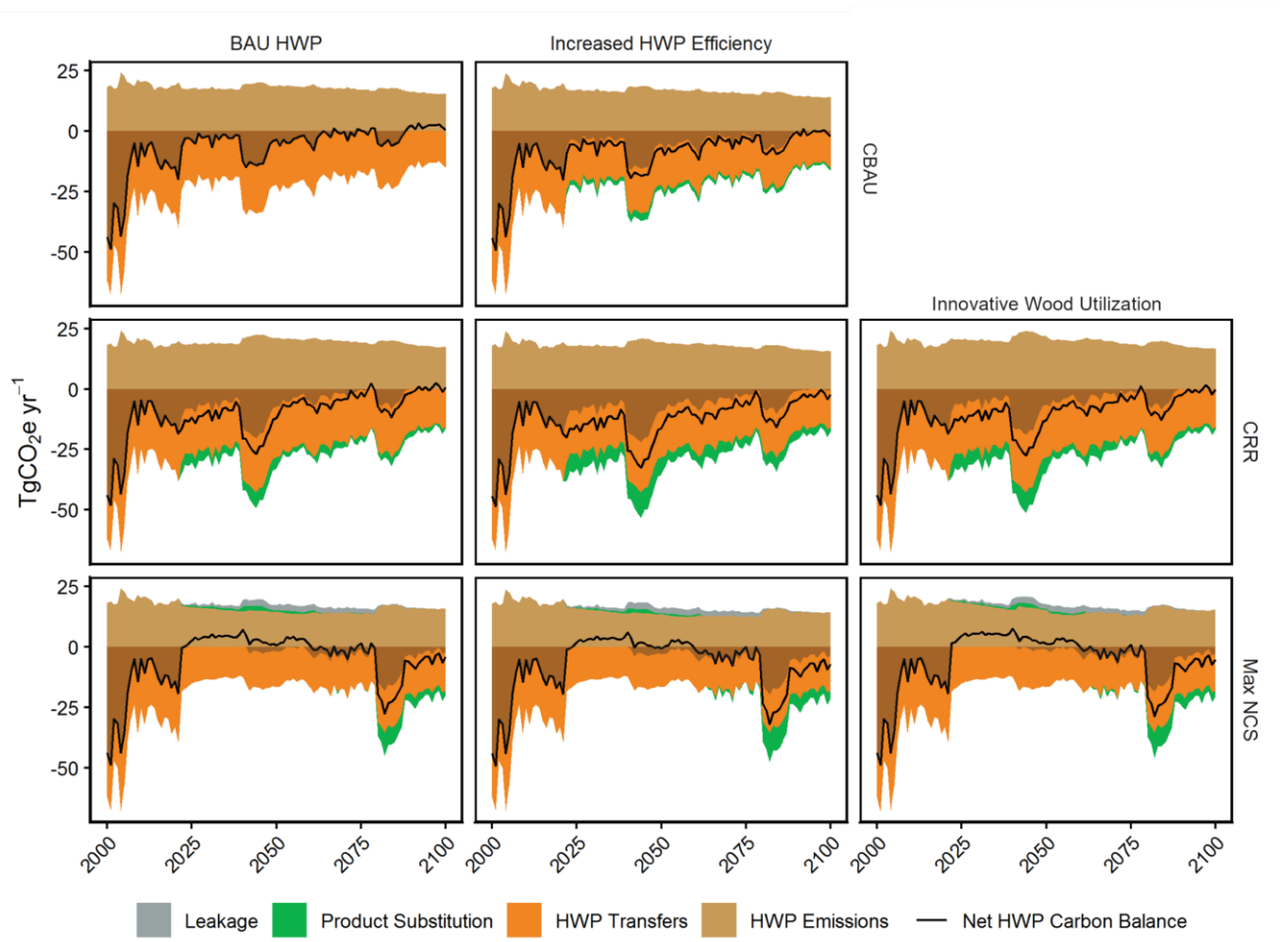


Figure 20. Annual net HWP carbon balance for selected scenarios (2000-2100, $TgCO_2e\ yr^{-1}$) by component for selected combinations of ecosystem and HWP scenarios. Net HWP carbon balance includes transfers of HWP from the forest to the forest products sector, emissions from wood products in use and in landfills, substitution benefits in years where harvest is different than CBAU, and leakage in years where harvest is less than CBAU. Negative values for net HWP carbon balance denote net carbon storage, whereas positive values denote net carbon emissions (a net carbon source). The brown shaded area within the HWP transfers fill indicates the annual storage of carbon, which occurs when HWP transfers exceed HWP emissions.

These reductions in net HWP carbon balance also propagate to each scenario's net carbon balance (**Figure 14b** and **Figure 21**). For example, when the BAU HWP assumptions are applied to the Max FAC portfolio, its net carbon balance is +97.9 $TgCO_2e$ (+9.2%) greater than CBAU. However, when the Increased HWP Efficiency Scenario is applied, the resulting drop in net HWP carbon balance causes net carbon balance to drop to -20.9 $TgCO_2e$ (-2.0%) less than CBAU (**Figure 21**). These dynamics illustrate the potential of alternative HWP dynamics and utilization to enhance the carbon storage capacity of Oregon's forest products sector beyond what would be possible if the current utilization scheme is maintained into the future. They also indicate a potential pathway for maintaining current levels of emissions abatement, even if alternative management practices which increase emissions from the ecosystem through reduced primary productivity or increased decomposition emissions are implemented.

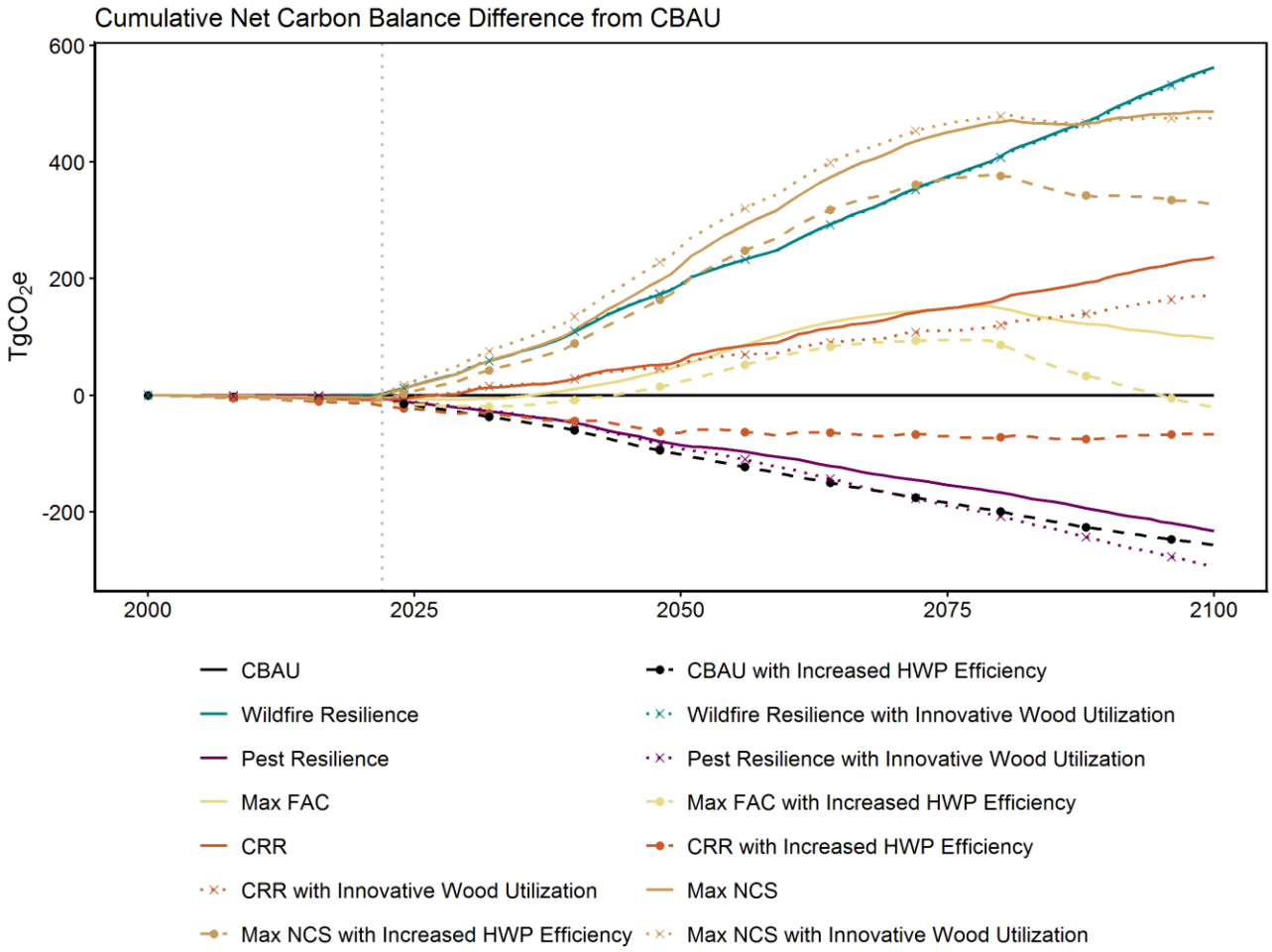


Figure 21. Net carbon balance for selected scenarios (2000-2100) depicted in cumulative terms, standardized to CBAU. Net carbon balance includes net ecosystem carbon flux in the forest, transfers to HWP, emissions from wood products in use and in landfills, substitution benefits in years where harvest is different than CBAU, and leakage in years where harvest is less than CBAU. Negative values denote carbon sequestration (a net carbon sink). Positive values denote carbon emissions (a net carbon source). Scenarios are shown with BAU HWP assumptions (solid line, no points), with Increased HWP Efficiency assumptions (dashed line, circular points), and with Innovative Wood Utilization assumptions (dotted lines, X points). Scenario abbreviations are as follows: CRR = Combined Resilience and Restoration, Max FAC = Maximum Forest Area and Carbon, Max NCS = Maximum Forests as Natural Climate Solutions. Scenarios not depicted are the No Deforestation Outside of the Urban Growth Boundary (UGB), Silvopasture, CMAI Based Rotations, 80-Year Rotations, Uneven-Aged Management, Net Zero Forest Loss via Decreased Deforestation (NZD), and Net Zero Forest Loss via Increased Afforestation (NZA), and Landscape Restoration scenarios.

Ecosystem Carbon Trends

In Oregon, effects of climate change, combined with continued business-as-usual forest management practices, are projected to reduce productive forest area, decrease forest carbon stocks, and increase forest carbon emissions substantially by 2100 (**Figure 4**). However, several of the alternative forest management scenarios assessed in this study may provide opportunities to minimize these trends and create a more stable forest ecosystem. Across the thirteen scenarios assessed, all but one scenario (Max NCS) had fewer acres of productive forest area in 2100 than in 2022 (**Figure 22a**). That said, all thirteen scenarios ended the simulation with a larger amount of productive forest area than the CBAU, with six of the thirteen scenarios returning a double-digit percent increase in productive forest area over CBAU. Results for ecosystem carbon stocks were more mixed (**Figure 22c**). Ecosystem carbon stocks declined from 2022-2100 in all thirteen scenarios, but eight scenarios had higher ecosystem carbon stocks in 2100 than CBAU, indicating improved carbon storage over business-as-usual practices in the context of future climate changes.

Of the scenarios tested, the Max FAC and Max NCS portfolios return the highest carbon stocks and largest productive forest area respectively at the end of the simulation (**Figure 22a, c**). From 2022-2100, the Max FAC portfolio loses 22% (a decline of 6.7 million acres) of its productive forest area. However, compared to the CBAU scenario, the Max FAC portfolio results in +23% (+4.5 million acres) more productive forest area (**Figure 22c**). At the same time, the Max NCS portfolio increases productive forest area by 7% (+2.1 million acres) from 2022-2100, and results in 70% (+13.4 million acres) more productive forest area than CBAU (**Figure 22c**). By 2100, the Max FAC portfolio will have accumulated 8.7 million acres (27% of total forest area) of post-fire regeneration failure, while the Max NCS portfolio will have accumulated only 0.07 million acres (0.2% of total forest area) of post-fire regeneration failure (**Figure 22b**).

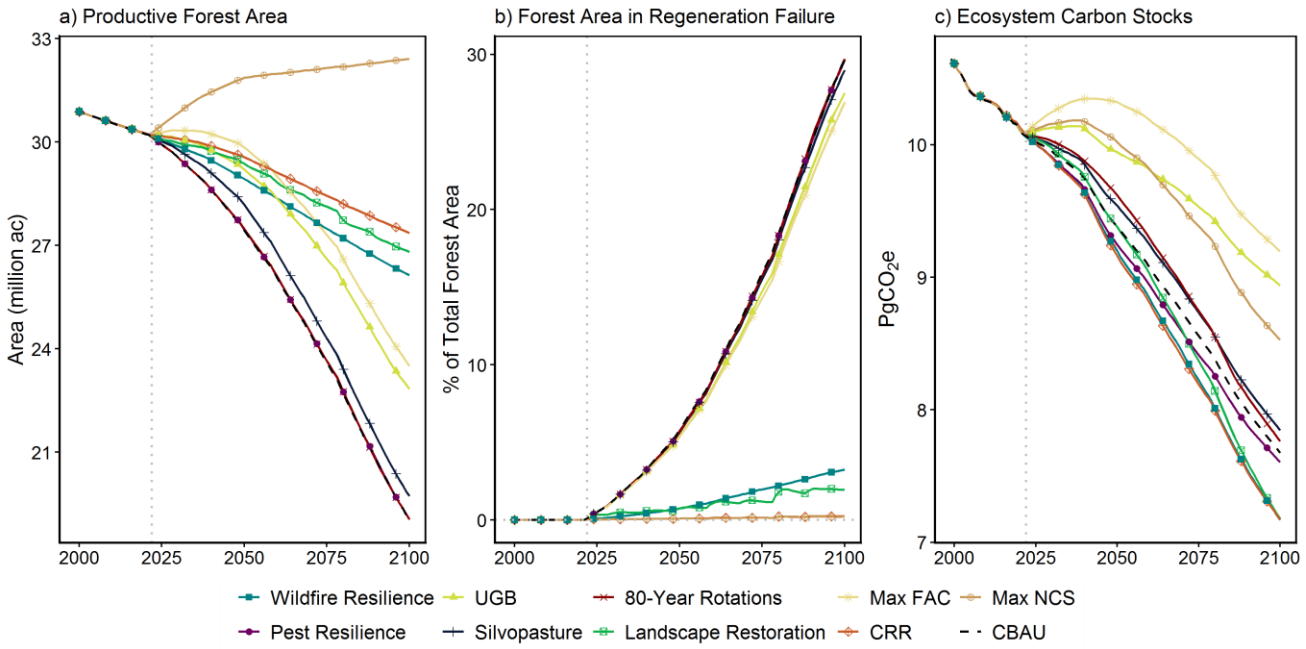


Figure 22. Ecosystem metrics for selected scenarios depicting a) productive (not in a state of regeneration failure) forest area (million acres), b) forest area in a state of post-fire regeneration failure (% of total forest area), and c) ecosystem carbon stocks ($PgCO_2e$) from 2000-2100. Scenario abbreviations are as follows: UGB= No Deforestation outside of the Urban Growth Boundaries, CRR= Combined Resilience and Restoration, Max FAC =Maximum Forest Area and Carbon, Max NCS = Maximum Forests as Natural Climate Solutions. Scenarios not depicted are the CMAI Based Rotations, 80-Year Rotations, Uneven-Aged Management, Net Zero Forest Loss via Decreased Deforestation (NZD), and Net Zero Forest Loss via Increased Afforestation (NZA) scenarios.

These large gains in forest area for the Max NCS portfolio, both overall and relative to CBAU, are the result of increased tree planting (from the Silvopasture scenario), while simultaneously lowering the rate of deforestation (from the UGB scenario). By combining these effects, not only is the base rate of land-use change reduced, but these newly planted forests are protected from future deforestation, an additive effect also evident in the Max FAC portfolio (**Figure 22a**). In the Max NCS portfolio these effects are further amplified by a reduction in the area subject to post-fire regeneration failure (from the Wildfire Resilience scenario), and treatments to restart growth in areas of regeneration failure (from the Landscape Restoration scenario). Here these effects are not additive, as in order for landscape restoration treatments to be necessary, the forest must first enter a state of post-fire regeneration failure. However, since wildfire resilience treatments significantly reduce the amount of high-severity fire and thus post-fire regeneration failure, when these two scenarios are combined, the effects of the landscape restoration treatments on productive forest area become more muted (**Figure 22a**). This is evident both for the Max NCS portfolio and for the CRR portfolio, both of which limit post fire regeneration failure to 0.07 million acres (0.2% of total forest area) by 2100 (**Figure 22b**). However,

unlike the Max NCS portfolio which gains productive forest area from 2022-2100, the CRR portfolio loses 9% (a decline of 2.8 million acres) of its productive forest area due to a trend of net forest loss due to land use change (**Figure 22a**).

When simulated independently the solo scenarios lead to more modest changes in productive forest area relative to CBAU (+4%, +0.7 million acres for Silvopasture; +20%, 3.8 million acres for UGB; +37%, +7.1 million acres for Wildfire Resilience; +41%, +7.8 million acres for Landscape Restoration; +4%, +0.8 million acres for NZA; +10%, +1.8 million acres for NZD; **Figure 22a**) although each scenario here does still lose productive forest area during the simulation from 2022-2100. Of these scenarios, those which either prevent or mitigate the effects of post-fire regeneration failure have substantially less of their total forest area in a state of post-fire regeneration failure (3%, 0.88 million acres for Wildfire Resilience; 2%, 0.52 million acres for Landscape Restoration), compared with those scenarios which either add forest area or prevent total forest area loss (28%, 8.7 million acres for UGB; 29%, 8.1 million acres for Silvopasture; 29%, 8.1 million acres for NZA; 29%, 8.4 million acres for NZD; **Figure 22b**).

Four scenarios (80-Year Rotations, Pest Resilience, CMAI Based Rotations, and Uneven-Aged Management) do not meaningfully impact productive forest area, as none of the changes implemented in any of these scenarios modify post-fire regeneration failure dynamics or the overall rate of forest area loss (**Figure 22a**). As such, all four scenarios end the simulation with less than 0.1% more productive forest area (<0.1 million acres), and 30% of their total forest area (~8.1 million acres) in a state of post-fire regeneration failure (**Figure 22b**). This level of difference is within the bounds of model uncertainty associated with stochastic application of disturbance to eligible inventory records.

In terms of ecosystem carbon storage, the Max FAC portfolio loses 9% (-0.9 $PgCO_2e$) of its ecosystem carbon stocks from 2022-2100 (**Figure 22c**), though this is still a 20% (+1.5 $PgCO_2e$) increase in ecosystem carbon stocks relative to CBAU. Comparatively, the Max NCS portfolio results in greater overall losses of carbon than the Max FAC portfolio, a -16% (-1.6 $PgCO_2e$) loss of ecosystem carbon from 2022-2100, and a smaller +11% increase (+0.9 $PgCO_2e$) in carbon stocks relative to CBAU (**Figure 22c**). Unlike the other two portfolios, the CRR portfolio exhibits losses of carbon stocks, both from 2022-2100 (-29%, -2.9 $PgCO_2e$) and relative to CBAU (-7%, -0.5 $PgCO_2e$; **Figure 22c**). Here we compare carbon stocks for the total forest area, not just the productive forest area, as a substantial quantity of carbon is contained in forest areas in a state of post-fire regeneration failure. Although this forest is no longer growing (and thus not sequestering carbon), it is still an important part of annual and cumulative net ecosystem carbon flux (**Figure 23**), as it is subject to emissions from disturbance and decomposition.

Of the solo scenarios, those which modify the overall trend of deforestation through land-use change lead to the smallest loss of ecosystem carbon (**Figure 22c**). Limiting forest losses to only within the UGB, as in the UGB scenario, adds +17% (+1.3 $PgCO_2e$) of ecosystem carbon stocks relative to CBAU, while low density silvopasture planting, as in the Silvopasture scenario, adds +2% (+0.2 $PgCO_2e$) of ecosystem carbon stocks relative to CBAU (**Figure 22c**). Attempting to achieve a net zero rate of forest loss, either via increased afforestation as in the NZA scenario, or by decreased deforestation as in the NZD scenario, adds 3% (+0.2 $PgCO_2e$) and 8% (+0.6 $PgCO_2e$) respectively (**Figure 22c**). Extending harvest rotations either to a minimum of 80 years, as in the 80-Year Rotations scenario, or to the age at which the forest reaches CMAI, as in the CMAI Based Rotations scenario, also has a marginal effect, in both cases leading to +1% (+0.09 $PgCO_2e$) more carbon in the forest at the end of the simulation than CBAU (**Figure 22c**). Here, most of this additional carbon is contained in forest stands which under these extended rotation plans are below the age of harvest eligibility. By contrast, resilience and restoration treatments reduce the amount of carbon storage relative to CBAU, either via thinning

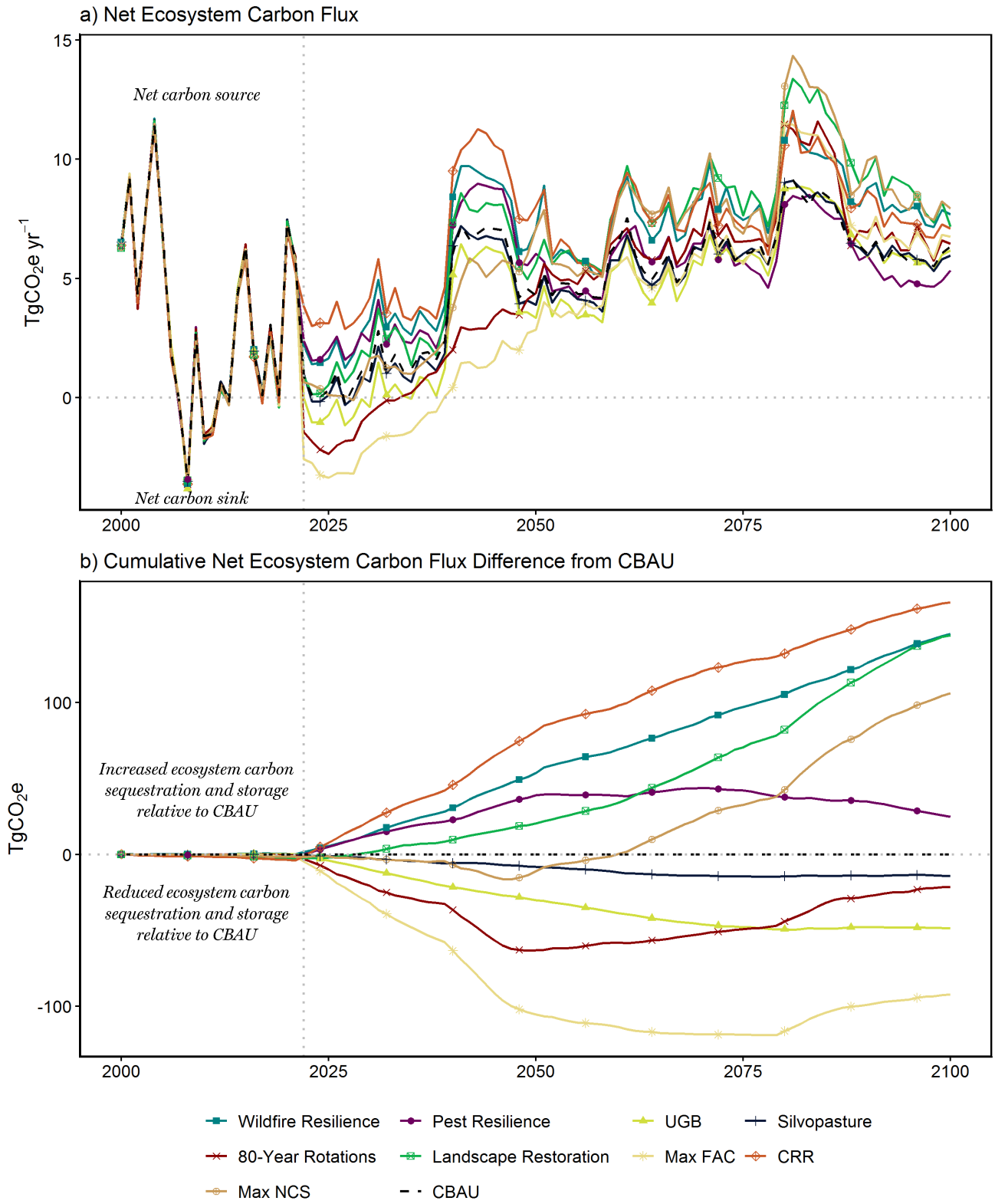


Figure 23. Net ecosystem carbon flux for selected scenarios (2000-2100) depicted in a) annual terms and b) cumulative terms, standardized to CBAU. Net ecosystem carbon flux refers to the net yearly sequestration of carbon by forests across all 14 ecosystem carbon pools, after accounting for decomposition, natural disturbance emissions, and wood product transfers. Negative values represent a net carbon sink and positive values represent a net carbon source. Scenario abbreviations are as follows: UGB= No Deforestation outside of the Urban Growth Boundaries, CRR= Combined Resilience and Restoration, Max FAC =Maximum Forest Area and Carbon, Max NCS = Maximum Forests as Natural Climate Solutions. Scenarios not depicted are the CMAI Based Rotations, 80-Year Rotations, Uneven-Aged Management, Net Zero Forest Loss via Decreased Deforestation (NZD), and Net Zero Forest Loss via Increased Afforestation (NZA) scenarios. Scenarios not depicted are the CMAI Based Rotations, Uneven-Aged Management, Net Zero Forest Loss via Decreased Deforestation (NZD), and Net Zero Forest Loss via Increased Afforestation (NZA) scenarios.

(-0.9%, -0.07 $PgCO_2e$), as in the Pest Resilience scenario, thinning and Rx fire (-7%, -0.5 $PgCO_2e$), as in the Wildfire Resilience scenario, or salvage and site preparation after high-severity fire and regeneration failure (-7%; -0.5 $PgCO_2e$), as in the Landscape Restoration scenario (**Figure 22c**). These reduced ecosystem carbon stocks are by design, as lower stand densities (represented by lower carbon stocks) should make these forests more resilient to future pest and wildfire disturbances. Finally, switching harvest management east of the Cascade crest to group selection, as in the Uneven-Aged Management scenario, has a negligible effect on carbon stocks (-0.1%, -0.004 $PgCO_2e$) relative to management practices in place under CBAU.

Overall trends in annual and cumulative net ecosystem carbon balance (**Figure 23**) are affected by changes in productive forest area and ecosystem carbon stocks, and when considered together and in the context of net carbon balance (**Figure 14**), they provide a holistic picture of the carbon and other co-benefits associated with climate-smart forestry. For example, despite the fact that the Landscape Restoration scenario loses more carbon stocks than CBAU (**Figure 22c**), most of the additional carbon loss is via salvage harvest, and thus a transfer of carbon to the forest products sector, leading to net emissions reduction benefits discussed in the **Wood Products Carbon Dynamics** section. In addition, landscape restoration treatments reverse the effects of post-fire regeneration failure, and as such limit the loss of productive forest area (**Figure 22a, b**), increasing NPP and thus the cumulative carbon sequestration capacity of the forest (**Figure 15a**). The Wildfire Resilience scenario preserves a similar level of productive forest area as the Landscape Restoration scenario, accomplished through a reduction in high-severity fire area via resilience treatments. As such, cumulative net emissions (**Figure 15a**) and cumulative net carbon balance (**Figure 14b**) are higher for this scenario. However, there are other non-carbon co-benefits to this scenario which are not fully captured by this analysis, such as decreased risks to mature and old growth forests, which harbor unique habitats, and a lower overall risk to health and property from reduced area of high-severity fire. When these and other scenarios are combined into management portfolios, more balanced and synergistic outcomes are possible, such as in the Max NCS portfolio which increases overall productive forest area (**Figure 22a**), accrues more ecosystem carbon stocks than CBAU (**Figure 22c**), and leads to fewer net emissions than the Wildfire Resilience scenario (**Figures 14a & 22**), while retaining co-benefits associated with reduced area of high-severity fire.

Ecosystem Carbon Trends by Region

As in the **Influence of Future Climate** section, ecosystem carbon fluxes for our alternate management scenarios vary substantially by ecoregion. To illustrate these effects, we present results aggregated by region, west of the Cascade crest (Coast Range, Willamette Valley, Klamath Mountains, and West Cascades ecoregions), and east of the Cascade crest (East Cascades and Modoc, Blue Mountains, and Eastern Oregon ecoregions), normalized by total forest area represented by each region.

Across all scenarios, cumulative net ecosystem carbon flux per acre is higher (meaning more net carbon emissions) on the east side than on the west side (**Figure 24a**), ranging from 1.2x higher (50.1 $MgCO_2e$ ac^{-1} on the east side vs 41.2 $MgCO_2e$ ac^{-1} on the west side, as in the Pest Resilience scenario) to 1.6x higher (37.3 $MgCO_2e$ ac^{-1} on the east side vs 23.0 $MgCO_2e$ ac^{-1} on the west side, as in the Max FAC portfolio). These dynamics are mainly driven by the fact that west side forests have substantially higher (more negative) per-acre net primary productivity than east side forests (**Figure 24b**). This higher rate of per-acre carbon sequestration helps the west side ecoregions to have lower per-acre net carbon flux despite higher per-acre rates of decomposition (**Figure 24c**) and HWP transfers (**Figure 24e**). Further, per-acre disturbance emissions are higher on the east side than the west side (**Figure 24d**), meaning that of the carbon that is sequestered in live biomass, more of it is lost to wildfire, pest, and abiotic disturbances on the east side than the west side.

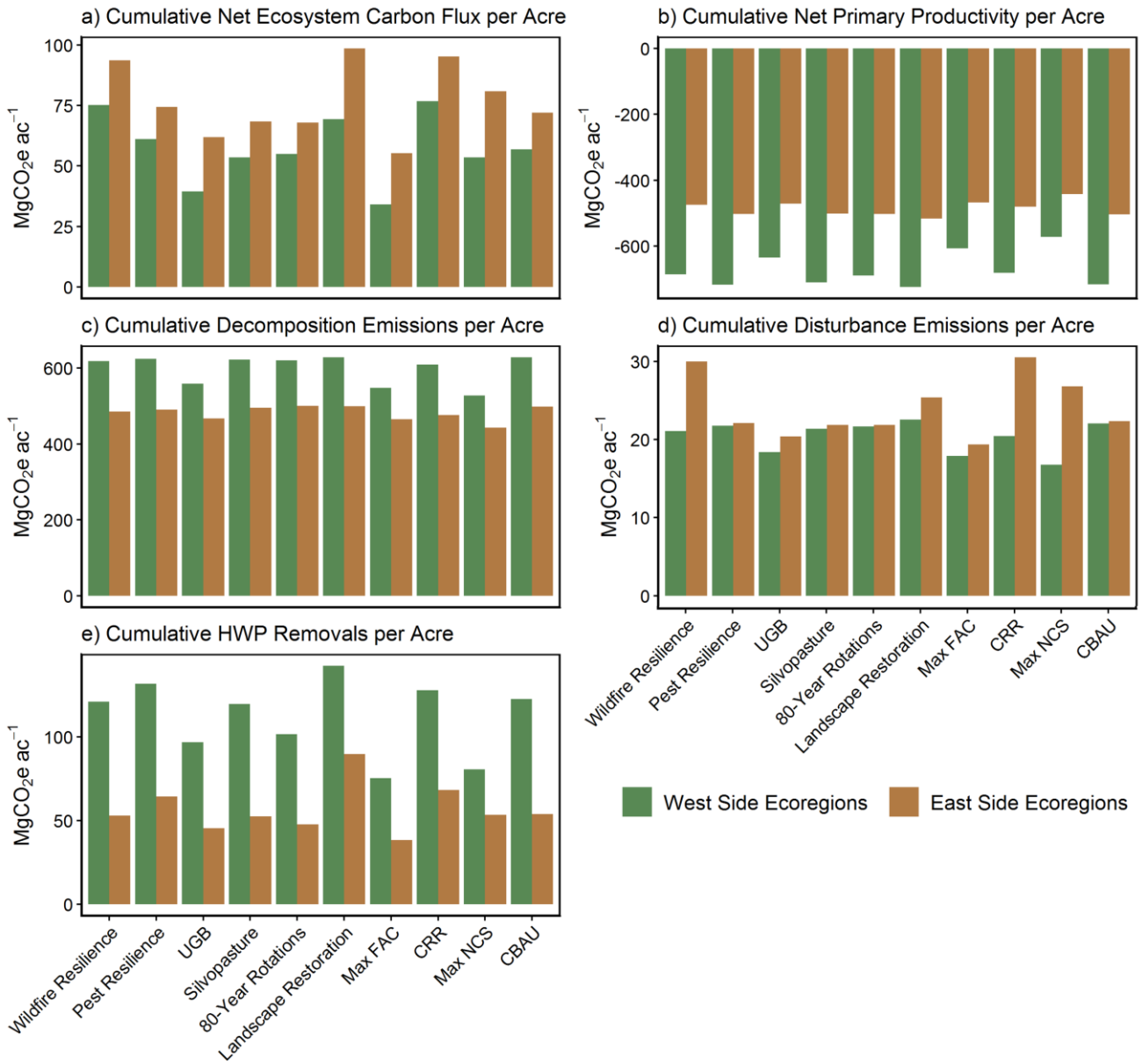


Figure 24. Cumulative a) net ecosystem carbon flux, b) net primary productivity, and c) decomposition emissions, d) disturbance emissions, and e) HWP removals on a per area basis ($MgCO_2e\ ac^{-1}$) for selected scenarios in 2100. Data re further subdivided by region, west of the cascade crest (Coast Range, Willamette Valley, Klamath Mountains, and West Cascades ecoregions), and east of the cascade crest (East Cascades and Modoc, Blue Mountains, and Eastern Oregon ecoregions. Negative values denote carbon sequestration and positive values denote carbon emissions.

Across all components of net ecosystem carbon flux, the ratio of fluxes east to west is stable among scenarios (**Figure 24**). The only exception is disturbance emissions, which, among certain scenarios, are highly variable east to west (**Figure 24d**). For example, in the scenarios with wildfire resilience treatments, disturbance emissions (which include emissions from management activities such as prescribed burns) are substantially higher on the east side than the west side (42% for Wildfire Resilience, 49% for CRR, 60% for Max NCS), compared to only 1% higher on the east side than the west side for CBAU (**Figure 24d**). This change comes as wildfire resilience treatments substantially increase the area of prescribed fire, particularly on the east side, which increases overall per-acre disturbance emissions (+7.6 $MgCO_2e\ ac^{-1}$, +34% relative to CBAU; **Figure 24d**) for this collection of ecoregions. At the same time, treatments also reduce the future occurrence of high-severity fire, thereby

reducing per-acre emissions (-0.96 $MgCO_2e\ ac^{-1}$, -4% relative to CBAU; **Figure 24d**) for the west side ecoregions.

Other scenarios lead to less pronounced effects, such as the Landscape Restoration scenario (12% higher east side emissions) and UGB scenario (11% higher east side emissions; **Figure 24d**). In both cases, these scenarios increase the total area subject to disturbance emissions and thereby reduce per-acre disturbance emissions, but with a bias towards the west side ecoregions. In the Landscape Restoration scenario this comes via treatments to address recent post-fire reforestation backlogs, the majority of which (52%) are centered in the West Cascades and Klamath ecoregions. In the UGB scenario all ecoregions experience a reduction in deforestation; however, most of the deforestation (67% in the CBAU) occurs in west side ecoregions, meaning these regions benefit more from the effects of reduced deforestation in the UGB scenario.

Impacts of Age Class Distribution on Ecosystem Carbon Stocks and Productivity

Age class distribution plays an important role in determining the ecosystem carbon trends of each scenario modeled in this analysis. At a stand or landscape scale, aging forests often exhibit slowing rates of biomass accumulation and productivity, stemming from interacting competition and resource-use dynamics of individual trees (Binkley et al. 2002; Coomes et al. 2012; Foster et al. 2014) and increases in mortality as mean stand age increases (Gray et al. 2016; Xu et al. 2012). These dynamics are captured in the plot level observations of stand age and volume used to parameterize our yield functions (USDA Forest Service 2021a), and thus are incorporated into the modeled relationship between stand-level growth and stand age (**Figure 25a**). In addition, as forests age, turnover rates increase (Boudewyn et al. 2007), and therefore so do modeled rates of decomposition emissions (**Figure 25b**). As such, with all else being equal, older forest stands tend to contain more carbon in biomass, DOM, and soil carbon pools, but also see diminishing potential for future biomass accumulation (Sleeter et al. 2018) and thus stable or declining *net ecosystem productivity* (**Figure 25c**), a dynamic that has been specifically well documented for forests in the Pacific Northwest (Gray et al. 2016). Net ecosystem productivity refers to the net yearly sequestration of carbon across all 14 ecosystem carbon pools, after accounting for decomposition, but is different from net ecosystem carbon flux in that it does not include carbon flux from natural disturbance emissions or wood product transfers. Many forest management plans emphasize the need to maintain a somewhat balanced age distribution across the forested landscape, in order to ensure continued carbon sequestration capacity, while also maximizing the ability of established forests to store carbon in live biomass and stable DOM pools (USDA Forest Service 2023c; Davis et al. 2022; Vangi et al. 2024). These management plans also promote critical forest co-benefits such as wildlife habitat and water resource stability (Ferrare et al. 2019; Seidl et al. 2016; Pelz et al. 2023; Clifton et al. 2018).

Dynamics of age and net ecosystem productivity are also influenced by model representation of climate change. To account for effects of future climate dissimilarity which may alter growth rates, we applied forest type group specific reductions in annual stand volume increment each decade between 2022 and 2100, effectively reducing growth and yield in proportion to projected declines in productivity (Stewart and Wright 2023). In addition, we progressively increased mean annual temperature from 8.3°C in 2000 to 13.6°C in 2100, in line with climate projections for forested landscapes in Oregon under RCP 8.5 (Wang et al. 2024). Altering the age-volume relationship has the effect of reducing stand-level growth and productivity through time (**Figure 25a**), while increasing mean annual temperature leads to a higher relative rate of decomposition (**Figure 25b**). The interaction of these effects is that net ecosystem productivity as a function of age decreases for all scenarios (aside from BAU, which does not include future climate impacts) as the simulation progresses (**Figure 25c**).

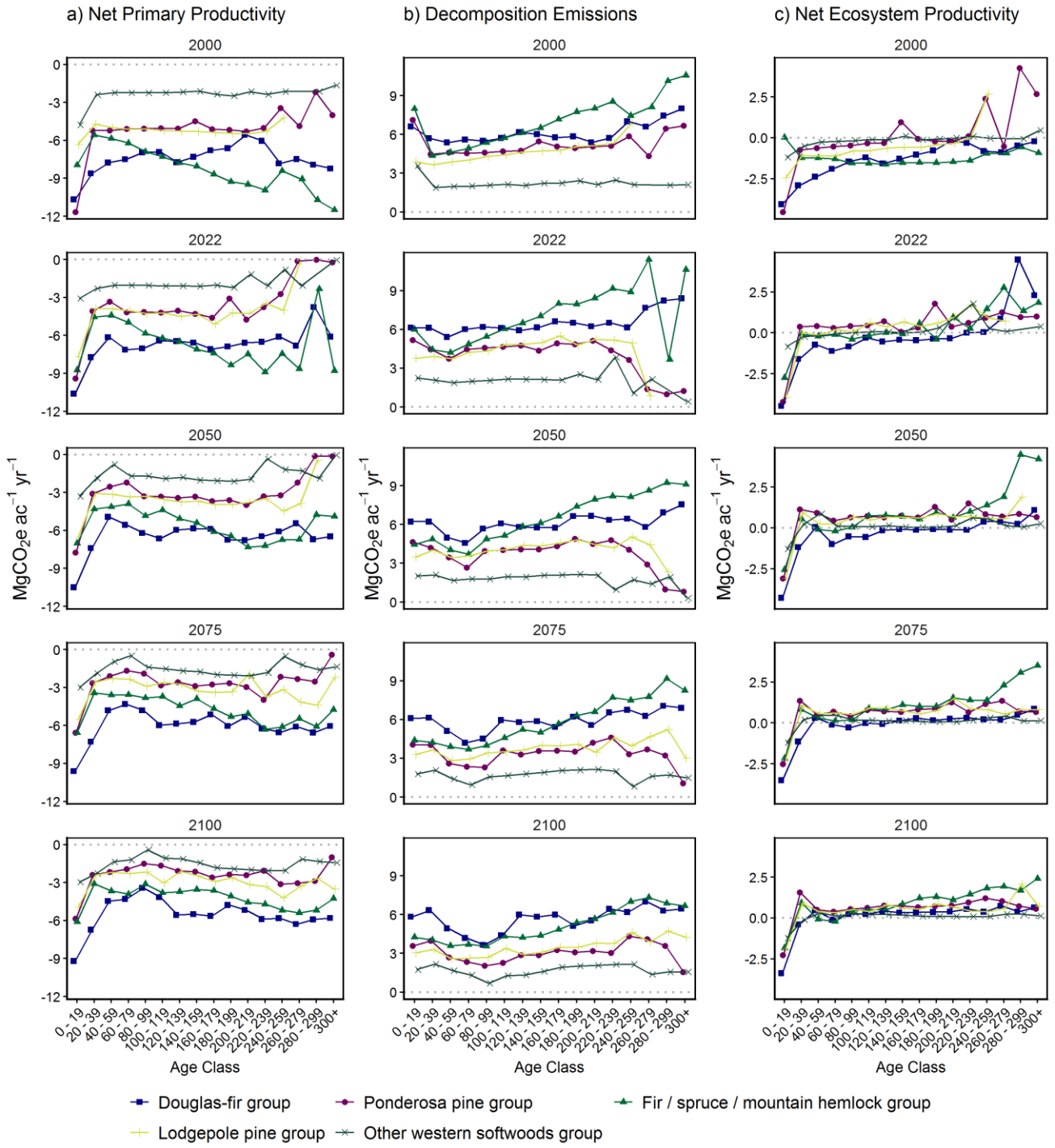


Figure 25. Relationship between forest age class and a) net primary productivity ($MgCO_2e\ ac^{-1}\ yr^{-1}$), b) decomposition emissions ($MgCO_2e\ ac^{-1}\ yr^{-1}$), and c) net ecosystem productivity ($MgCO_2e\ ac^{-1}\ yr^{-1}$) by forest type group at five points through the 101 years of simulation. Forest type groups depicted are the five most common in Oregon and represent 81% of the total forest area at the start of the simulation. Data are from the CBAU scenario and are standardized on a per acre basis for ease of comparison.

As discussed in the **Influence of Future Climate** section, age class distribution under CBAU shifts significantly through time, becoming increasingly bimodal with 49% of the landscape over 140 years old and 29% in the 0–39 year age class in 2100 (**Figure 11**). Though these percentages suggest an aging forest landscape, they do not include increasing areas in a state of post-fire regeneration failure, which covers 30% of the landscape in 2100 and stays at age zero unless the forest begins to grow again. When

these regeneration failure acres are included in the age class distribution, average forest age is the same at the start and end of the simulation (93 years; **Figure 26a**). When accounting for the age of all forests (both productive forests and forests in a state of post-fire regeneration failure) average age peaks at 103 years in 2076, before declining due to an increasing amount of forest area in a state of post-fire regeneration failure (**Figure 22b**, **25a**). For the purpose of assessing the impact of forest age on carbon sequestration across scenarios, it is more instructive to only consider productive forest area (i.e. forest not in a state of post-fire regeneration failure), as only productive forests are capable of growth and carbon sequestration. When only productive forest area is considered, the average forest age in the CBAU scenario increases from 87 years in 2022 to 125 years in 2100 (**Figure 26b**).

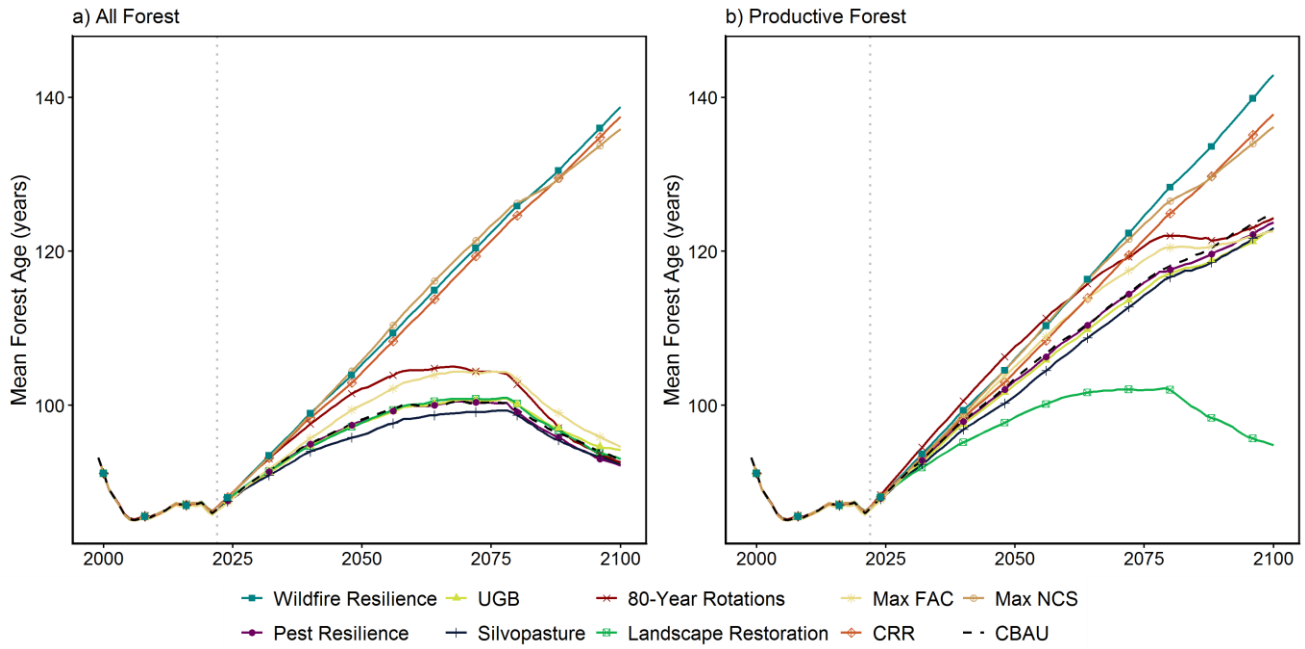


Figure 26. Average forest age (years) for a) all forested lands, b) productive forested lands (i.e. those not in a state of post-fire regeneration failure), for selected models (2000 – 2100). Forests in a state post-fire regeneration failure are assumed to be age 0, regardless of time since disturbance.

Of the scenarios modeled, those that address wildfire impacts have the largest influence on Oregon's forest age class distribution, either by decreasing the occurrence of stand-replacing high-severity wildfire (as in the Wildfire Resilience scenario) or by reforesting previously burned areas currently in a state of post-fire regeneration failure (as in the Landscape Restoration scenario; **Figure 27a**). In the Wildfire Resilience scenario, mean productive forest age increases from 87 years in 2022 to 143 years in 2100 (+18 years relative to CBAU), while for the Landscape Restoration scenario, mean productive forest age increases from 87 years in 2022 to just 95 years in 2100 (-30 years relative to CBAU; **Figure 27a**).

In the Wildfire Resilience scenario, a reduction in the area of stand-replacing wildfire relative to CBAU leads to a more heavily top weighted age class distribution, where 56% of the productive forest area is over 140 years old by 2100, and just 20% of the productive forest area is less than 40 years old by 2100 (**Figure 27a**). This large increase in older forests is in part influenced by our modeled maximum harvest age of 140 years (as determined from analysis of FIA removals data (USDA Forest Service 2021a)) meaning that any forest reaching 141+ years of age can no longer be targeted by harvest in our simulation and will continue to age unless affected by a natural disturbance or land-use change event. By contrast, the aggressive post-fire reforestation treatments associated with the Landscape Restoration scenario, in combination with the dramatic ramp up of high-severity wildfire toward the

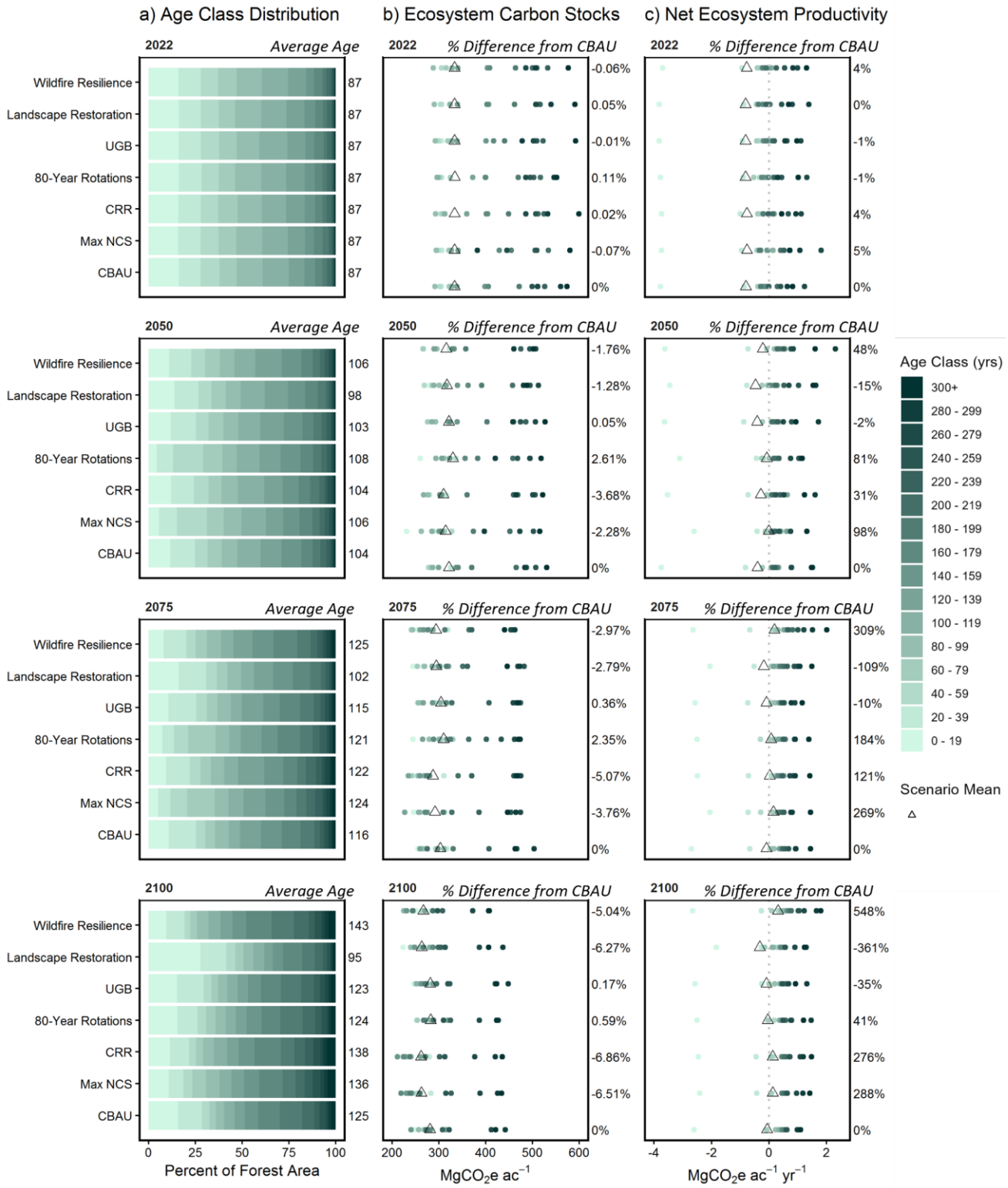


Figure 27. a) Age class distribution, b) ecosystem carbon stock density ($MgCO_2e\ ac^{-1}$), and c) per-acre net ecosystem productivity ($MgCO_2e\ ac^{-1}\ yr^{-1}$) for undisturbed, productive (i.e. not in a state of post-fire regeneration failure) forest in selected scenarios in 2022, 250, 2075, and 2100. Net ecosystem productivity refers to the net yearly sequestration of carbon per acre of forest across all 14 ecosystem carbon pools, after accounting for decomposition but not including carbon flux from natural disturbance emissions or wood product transfers. In panel b), positive values denote accruing carbon stocks. In Panel c), negative values denote carbon sequestration and positive values denote carbon emissions.

end of the simulation, means that in 2100 the Landscape Restoration scenario has just 33% of its productive forest area greater than 140 years old and 42% of its productive forest area less than 40 years old (**Figure 27a**). Both the CRR and Max NCS portfolios, which combine the effects of the Wildfire Resilience and Landscape Restoration scenarios, experience more moderate increases in mean productive forest age (**Figure 26b**). In the CRR portfolio, mean productive forest age increases from 87 years in 2022 to 138 years in 2100 (+13 years relative to CBAU), while in the Max NCS portfolio mean productive forest age increases from 87 years in 2022 to 136 years in 2100 (+11 years relative to CBAU; **Figure 26b**). However, by 2100 both portfolio's age class distributions are still somewhat top weighted like the Wildfire Resilience scenario (52% and 48% of productive forest area over 140 years old, 21% and 18% of productive forest area less than 40 years old, for the CRR and Max NCS portfolios respectively; **Figure 27a**).

Scenarios and portfolios which alter the timing of timber harvest management (CMAI Based Rotations, 80-Year Rotations, Uneven-Aged Management, and the Max FAC portfolio) have less of an effect on average age and age class distribution (**Figure 27a**). For example, in the 80-Year Rotations scenario, harvest deferrals lead to an increase, then decrease, in mean forest age compared to CBAU (**Figure 26b**). This increase in age for the 80-Year Rotations scenario peaks in 2065, with a mean productive forest age 5.4 years greater than CBAU. In this same year, the 80-Year Rotations scenario has 52% of its productive forest area between ages 40 and 139, while the CBAU has just 38% of its productive forest area between ages 40 and 139. However, by the end of the simulation in 2100, after the first round of deferred harvest is completed (2080-2087), the age class distribution in the 80-Year Rotations scenario returns closer to that of the CBAU (47% of the productive forest area over 140 years old and 27% of the productive forest area less than 40 years old), with a mean productive forest age -0.7 years less than CBAU (**Figure 27a**). This reflects the fact that harvest deferral is only a temporary effect, and although it leads to a faster rate of forest aging during the deferral period (**Figure 26b**), once harvests resume, forest age dynamics return to a pattern like the CBAU (**Figure 27a**).

The changes in management, natural disturbance, and land-use change dynamics associated with the remaining scenarios (Pest Resilience, Silvopasture, NZA, NZD, UGB) had minimal impacts on mean productive forest age (**Figure 26b**) or age class distribution (**Figure 27a**). Further, by 2100, none of the scenarios or portfolios we tested meaningfully increase the ratio of forests between 41-139 years old. However, this is not surprising given that this age range aligns with harvest age eligibility for high and moderate intensity harvest. So, while some scenarios are likely increasing the amount of stands which reach this age (either via resilience treatments, afforestation, or reduced deforestation), unless they are designated as non-harvest eligible, they will likely enter the normal harvest rotation, and cycle into the accumulation of stands between ages 0 and 39.

Next, to assess the impact of alternative management scenarios on the forest age-carbon relationship, we can assess per-acre carbon storage (*carbon stock density*; **Figure 27b**) and per-area net ecosystem productivity (**Figure 27c**). These metrics vary by age class, depending on the respective biomass volumes and growth rates exhibited by forests as they mature. In scenarios like those modeled here, where total forest area varies widely, these metrics are helpful for more consistently comparing the carbon dynamics of the existing forest land base. These values also account for growth and decomposition in the forest ecosystem prior to harvest removals, therefore including the growth of wood that may later be transferred to the forest products sector. In general, climate-smart management strategies attempt to balance these two dynamics across the forested landscape (Verkerk et al. 2020), preserving carbon stocks while promoting net ecosystem productivity either via reduced decomposition emissions or increased growth.

Under CBAU, carbon stock densities decrease through time, dropping from 333.5 $MgCO_2e$ ac^{-1} in 2022 to 280.8 $MgCO_2e$ ac^{-1} in 2100 (**Figure 27b**). This decline occurs due to projected increases in climate-related disturbance, which lead to higher ecosystem emissions and thus larger losses of carbon stocks to the atmosphere (**Figure 6**). Further, because productivity also decreases as the result of climate change, average annual biomass accumulation declines through time (**Figure 25**). As such, even though mean productive forest age increases through time under the CBAU (**Figure 27a**) and older stands contain more carbon per acre on average (**Figure 27b**), climate effects still lead to a net decline in carbon storage per forest acre for the CBAU.

In the scenarios which alter wildfire impacts, carbon stock densities also decline over the model period (2022-2100) from 333.3 $MgCO_2e$ ac^{-1} to 266.7 $MgCO_2e$ ac^{-1} in the Wildfire Resilience scenario and from 333.6 $MgCO_2e$ ac^{-1} to 263.2 $MgCO_2e$ ac^{-1} in the Landscape Restoration scenario (**Figure 27b**). Both scenarios end the simulation with lower carbon stock densities than CBAU (-5% for the Wildfire Resilience scenario and -6% for the Landscape Restoration scenario; **Figure 27b**). For the Wildfire Resilience scenario, this decrease in carbon stock density is the intentional result of the resilience treatments themselves (thinning and Rx fire), and represents management that aims to strike a balance between minimizing forest loss to wildfire and post-fire regeneration failure while maintaining current (older) forest acres at more climate-adapted variable and low-density stand structures (Meyer et al. 2021; North et al. 2019). For the Landscape Restoration scenario, this decrease in carbon stock density is the result of salvage logging prior to reforestation and the restoration of productive forest area at lower stand densities and younger age classes and thus a lower carbon stock density (**Figure 27b**). These same dynamics, when combined in the CRR and Max NCS portfolios, lead to larger losses of carbon stock densities than are seen in each of the solo scenarios. In the CRR portfolio carbon stock density declines from 333.5 $MgCO_2e$ ac^{-1} in 2022 to 261.6 $MgCO_2e$ ac^{-1} in 2100, while in the Max NCS portfolio carbon stock density declines from 333.2 $MgCO_2e$ ac^{-1} in 2022 to 262.5 $MgCO_2e$ ac^{-1} in 2100 (**Figure 27b**), the latter being moderated in part by other management objectives included in the portfolio.

Other scenarios have more moderate effects on carbon stock density, and only selected examples are provided here. In the UGB scenario, carbon stock density declines from 333.4 $MgCO_2e$ ac^{-1} in 2022 to 281.3 $MgCO_2e$ ac^{-1} in 2100 (**Figure 27b**). However, this decline is slightly more moderate (+0.17%) than the decline under CBAU, due in part to a lower rate of deforestation, which protects highly carbon dense stands from being removed from the forest land base. In the 80-Year Rotations scenario, carbon stock densities also decline throughout the simulation (**Figure 27b**). The difference in stock density between the 80-Year Rotations scenario and CBAU initially increases from +0.4 $MgCO_2e$ ac^{-1} (+0.1%) in 2022 to a peak of +8.4 $MgCO_2e$ ac^{-1} (+2.6 %) in 2045, before declining to +1.7 $MgCO_2e$ ac^{-1} (+0.6%) in 2100 (**Figure 27b**). This reflects the fact that harvest deferral is only a temporary effect, with higher relative carbon stock density than CBAU only during the initial harvest deferral period.

Per-acre net ecosystem productivity trends through time, both overall and by age class (**Figure 27c**), in part mirror each scenarios trends in carbon stock densities (**Figure 27b**). Under CBAU, per-acre net ecosystem productivity decreases (meaning lower rates of net carbon sequestration, a less negative value) through time, changing from -0.81 $MgCO_2e$ ac^{-1} yr^{-1} in 2022 to -0.07 $MgCO_2e$ ac^{-1} yr^{-1} in 2100 (**Figure 27c**). This occurs as climate change reduces productivity, disturbances increase, higher mean annual temperature leads to higher decomposition emissions, and the mean age of the productive forest area increases, diminishing average annual biomass accumulation (**Figure 25**). These trends can also be observed in the UGB scenario, where mean stand age is similar to CBAU (**Figure 27a**), and per-acre net ecosystem productivity decreases (becomes less negative) from -0.81 $MgCO_2e$ ac^{-1} yr^{-1} in 2022 to -0.09 $MgCO_2e$ ac^{-1} yr^{-1} in 2100 (**Figure 27c**). In the 80-Year Rotations scenario, per-acre net ecosystem productivity also follows a similar trend, decreasing from -0.82 $MgCO_2e$ ac^{-1} yr^{-1} in 2022 to -0.04 $MgCO_2e$ ac^{-1} yr^{-1} in 2100 (**Figure 27c**). However, in the 80-Year Rotations scenario, per-acre net

ecosystem productivity reaches a minimum value of 0.11 $MgCO_2e\ ac^{-1}\ yr^{-1}$ (where a positive number indicates a net carbon source) in 2081. This temporary switch from net carbon sink to net carbon source in the 80-Year Rotations scenario corresponds to the period just after harvest deferral causes mean stand age to peak (**Figure 26b**) and is further reflective of the age effect on net ecosystem productivity. Age impacts on per-acre net ecosystem productivity are also readily apparent in the Wildfire Resilience and Landscape Restoration scenarios (**Figure 27c**). In the Wildfire Resilience scenario, net ecosystem productivity decreases (meaning less net carbon sequestration) consistently throughout the simulation, from -0.78 $MgCO_2e\ ac^{-1}\ yr^{-1}$ in 2022 to 0.31 $MgCO_2e\ ac^{-1}\ yr^{-1}$ in 2100 (**Figure 27c**). By 2100, forests in the Wildfire Resilience scenario are a per-acre net carbon source (i.e., higher emissions than sequestration), with a per-acre net ecosystem productivity value 548% less negative than CBAU (**Figure 27c**). This change in per-acre net ecosystem productivity matches closely to the dynamics of average stand age, which also increase through time, due in part to a reduction in high-severity wildfire acting as a stand-replacing disturbance in the Wildfire Resilience scenario (**Figure 27a**). Although the age class specific per-acre net ecosystem productivities are similar between the CBAU and Wildfire Resilience scenarios (**Figure 27c**), because the age distribution of the Wildfire Resilience scenario is so heavily weighted toward older forests (**Figure 27a**), mean per-acre net ecosystem productivity is substantially lower (indicating a net carbon source) for the Wildfire Resilience scenario than CBAU.

Per-acre net ecosystem productivity dynamics for the Landscape Restoration scenario are different than the Wildfire Resilience scenario (**Figure 27c**), though they also match closely to mean forest age (**Figure 27a**). Per-acre net ecosystem productivity in the Landscape Restoration scenario decreases from -0.81 $MgCO_2e\ ac^{-1}\ yr^{-1}$ in 2022 to -0.18 $MgCO_2e\ ac^{-1}\ yr^{-1}$ in 2075, before increasing to -0.32 $MgCO_2e\ ac^{-1}\ yr^{-1}$ in 2100 (**Figure 27c**). Again, this pattern matches closely to the mean age of the productive forest, which in the Landscape Restoration scenario initially increases, but is eventually reduced by reforestation of areas that enter a state of post-fire regeneration failure (**Figure 26b**). As such, this newly reforested area is young, and grows rigorously, increasing (making more negative) average per-acre net ecosystem productivity and leading to more net carbon sequestration. However, when we compare the per-acre net ecosystem productivity for the youngest age class (0-19 years) between the Landscape Restoration scenario and the CBAU, we find that per-acre net ecosystem productivity is lower (i.e., more emissions or less growth) in the Landscape Restoration scenario (**Figure 27c**). This is reflective of the fact that in the Landscape Restoration scenario, this youngest age cohort now represents forest types and low-density stand structures more appropriate in fire prone environments, which, all else being equal, tend to have lower growth rates than those which are managed for timber production, the latter of which make up the bulk of this age cohort under CBAU. Overall, mean per-acre net ecosystem productivity values for the Landscape Restoration scenario are higher than CBAU in all years from 2022-2100, meaning on a per-acre basis the Landscape Restoration scenario is more of a net carbon sink than CBAU (**Figure 27c**).

When Landscape Restoration and Wildfire Resilience are combined in the CRR and Max NCS portfolios, the impacts of wildfire resilience treatments on stand age (and thus per-acre net ecosystem productivity) dominate (**Figure 27c**). This is because in order for landscape restoration treatments to occur, the forest must first enter a state of post-fire regeneration failure. However, when these two scenarios are combined, the wildfire resilience treatments significantly reduce the amount of high-severity fire and thus post-fire regeneration failure, meaning less restoration is possible and stand age increases through time (**Figure 27a**). As a result net ecosystem productivity decreases (meaning less net carbon sequestration) in both portfolios, from -0.77 $MgCO_2e\ ac^{-1}\ yr^{-1}$ in 2022 to 0.12 $MgCO_2e\ ac^{-1}\ yr^{-1}$ in 2100 for the CRR portfolio, and from -0.77 $MgCO_2e\ ac^{-1}\ yr^{-1}$ in 2022 to 0.13 $MgCO_2e\ ac^{-1}\ yr^{-1}$ in 2100 for the Max NCS portfolio (**Figure 27c**).

Uncertainties and Limitations

The models and assumptions used in this analysis introduce a few key uncertainties and limitations:

1. The aspatial nature of CBM-CFS3 means that scenarios do not provide information about the location of predicted carbon sequestration and storage over time. Our full classifier list does include spatial references (ecoregions and private forest districts in Oregon), which can be used to filter results to certain areas. However, the results in these spatial units are based on historical trends and not predictions of future management activities. Furthermore, this scale of analysis does not allow for important stand-level considerations and management targets such as species composition, stand structure, and diameter distributions.

2. Using an average of historical trends for our projections removes the possibility of extreme future events from our model – for example, since we apply high-severity wildfire to an average of 38,800 acres per year from 2022-2100, our model will not capture the probability or impact of a megafire like those from the 2020 or 2024 fire seasons. This also does not allow for novel events that have not happened historically, like wildfires in forest types or regions that have not typically burned in large amounts, such as the Coast Range. Similarly, due to the continuation of average historical business-as-usual management practices, certain climate-related management activities will not scale with increasing climate effects. For example, salvage treatments to remove standing dead woody material post-wildfire are modeled to remain at the historical average for this activity type, even as the area of high-severity wildfire (and thus the availability of salvaged wood) increases dramatically in the CBAU scenario. Finally, the use of an average of historical management prevents the model from adjusting future management activities based on changing economic, social, environmental, and cultural conditions across the landscape. For example, the current harvest moratoriums in place for land covered by the Northwest Forest Plan will stay in place in the model, even if the Northwest Forest Plan is amended and adapted to better address current needs and emerging management priorities (Spies et al. 2019).

3. The volume-age curves, or yield curves, developed for this study are designed to represent unique combinations of forest type group, ownership, and productivity class. However, in certain cases the data required to create a unique yield curve was not available, due either to limitations in the quantity of plot-level FIA data or lack of plot-level volume measurements across a sufficient age distribution. In these cases, we instead assigned yield curves from the most similar classifiers, aggregating first across ownership, then productivity class, and finally forest type group, the latter only in cases where fewer than 25 observations per forest type group were available. As such, our yield curves represent growth and yield for a statewide average stand within a given forest type group, ownership, and productivity class. They do not capture regional dynamics of growth/productivity (e.g., east side vs west side Douglas-fir) nor do they reflect the fact that stocking levels may be variable within ownerships, which limits our ability to draw inference from results at these more local levels. However, at a statewide level, we expect trends in growth and productivity to reflect real world dynamics, barring other model uncertainties outlined in this section.

4. The 79-year simulation timeframe introduces increasing uncertainty as simulations move further into the future. Uncertainties may stem from factors like future forest management decisions, future policies, future market dynamics, or climate change. Especially for the CBAU scenario, our choice of global emissions pathway (RCP 8.5) and future climate conditions represent just one possible future, and our scenario results apply best within that context. Though we considered three important angles of climate change impacts (declining

productivity, increasing natural disturbance, and post-fire regeneration failure), there are other possible impacts (such as species range shifts, reburns in previous high-severity wildfire patches, and CO_2 fertilization) we did not consider here which warrant further study. Compounding dynamics, such as increases in high-severity wildfire that affect post-fire regeneration, add further uncertainty to our projections. As addressed in the **Business-as-Usual Scenario** section, we chose to model a 79-year period to align with other studies which project forest carbon trends to the end of century. We have not conducted a sensitivity analysis for these scenarios, so our results here present one set of possible outcomes. However, even with uncertainty around the quantified climate mitigation benefits presented in this report, we can reasonably have confidence in the trends and directionality indicated by these results.

5. We did not directly model or assess the impacts of the large-scale Douglas-fir (*Psuedotsuga menziesii var. menziesii*) die-off currently occurring in Southwest Oregon (Bennett and Adlam 2023). This die-off is predicated by stress from warmer and drier climates, which exposes Douglas-fir trees (particularly in the Klamath Mountains ecoregion) to increased vulnerability to secondary mortality agents such as the flatheaded fir borer (*Phaenops drummondi*) or other biotic and abiotic stress factors (Bennett et al. 2023). While we did model projected declines in productivity and climate modified natural disturbance events as part of our CBAU and subsequent scenarios (**Table 3**), we did not specifically incorporate data on Douglas-fir die-off, in part as the rate of die-off has increased substantially since 2022, while our model's "historical" observation period covers 2000-2021 (Buhl et al. 2024; Cline et al. 2025). Current projections indicate that Douglas-fir die-off could radically alter DOM dynamics, decrease productivity, and increase fire risk across Southwestern Oregon (Bennett and Adlam 2023; Bennett et al. 2023), potentially exposing the forest to a loss of ecosystem carbon stocks beyond what was modeled in our assessment.

6. The assumptions made in constructing each scenario represent one of many possible ways to implement each forest management and wood utilization practice. Where these assumptions are inaccurate for local conditions, actual climate mitigation results will vary. Our scenarios represent simplified versions of likely future dynamics intended to support forest management and policy decision makers in understanding the climate mitigation potential of forests in Oregon. We do not make assumptions based on the feasibility of implementing each modeled management practice; rather, we focus on our state partners' objectives for forest management and land use and offer our assessment of the climate benefits of certain implementation levels. Each practice should be further examined for biophysical, political, and economic feasibility by land managers and decision makers in planning and policymaking processes. This is especially important for management practices which increase the transfer of wood to the forest products sector, as we assume that any additional material, regardless of where in the state it is harvested, can be utilized while maintaining the current timber product production and export ratio. For novel product pathways, we have designed a gradual increase in product production, but we acknowledge that these assumed timelines may not fully align with what is feasible given current and projected market dynamics and production capacity.

7. A central assumption for our restoration and resilience treatment scenarios is that modeled practices are effective at producing the landscape outcomes they target. Though we based our assumptions on the growing body of science addressing treatment effectiveness (Davis et al. 2024; Ott et al. 2023; Shaw et al. 2011; MacLean 2019; Cansler et al. 2022; Dodge et al. 2019; Meyer et al. 2021; North et al. 2019), in reality this effectiveness is uncertain and will be affected by many factors, including climate change, agency operational capacity, seed supply, workforce capacity, and others. Similarly, our choice of treatment extent (e.g., area covered, treatment

return interval, treatment intensity) for our resilience treatments was based on a prioritization scheme in which all eligible acres would be treated by 2050. Because of the aspatial nature of CBM-CFS3, as well as constant changes in forest area during simulations, it is not possible to implement a "herd immunity" concept in which once a sufficiently large proportion of the landscape receives treatment, the whole landscape becomes resilient. Likewise, propagating resilience among spatially adjacent stands is not possible in CBM-CFS3. As such, it is possible that a smaller treatment footprint, more restrictive treatment eligibility, or treatments at lower intensity could be sufficient to achieve the desired landscape outcomes, with smaller disruptions to BAU management practices and landscape and carbon dynamics.

8. Our scenarios require assumptions about which classifiers (forest type group, ownership, ecoregion, stand age, etc.) will be targeted by each modeled management practice. Where forests with these classifiers do not have sufficient area in our inventory, modeled practices will reach partial accomplishment, and our models will only show the carbon impacts of implementing the practices as coded. In reality, forest managers would have the flexibility to target different forest types or acres than originally intended, so actual rates of accomplishment and associated carbon impacts will vary from our scenario results. We also imposed a maximum harvest age to avoid modeled harvest of old-growth or protected stands, which would in reality be more flexible for landowners without harvest restrictions. Further, CBM-CFS3 only allows a single disturbance type for each inventory record in a given year. This means that common combinations of management (e.g., thin and pile burn) must be simulated as two discrete events, which have implications for disturbance and decomposition emissions during the intervening year. While these assumptions may add uncertainty to the numerical carbon trajectory of each scenario, they do not change our confidence in the impacts or directionality of scenarios relative to each other.

Takeaways and Policy Opportunities

Forest ecosystems are an integral part of nature-based climate solutions (Griscom et al. 2017; Fargione et al. 2018), sequestering and storing carbon from the atmosphere each year while also supporting a vibrant bioeconomy through the provision of wood products (Skog 2008; Smyth et al. 2014; Lemprière et al. 2013). Results of this analysis indicate that several forest management practices represented by our scenarios have the potential for additional climate mitigation benefits beyond CBAU in Oregon, minimizing forest carbon losses expected to occur under future climate conditions. These practices generally follow CSF principles, balancing forest resilience, adaptation, and mitigation capacity with the continued supply of HWP and ecosystem services. Key factors for success in these scenarios include addressing wildfire impacts, fostering landscape health and resilience, and maintaining forest area with a diverse age structure. Based on these criteria, climate-smart forest management and wood utilization strategies in Oregon include:

- Address post-fire regeneration failure through *landscape restoration* activities such as site preparation techniques (including salvage of commercially viable timber where legally permissible) to prepare the landscape for safe planting efforts and reduce future fuel hazards in post-burn areas, and subsequent reforestation.

- Reduce the impact and severity of future pest outbreaks and wildfires through *resilience treatments*, including thinning and prescribed fire, at a landscape scale.

- Use additional woody material removed from landscape restoration and resilience treatments in *innovative wood products* to store carbon in durable pools within the forest products sector

while gaining substitution benefits from using the wood in place of more emissions-intensive alternatives.

- Increase the efficiency of the forest products sector through shifting production toward longer-lived HWP, longer retention of products in use, and higher rates of reuse and recycling.

- Reduce the rate of permanent forest loss through *reduced deforestation, afforestation,* and management practices that prioritize *landscape restoration* and *silvopasture*

- Prepare for increasing negative impacts of climate change and use climate-adapted species and stand structures to promote forest health and resilience.

Depending on which management practice is implemented or how multiple management practices are concurrently applied across the landscape, CSF practices can accomplish up to a **45% decrease in annual emissions** from Oregon's forests over CBAU and **capture an additional 476 TgCO_2e** by 2100. This scale of potential emissions reductions from various CSF practices means that climate-smart forestry can help make significant progress towards Oregon's emissions reduction goals (Oregon Global Warming Commission 2023), and natural and working lands targets (Oregon Global Warming Commission 2021a). Though forests alone will not be able to act as a carbon sink to offset additional emissions from other sectors, CSF practices, like those modeled here or others being investigated across Oregon (e.g., Rose and Coate 2000; Wightman, Gonzalez-Benecke, and Dinger 2019; Kim et al. 2017), can reduce net forest carbon emissions and confer other important landscape benefits.

Oregon may work to achieve these outcomes by adjusting management priorities and interventions on public lands and through education, incentives, and engagement with consulting forestry professionals to reach private actors. Given the strong impacts of climate change projected in our CBAU scenario on USFS, private, and Native American lands, coordinating resilience and restoration treatments across both public and private forests with these land managers will be key for successful management. Given the large modeled benefits from post-fire reforestation, essential actions here include building more robust seed and seedling supply chains, developing a year-round workforce of reforestation professionals, and sharing information about reforestation needs and progress through centralized, cross-agency data hubs (McCarley et al. 2025). Further, focusing on resilience treatments in the West Cascades, East Cascades and Modoc, and Klamath ecoregions will also be crucial for minimizing future forest carbon losses from those areas.

Among the CSF practices listed above, substantial tradeoffs exist, and a one size fits all approach may not be appropriate for Oregon. For example, wildfire resilience treatments substantially reduce the area of high-severity wildfire, limiting post-fire regeneration failure, which along with demonstrated carbon benefits helps to preserve existing forest habitat, reduces the risk of fire impacts on people and property, and can help bolster local economies once dependent on timber revenues (Hjerpe et al. 2024). However, because these treatments substantially reduce a major source of stand-replacing disturbance, if implemented in otherwise unmanaged stands like those under USFS management in the East and West Cascades, forest age distributions may become increasingly weighted toward older stands. At a stand or landscape scale, aging forests often exhibit slowing rates of net growth and NPP, stemming from interacting competition and resource-use dynamics of individual trees (Binkley et al. 2002) and increases in mortality and stand-level respiration and decomposition (Gray et al. 2016; Xu et al. 2012; Foster et al. 2014; Coomes et al. 2012), eventually switching from a net carbon sink to a net carbon source. As such, while older forest stands tend to contain more carbon in biomass and DOM pools, they can also see diminishing potential for future biomass accumulation (Sleeter et al. 2018), a trend which

has been extensively documented in productive forests in the Pacific Northwest (Gray et al. 2016). These dynamics are central in the tradeoff between building and maintaining carbon storage capacity in the forest, and a desire for future carbon sequestration capacity to fuel further mitigation. For this reason, many forest management plans emphasize the need to maintain a somewhat balanced age class distribution across the forested landscape, to ensure continued carbon sequestration capacity while also safeguarding established mature forests which store large amounts of carbon in live biomass and stable DOM pools. These mature forests also provide critical co-benefits such as wildlife habitat and water resource stability (Ferrare, Sargis, and Janowiak 2019; Seidl et al. 2016; USDA Forest Service 2023b; Davis et al. 2022; Pelz et al. 2023; Vangi et al. 2024; Clifton et al. 2018).

Landscape restoration treatments are another primary strategy for combatting wildfire effects, but they too possess tradeoffs. In order for them to be effective, the forest must incur an upfront cost (high-severity wildfire and possibly post-fire regeneration failure), which can have catastrophic consequences for local habitats, human health, and property values. In addition, to implement landscape restoration at scale, Oregon must have a dedicated reforestation workforce and seedling supply, ready to respond to reforestation needs across jurisdictions (McCarley et al. 2025). Finally, from a systems-based carbon perspective, salvaged wood from landscape restoration treatments must be used in long-lived and durable wood products to counteract increased ecosystem-level emissions from fire. If workforce or wood processing capacity lags the anticipated increase in high-severity wildfire in the second half of the century, landscape restoration could become untenable as a leading CSF management strategy (Dobrowski et al. 2024).

Improvements in efficiency within the forest products sector, along with novel wood products, can further improve carbon trajectories associated with the CSF management practices listed above. Policies aimed at increasing the lifespan and recycling rate of construction lumber and investing in the production of durable wood products such as mass timber and wood fiber insulation can substantially reduce direct HWP emissions. Further, these practices contribute to economy-wide emissions reduction via displacement of non-wood commodities such as plastic, linoleum, steel, and concrete. Likewise, by prioritizing material removed from wildfire and pest resilience treatments in innovative wood products like lumber and biochar, further reductions in HWP emissions and thus improvements in net carbon balance are possible. These dynamics illustrate the potential of alternative HWP utilization to enhance the sink strength of Oregon's forest products sector beyond what would be possible if the current utilization scheme is maintained into the future. Expanded use of wood products and their substitution effects also indicate a potential pathway for maintaining current levels of emissions abatement, even if alternative management practices which increase emissions from the ecosystem through reduced productivity or increased decomposition emissions are implemented. By applying alternative management and alternative HWP utilization together, Oregon can achieve its forest management goals while maximizing the available climate mitigation benefits.

The practices listed above are considered climate-smart because they balance both carbon storage and sequestration rates with forest health and resilience. Focusing primarily on ecosystem carbon storage may not lead to lasting climate mitigation benefits, as an approach that relies solely on long-term ecosystem carbon storage is exposed to risks of natural disturbance and climate change. As modeled in older stands in the West Cascades, East Cascades and Modoc, and Klamath Mountains ecoregions, carbon stocks and forest productivity may reach a saturation point beyond which additional carbon sequestration, and thus climate mitigation benefits, diminish. Likewise, any strategy which focuses primarily on increased harvest levels as a means of storing additional carbon in durable wood products may come at the cost of future forest health, ignoring the essential ecosystem services forests provide. This approach also depends on stable future market conditions for HWP, which may become turbulent

if climate change substantially alters timber supply and demand. In order to make the necessary progress in mitigating climate change through CSF practices, we must both maintain our current carbon stores and sequester as much additional carbon from the atmosphere as possible (Verkerk et al. 2020). Future projections for Oregon are not optimistic, with a continuation of business-as-usual management leaving forests vulnerable to future climate and wildfire impacts (losses of 24% of forest area and 37% of forest carbon) and potentially destabilizing the future climate mitigation potential of forests in the state. To prepare for this future, and maintain forest health and carbon storage, Oregon must consider what balance of climate adaptation, mitigation, and resilience is most appropriate, how widespread these actions will be, and critically - as the cost of inaction will be significant - over what timeframe they should be carried out.

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Appendix

Model Development Methodology

This section describes our model development methodology in more detail, including data inputs, assumptions, and calculation factors for the forest ecosystem (CBM-CFS3) and harvested wood product (CBM-HWP-OR) models, leakage and product substitution calculations, and scenario parameterization.

Forest Ecosystem Model Methodology

The forest ecosystem model (CBM-CFS3) requires 7 input tables for each scenario: 1) classifier list; 2) age classes; 3) forest inventory; 4) volume-age curves, also called yield curves; 5) disturbance types; 6) disturbance event schedule; and 7) post-disturbance transition rules. Additionally, we updated the Archive Index Database (AIDB), which houses default inputs and assumptions for CBM-CFS3, with customized volume-to-biomass conversions, disturbance matrices, and mean annual temperature (both current and projected) based on Oregon-specific data rather than keeping the CBM-CFS3 defaults developed for Canada. Data and assumptions for each input table are described below. Models were run in Jupyter notebooks (Kluyver et al. 2016) using code provided by and adapted from the CBM-CFS3 Python GitHub repository (Morken 2018; DeLyser 2024). AIDB data is stored in an Access database (Microsoft 2016a).

The flexibility of this model easily allows parameterization with Oregon-specific data using USDA Forest Service Forest Inventory and Analysis (FIA) data. These data underpin several of the required input tables, as described below.

Classifier List

Classifiers are used to define relevant characteristics of the forest landscape (i.e., forest type, ownership, or productivity class) or reference spatial units within the study area (i.e., districts or ecoregions). These classifiers are used as categories in forest inventory inputs and to develop specific volume-age curves so that growth and yield trends can be linked to appropriate inventory records during model runs. When running scenarios, classifiers can be used to direct management practices to certain categories (e.g., in this study, we distinguish between the management activities on private, federal, and state lands listed in **Table 2** using the FIA OWNGRPCD classifier). Classifiers also serve as filters for scenario results.

We used 10 classifiers in this study (**Table S1**), five of which were derived from FIA data (USDA Forest Service 2021a). Two additional classifiers provide spatial references for our data, one of which ("ODF_District") is based on ODF Private Forest Districts (Oregon Department of Forestry 2019), while the second ("Ecoregion") uses an aggregation of the USDA Ecological Sections (Cleland et al. 2007) to define seven ecological regions within Oregon. We added 3 additional custom classifiers, one to tag forest undergoing a thinning treatment ("Thinned"), one as a trigger for future climate events and climate-modified yield curves under CBAU ("Climate Mod"), and one ("LastDistID") to track the last non-climate modification disturbance type so that follow up disturbance events can be appropriately scheduled. Each unique combination of classifiers (e.g., ODF_District 1 + OWNGRPCD 10 + … etc.) is used to structure the remaining model input tables, with input values required for each unique combination.

Table S1. List and descriptions of classifiers for Oregon used in this study.

Classifier	Description	Values	
ODF_District	District boundaries for the Oregon Department of Forestry's Fire Protection, State Forest, and Private Forest programs	1	Astoria
		2	Central Oregon
		3	Western Lane
		4	Douglas
		5	Forest Grove
		6	Klamath-Lake
		7	North Cascade
		8	Northeast Oregon
		9	South Cascade
		10	Southern Oregon
		11	Tillamook
		12	West Oregon
Ecoregion	Ecoregions of Oregon, from the USDA Ecological Section map (Cleland et al. 2007)	1	Coast Range
		2	Eastern Oregon
		3	East Cascades Modoc
		4	West Cascades
		5	Klamath Mountains
		6	Blue Mountains
		7	Willamette Valley
OWNGRPCD	FIA condition code to delineate stand ownership	10	US Forest Service
		20	Other Federal
		30	State and Local Government
		40	Private and Native American
RESERVCD	FIA condition code to denote reserve status for public lands, where reserved land is permanently prohibited from being managed for wood products; however, logging may occur to meet other management objectives	0	Not reserved
		1	Reserved
TYPGRPCD	FIA reference code indicating forest type group	0	Nonforest
		180	Pinyon / juniper group
		200	Douglas-fir group
		220	Ponderosa pine group
		240	Western white pine group
		260	Fir / spruce / mountain hemlock group
		280	Lodgepole pine group
		300	Hemlock / Sitka spruce group
		320	Western larch group
		340	Redwood group
		360	Other western softwoods group
		700	Elm / ash / cottonwood group
		900	Aspen / birch group
		910	Alder / maple group
		920	Western oak group
		940	Tanoak / laurel group
		960	Other hardwoods group
		999	Nonstocked
ALSTKCD	FIA condition code indicating stocking code for all live trees including seedlings	1	Overstocked (100+%)
		2	Fully stocked (60-99%)
		3	Medium Stocked (35-59%)
		4	Poorly Stocked (10-34%)
		5	Non-stocked (0-9%)
Productivity Class	FIA condition code to site productivity class, aggregated into 3 classes. The Nonproductive class was created specifically for post-fire regeneration failure as part of the CBAU scenario	0	Nonproductive (0 cu ft ac^{-1} yr^{-1})
		1	Unproductive (0-19 cu ft ac^{-1} yr^{-1})
		2	Low productivity (20-119 cu ft ac^{-1} yr^{-1})
		3	Productive (120-225+ cu ft ac^{-1} yr^{-1})
Thinned	Binary code to denote whether a stand has undergone a thinning treatment to trigger transition to post-thinning yield curve	0	Not commercially thinned
		1	Commercially thinned

Table S1, cont. List and descriptions of classifiers for Oregon used in this study.

Classifier	Description	Values	
Climate Mod	Code to trigger transition to future climate events and climate-modified yield curves	0	Past climate (2000-2021)
		1	Future climate 1 (2022-2029)
		2	Future climate 2 (2030-2039)
		3	Future climate 3 (2040-2049)
		4	Future climate 4 (2050-2059)
		5	Future climate 5 (2060-2069)
		6	Future climate 6 (2070-2079)
		7	Future climate 7 (2080-2089)
		8	Future climate 9 (2090-2100)
LastDistID	Code to track the last disturbance type ID to trigger a disturbance type that must follow a specific prior disturbance type	0	No Past Qualifying Disturbance
		3	High-severity Fire
		15	Disease - Mortality (High-severity)
		16	Disease - Mortality (Moderate-severity)
		24	High Harvest
		25	Intermediate Harvest
		26	Commercial Thin
		27	Precommercial Thin
		29	Thinning for Haz Fuels
		34	Wildfire Resilience- Thin without removal
		35	Wildfire Resilience - Thin with removal
		36	Wildfire Resilience - Rx burn
		37	Wildfire Resilience - Pile burn
		39	Pest Resilience- Thin with removal

Geospatial Classifier Data

Though the CBM-CFS3 itself is not spatially explicit, several of our input datasets are (as described below). To successfully incorporate this spatial data and assign it the appropriate classifiers, we created geospatial versions (in raster form) of most FIA-derived classifiers to supplement the maps of "ODF_District" and "Ecoregion" mentioned above. We categorized land ownership data into FIA ownership codes to create a map of "OWNGRPCD." To map "RESERVCD", we used data from the 2018 Protected Areas Database of the United States (USGS 2018) to find areas of designated wilderness or other protection status reserved from management for wood products. We did not have sufficient data to map "ALSTKCD," and it was not relevant for our other geospatial inputs, so we did not create a geospatial dataset for this classifier.

To map "TYPGRPCD", we utilized forest type group maps circa 2017 created for our team by LEMMA (2022), at the request of our state partners. Because the LEMMA data use a more permissive forest mask than FIA (Matthew Gregory, personal communication), the use of these data does introduce some discrepancies in forest area from the FIA inventory data (USDA Forest Service 2021a) which underpin our other model inputs, particularly for short stature or sparse forest type groups like the Pinyon/juniper forest type group. As an alternative/supplement we tested the USFS BIGMAP circa 2018 (USDA Forest Service 2018a); however, this dataset led to larger discrepancies than LEMMA and was thus not used. Finally, to map "Productivity Class" we used a linear inverse distance weighting approach to interpolate regional variations in productivity based on reported FIA productivity class from "fuzzed" FIA plot locations (USDA Forest Service 2021a). We had initially tested geospatial layers of forest productivity from Latta et al. (2009); however, like the maps of "TYPGRPCD", large discrepancies existed between the reported FIA "Productivity Class" and the Latta productivity estimates.

Age Classes

This input table defines the number of age classes and age class size (in years) for growth and yield data. For this analysis, we determined age class categories from FIA data (USDA Forest Service 2021a) using

5-year age classes. To match the age ranges used in our volume-age curves (see below), our age classes ranged from 0-226.

Forest Inventory

Forest inventory in CBM-CFS3 is spatially referenced rather than spatially explicit, meaning that exact locations of inventory records are not known or tracked. Instead, inventory data are categorized using the classifiers mentioned above, and total area (in hectares) is estimated for each unique combination of classifiers. Additionally, CBM-CFS3 requires information for each inventory record on United Nations Framework Convention on Climate Change (UNFCCC) land class (the default is 0, which represents forest), historical disturbance type (the most common disturbance type over the last 500+ years), and last disturbance type that created the current forest stand.

For this analysis, we used methodologies derived from Bechtold & Patterson (2005) and Pugh et al. (2018) to estimate Oregon's forest inventory from population estimates by pooling data from the most recent FIA survey cycle (2010-2019). Across this survey cycle, roughly 10% of FIA plots in Oregon are measured each year in what is called a panel, with all panels being measured over the course of 10 years for a complete survey. Pooling these annual panels across the survey cycle reduces estimate variation from any given year (Bechtold and Patterson 2005). We used the rFIA package (Stanke et al. 2020) in the R programming environment (R Core Team 2020) to run spatio-temporal queries on the FIA database and format data inputs. These queries included historical disturbance and last disturbance data for each inventory record.

When a complete set of classifiers was not available for every inventory record due to gaps in FIA data, the blank records were gap filled using existing data to avoid undercounting forest acreage in rFIA's area function. This process is especially important for stand age, as CBM-CFS3 relies on accurate stand age estimates for growth projections. We filled empty records for ALSTKCD, RESERVCD and Productivity Class with the lowest value for each (e.g., unproductive for productivity class, 0 for RESERVCD, 1 for ALSTKCD). Stand age was gap filled following a U.S. Forest Service methodology using quadratic mean diameter (QMD), tree height, and site class code (Andrew Gray, personal communication). If missing stand ages could not be calculated using this methodology, we recorded them as 0.

Volume-Age Curves and Volume-to-Biomass Conversions

Volume-age curves, or yield curves, are used to determine carbon stocks and sequestration rates by age class for the study area in CBM-CFS3. To estimate empirically derived yield curves, we utilized a Chapman-Richards growth function to model the relationship between merchantable volume (excluding bark, in cubic meters per hectare) and average stand age from FIA data (USDA Forest Service 2021a). This growth function is a common exponential function used to estimate various forest growth attributes (Fekedulegn et al. 1999; Chisholm and Gray 2024). Our Chapman-Richards function took the following form:

$$y(t) = b_0\left(1 - e^{-b_1 t}\right)^{b_2}$$

where $y(t)$ equals total volume at time t, t equals stand age (in years), and b_i are regression parameters to be estimated (b_0 is the upper asymptote of stand volume, b_1 is a growth reduction parameter, and b_2 is the growth rate parameter). We derived yield curves for each unique combination of forest type group, ownership, and productivity class as data allowed (see **Figure S1** for an example). In cases where there were not enough plots within a grouping to create a unique yield curve, we instead assigned yield curves from the most similar classifiers. For example, the aspen/birch forest type group had insufficient plot density for unique yield curves and were instead assigned values from the elm/ash/cottonwood group.

Yield curves were modeled out to 1,130 years of age to account for the range of stand ages in the current FIA database.

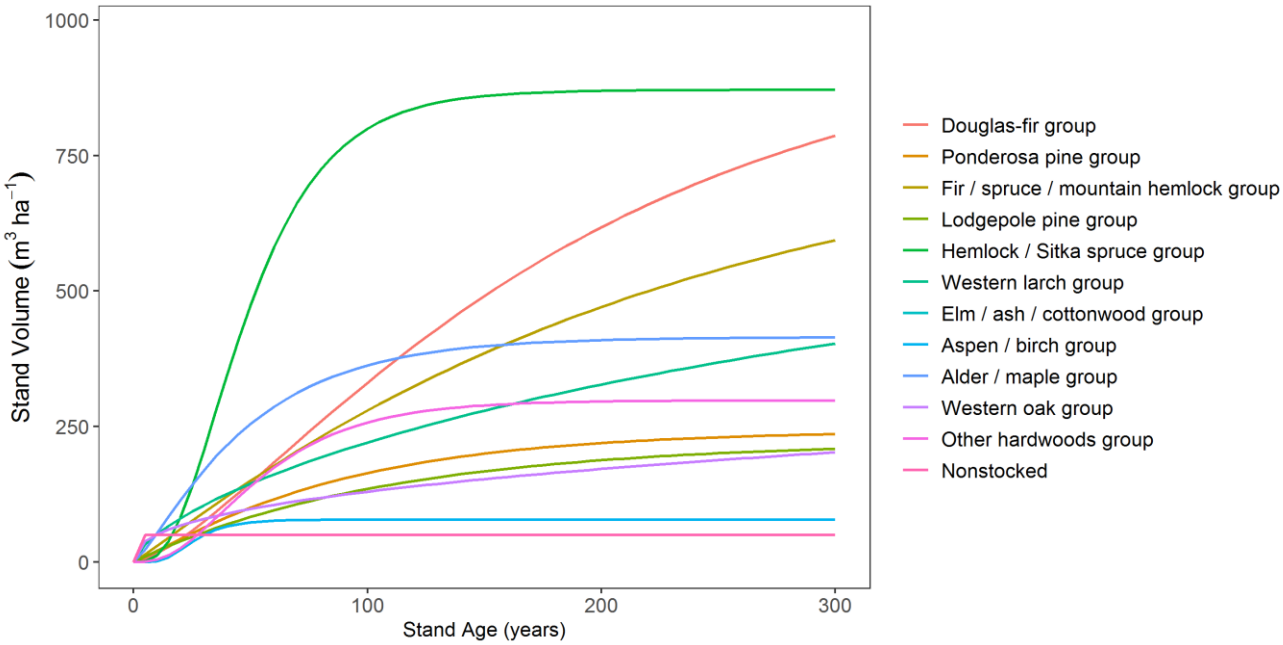

Figure S1. Example of empirically derived yield curves for forest type groups in Oregon under USFS ownership (OWNGRPCD = 10) with a low productivity class (Productivity Class = 2) or average productivity or ownership (where all productivity classes or ownership groups have been aggregated due to small sample sizes).

Due to limitations of using stand age to estimate merchantable volume in uneven-aged stands following harvest events, we derived modified yield tables following Pilli et al. (2013), specifically focused on annual growth increments of uneven-aged systems following commercial thinnings conducted at an early stand age. These modified yield curves were developed to facilitate more accurate simulation of uneven-aged management and growth dynamics, which we triggered using the "Thinned" classifier (transitioning thinned stands from Thinned=0 to Thinned=1). This methodology outlines that following the removal of a specific proportion of merchantable volume, stand volume will continue to approach the same asymptote as unthinned stands, representing an anticipated temporary increase in growth in response to the thinning. Specific considerations and assumptions should be accounted for when deriving modified yield curves such that:

(a) Stand age is a product of selective removal of groupings of trees (i.e., partial cutting) of the dominant canopy dominant class.

(b) The removal of biomass allows for the faster accumulation of biomass from younger age cohorts becoming more canopy dominant in the stand.

(c) For simplicity, harvest age of tree cohorts is lumped into large age classes where, following the removal of biomass, the remaining tree cohorts accumulate biomass more quickly.

In our Chapman-Richards function, post-thinning merchantable volume at a given stand age ($y(t)$) was modeled originating at a volume 30% less than the pre-thinned stand, with a modified growth rate parameter (b_2), and an identical growth asymptote parameter (b_0). This is based on the assumption that after thinning, younger cohorts of trees move more quickly towards canopy dominance once patches are created through harvesting. We used a volume reduced by 30% based on the assumed

harvest intensity of a commercial thinning (**Table S2**), applied in the age class corresponding with the median modeled thinning age for each forest type group, ownership, and productivity class combination (ranging from 30-40 years, or age classes 7-9). Modified yield curves were assigned to stands undergoing thinning treatments proportionally to the original area of each age class being treated. These modified curves were not created for other thinning activities, such as hazardous fuel reductions or resilience treatments, because these activities can happen in stands of any age and do not necessarily produce accelerated growth in remaining trees.

Since all our yield curves only consider merchantable volume, CBM-CFS3 uses allometric equations to predict wood volume-to-biomass relationships during model runs to convert yield curves into carbon values. These volume-to-biomass relationships also account for the non-merchantable portions of trees (tops and limbs, stumps, bark, and foliage). The allometric equations are specific to forest type and environmental conditions, such that equations for Canadian species (used as defaults in CBM-CFS3) are not applicable to similar species or forest types in Oregon. We replaced existing default allometric equations for relevant forest types with recalibrated equations for Oregon conditions, calculated by applying coefficients from Boudewyn et al. (2007) to volume and biomass values from FIA (USDA Forest Service 2021a) following the equation:

$$b_m = a \times volume^b$$

where b_m is total biomass in metric tons per hectare, *volume* is merchantable volume in cubic meters per hectare, and a and b are model coefficients calculated using Canadian forest inventory data. Using FIA inputs by forest type group for b_m and *volume*, we chose the best-fit coefficients from Boudewyn et al. to recalibrate allometric equations for each forest type group in Oregon. Note that these calculations were done using the 2021 version of the FIA Database, and therefore our *volume* and b_m values from FIA do not reflect the 2023 release of new National Scale Volume and Biomass Estimators (NSVB; Westfall et al. 2024) which updated FIA volume and biomass estimates. Overall, these updated NSVB equations are expected to decrease estimates of merchantable wood volume in Oregon by 0.7%, though changes vary by tree species ("NSVB: State Report for Oregon" 2023).

Disturbance Types and Disturbance Matrices

Once inventory and growth data have been determined, forest management, natural disturbance, and land-use change events (collectively termed *disturbances*) must be defined for use in CBM-CFS3. We determined the list of disturbances for Oregon using information provided by our state partners during our discussions identifying forest management priorities and by collecting historical data. See **Report Table 2** for the list of disturbances included in the BAU and CBAU scenarios, and **Report Table 4** for the list of disturbances included in the alternative management scenarios. Geospatial disturbance data inputs were processed using ArcGIS Pro (Esri Inc. 2021) with data tables processed in Jupyter notebooks (Kluyver et al. 2016).

Forest management

We compiled management activity data for 2000-2021 from publicly available sources from ODF (Oregon Department of Forestry 2022b, 2022a), USDA Forest Service (USDA Forest Service 2021b), and LANDFIRE (USGS 2016). There are no all-encompassing detailed forest management databases across all landowner categories in Oregon, which led us to compiling these multiple data sources. Despite using multiple databases, including timber management plans, we believe that our estimates of harvest area may be an undercount, especially for private lands where activity reporting is not comprehensive.

All datasets listed above are spatially explicit, providing shapefiles for various management practices and ownerships. ODF datasets include the Forest Activity Electronic Reporting and Notification

System (FERNS), and the Smoke Management Reports (SMR). In Oregon, there is a legal requirement to report all harvest, site preparation, and reforestation harvest activities on non-federal lands to FERNS, and these data have been collected from 2014-present, although we excluded data from 2014 as it was only partially reported. SMR data characterize the location and timing of prescribed fire activities (pile burn, under burn, and broadcast burn) across all ownerships in Oregon, and have been collected from 2012-present. USDA Forest Service data from the Forest Service Activity Tracking System (FACTS) include information on harvest, restoration, and prescribed fire activities on NFS lands from 1900-present. LANDFIRE data from the Historical Disturbance (HDist) dataset include harvest and prescribed fire activities across all ownerships from 2007-2016, based on a publicly reported disturbance database and change detection from Landsat imagery. Each dataset uses slightly different practice definitions and covers different time periods, so we cleaned and aggregated our data as follows:

1. The FACTS dataset, which extends beyond our historical model period (2000-2021), was clipped to include just our target years. Datasets that did not cover this full period (FERNS, SMR and LANDFIRE) were backfilled at the end of our data cleaning process (see Step 6 below).
2. FERNS datasets included activity start and end dates (one year maximum); however, they do not contain any verification of activity completion. As such, activity areas are routinely resubmitted to FERNS if the activity was not completed in the initially approved timeframe. In addition, many of the FERNS polygons overlap, with multiple activities being proposed for the same spatial extent within the same year. To account for these complicating factors, we undertook additional data filtering and validation processes to try and quantify the rate at which unique FERNS activities were completed. We first began by assigning each FERNS activity type a rank, based on the assumed level of disturbance to the forest, with "Clearcut/Overstory Removal" as the highest ranked activity and "Treatment of Slash" the lowest ranked activity. We then queried the data for activity overlaps in the same year, switching the lower ranked activity(s) to the higher ranked activity where there was overlap. Next, we assessed overlap in successive years, defaulting to the latest activity year where there was overlap. Finally, at the recommendation of our state partners, we reclassified any activity listed as "Clearcut/Overstory Removal" as "Biomass Removal" if the activity area was within the footprint of a high-severity fire which had occurred within two years of the removal. Once the temporal and activity type overlaps had been corrected, we began the process of validating actual completion of activities. For this process we used the forest loss dataset produced by Hansen et al. (2013), which is updated annually and publicly available via Google Earth Engine. Because not all FERNS activities would create sufficient disturbance to be detected in the Hansen dataset, we focused this validation on only "Clearcut/Overstory Removal" activities, overlaying these activity areas with the annual Hanson forest loss dataset. Based on this overlay, we then estimated a completion percentage for "Clearcut/Overstory Removal" activities, which we aggregated by ownership and ecoregion. We then randomly sampled the remaining activity types based on the ownership and ecoregion specific completion percentage. For example, if 10 of 20 "Clearcut/Overstory Removal" activities (50%) could be validated for USFS managed land in the Coast Range, and there were 60 unique activity records for "Treatment of Slash" for this same ownership and ecoregion combination, then 30 of the 60 records would be dropped, and the remaining 30 of 60 (50%) would be kept. FACTS, LANDFIRE, and SMR data do not have overlapping activity polygons, and we assumed all activities were completed as reported for these datasets.
3. Across different datasets, there was some overlap of management polygons on the same acres in a given year. This may have been the result of spatial errors, or duplicate reporting, especially as the LANDFIRE dataset pulls from a publicly reported disturbance database into which

FACTS records are often reported. To avoid double counting practice acres in the same year from different data sources, we used a simple dataset hierarchy based on our confidence in each one to choose which data to keep: first FACTS data, then FERNS data, then LANDFIRE data, and finally SMR data. We also estimated acres of sequential treatments of thinning followed by prescribed fire by isolating overlapping polygons from different years to allow for accurate representation of this typical sequence in our model. Notably, pile burns were assumed to occur only following other management practices, such as harvest, thinnings, and salvage.

4. Most datasets included practices we could not model with CBM-CFS3 (such as fertilizer application), so we filtered each dataset down to practices applicable to our model scenarios. We then aggregated these practices in generalized categories with similar practice implementation and intensity (**Table S2**).
5. After this data cleaning process, we overlaid each activity dataset with rasters of our model classifiers (**Table S1**) to extract a table of total acreage by practice and classifier set for each year (e.g., owner, forest type, ecoregion, etc.), since the original datasets did not include all our required classifier information. This data table allowed us to aggregate management data into the aspatial form needed for CBM-CFS3.
6. Where years were missing from the LANDFIRE, FERNS, and SMR datasets (LANDFIRE only provides data from 2007-2016, SMR only provides data from 2012-present, and complete reporting of FERNS data begins in 2015), we assumed this was because the data was not collected or reported, not because the management practices did not occur. We used our aggregated data table to backfill these missing years based on relative proportions of management activities for each ecoregion in the LANDFIRE, FERNS, and SMR datasets for years where we had data, which we applied to events from the other datasets in those missing years. This approach assumes that LANDFIRE, FERNS, and SMR activities would occur in the same proportion relative to other datasets in those missing years.

Once we completed this cleaned and aggregated forest management dataset, we estimated stand age limits for each practice (**Table S2**) based on comparisons of volumetric removals by age class from FIA data (USDA Forest Service 2021a) and consultation with state partners and experts. These age limits determine which inventory records can be targeted by certain management practices and represent a typical practice in Oregon, though they may not include all possible or special cases. Along with these age limits, we also collected data on typical harvest intensity for our list of management practices (**Table S2**). Harvest intensity is modeled through *disturbance matrices* – tables that describe the movement of carbon between various ecosystem pools in response to a disturbance, including treatment of harvest residues and removals for HWP (see **Report Figure 1** for the carbon pools included in CBM-CFS3). CBM-CFS3 provides default disturbance matrices for over 200 disturbance types, but after discussion with our state partners we opted to develop custom disturbance matrices for Oregon management practices.

We also created custom disturbance matrices for prescribed fire practices, since CBM-CFS3 does not have a default low-severity or prescribed fire disturbance matrix. Based on literature review, we determined that prescribed fire (broadcast/under burn) in Oregon consumes roughly 52% of understory material with low overstory mortality, though impacts differ by carbon pool. By contrast, pile burns consume an average of 75% of piled material with no impact on live trees (see **Table S3**; Stephens et al. 2009; Caldwell et al. 2002; Pellegrini et al. 2021; CARB 2022a; Bernau, Strand, and Bunting 2018). Proportions of greenhouse gas emissions from prescribed fire follow CBM-CFS3 defaults (burned material emissions are 90% CO_2, 9% CO, and 1% CH_4).

Table S2. Management practice type, data sources, and harvest intensity modeled for Oregon. Harvest intensity refers to the amount of merchantable biomass affected by each practice, where % removed denotes transfer to wood products.

Modeled management type	Included practices	data sources	Stand age limits	Harvest intensity
High harvest	Patch clearcut Stand clearcut Harvest Without Restocking Harvest – high-severity Clearcut Clearcut/Overstory Removal Felling Harvest Unit	FACTS FACTS FACTS LANDFIRE LANDFIRE FERNS FERNS	Private industrial: 40-140 Public: 50-140 Private non-industrial: 60-140	90% cut, 85% removed
Intermediate harvest	Coppice cut Seed Cut Establishment Cut Preparatory Cut Liberation Cut Two-aged Patch Clearcut Two-aged Stand Clearcut Removal Cut Final Cut Improvement cut Sanitation cut Harvest – medium severity Juniper Eradication Juniper Harvest	FACTS FACTS FACTS FACTS FACTS FACTS FACTS FACTS FACTS FACTS FACTS LANDFIRE FERNS FERNS	Phase 1, private: 40-99 Phase 2, private: 100-140 Phase 1, public: 50-99 Phase 2, public: 100-140	50% cut, 45% removed
Group selection	Group selection cut	FACTS	All: 100-140	50% cut, 45% removed
Commercial thin	Commercial thin Harvest – low-severity Commercial Thinning/Selective Cutting	FACTS LANDFIRE FERNS	All: 25-50	30% cut, 25% removed
Hazardous fuels thin	Thinning for hazardous fuels reduction Thinning – high-severity Fuels Reduction	FACTS LANDFIRE FERNS	-	30% cut, no removal
Precommercial thin	Precommercial thin Thinning – low-severity	FACTS, FERNS LANDFIRE	All: 10-20	10% cut, no removal
Salvage	Salvage cut Salvage Biomass Removal	FACTS FERNS FERNS	-	90% cut, 90% removed

Several of our scenarios included new management practice types, such as resilience treatments, reforestation, post-fire restoration, and silvopasture, which also required associated disturbance matrix development. Methodologies and assumptions for these practices are described in the **Scenario Parameterization** section below.

Table S3. Impacts of prescribed fire and pile burns on carbon pools in CBM-CFS3 in Oregon, based on literature review. DOM stands for dead organic matter.

Pool	Description	Prescribed Fire Impact	Pile Burn Impact
Aboveground Very Fast DOM	1-hr fuels, leaf litter, herbaceous material	64% consumed	95% consumed
Aboveground Fast DOM	10-hr fuels, small wood	91% consumed 3% gain from Foliage pool 5% gain from Other pool 7.5% gain from Roots pools	91% consumed
Medium DOM	100-hr fuels, medium wood	-	50% consumed
Aboveground Slow DOM	1000-hr fuels, large wood	-	50% consumed

Table S3, cont. Impacts of prescribed fire and pile burns on carbon pools in CBM-CFS3 in Oregon, based on literature review. DOM stands for dead organic matter.

Pool	Description	Prescribed Fire Impact	Pile Burn Impact
Belowground Very Fast DOM	Dead fine roots	-	20% consumed
Belowground Fast DOM	Dead coarse roots	21% consumed	21% consumed
Branch Snags	All snags excluding the merchantable stem wood portion	71% consumed	90% consumed
Merchantable	Live merchantable stem wood	3% to stem snags 2% consumed	-
Other	Live nonmerchantable stem wood and all branches, tops, stumps, and bark	25% consumed	-
Foliage	Live foliage	2% consumed 3% to Fast DOM pools	-
Coarse Roots	Live coarse roots	5% to Fast DOM pools	-
Fine Roots	Live fine roots	2.5% consumed 2.5% to Fast DOM pools	-

Natural disturbances

Natural disturbance data were collected from various geospatial data sources: wildfire data from the Monitoring Trends in Burn Severity database (MTBS 2020), and the Rapid Assessment of Vegetation Condition after Wildfire Program (RAVG 2021); and insect/disease/abiotic disturbances from the ODF Aerial Insect and Disease Survey (IDS) dataset (Oregon Department of Forestry 2023b). We aggregated specific events into more general disturbance and severity categories (e.g., all insect disturbances noted to cause defoliation were combined into an "Insect – Defoliation" disturbance type with low, moderate, or high-severity as noted by the data source), resulting in 21 separate natural disturbance types (see **Table 2** for a complete list). CBM-CFS3 only allows for one disturbance type to occur on a given acre in a single year, so where multiple disturbances occurred in a given pixel in the same year, we followed a modified version of LANDFIRE's data hierarchy (USGS 2022) to select for disturbances with greater influences on Oregon vegetation and therefore carbon (wildfire > insects > disease > abiotics). We then combined these disturbance datasets with rasters of our model classifiers to extract disturbance information for each unique set of classifiers into a data table, filtering out disturbance acres that occurred on non-forest lands as they are not included in our model.

We determined appropriate disturbance matrices for these events using severity information from MTBS, RAVG, and IDS, where available, otherwise relying on literature review. MTBS and RAVG measure wildfire severity with different metrics, so we used MTBS categories for data from 2000-2020 and crosswalked RAVG data into MTBS categories for 2021 fires (where MTBS data was not yet available). This crosswalk was based on descriptions of MTBS burn severity classes, which employ a threshold of <25% mortality of overstory trees for low-severity fire and >75% overstory tree mortality for high-severity, with mortality between 25% and 75% lumped into a moderate severity category (MTBS, n.d.). We categorized the % Basal Area mortality metrics from RAVG to match these MTBS mortality thresholds and reclassified 2021 RAVG data accordingly. Based on averages from MTBS and Whittier and Gray (2016), we constructed disturbance matrices for low-severity wildfire with 11% mortality of overstory trees (represented by the merchantable carbon pool), moderate-severity wildfire with 50% mortality, and high-severity wildfire with 90.6% mortality. We did not include the "Increased Green" and "Unburned" categories from MTBS in our analysis because they are not relevant for the focus of our model. We further incorporated combustion factors from Campbell et al. (2007) and snag dynamics from Stenzel et al. (2019) to inform disturbance matrix values and transfers for non-merchantable and merchantable carbon pools, respectively.

We used average severity data for insect, disease, and abiotic disturbances from IDS to inform our disturbance matrices for those events. We separated these disturbances into two categories: those that caused tree mortality and those that did not (in the case of insects, these was noted as defoliation events). Disturbance severity averages were the same for both mortality and no mortality categories, with the no mortality events only affecting non-merchantable carbon pools. Low-severity events resulted in roughly 7% of trees affected and moderate-severity events affected an average of 20% of trees. High-severity events exhibited a wider average range, so based on the relative mortality impacts of insects and wildfire from Hicke et al. (2016), we set high-severity insect impacts equal to moderate-severity wildfire impacts (50% of trees affected) and applied this same percentage to high-severity disease and abiotic disturbance events.

Land-use change

We assessed land-use change trends from a time-series comparison of National Land Cover Database (Dewitz and USGS 2021) from 2001 versus 2019. We chose this period to match as closely as possible with the IPCC Guidance threshold of 20 years for classifying land-use change (Aalde et al. 2006) while working within the constraints of available data. Although 1992 and 1996 NLCD products exist, they are not comparable to the more recent datasets and cannot be used for change detection. This longer timeframe avoids temporary land cover changes (such as temporary loss of trees from a clearcut harvest followed by reforestation or wildfire followed by natural or artificial regeneration) that do not constitute permanent land-use change. However, it should be noted that FIA maintains the forest land-use for 30 years following a disturbance where recovery of forest vegetation is still possible; if after 30 years tree establishment has not recovered then it is deemed a land-use change (USDA Forest Service 2023b).

Annual averages of land-use change by ownership, forest type group, and ecoregion were derived by overlaying rasters of those model classifiers with NLCD products from 2001 and 2019. We assessed land cover classification changes between the two NLCD years, focusing on transitions between forest and woody wetlands (NLCD codes 41, 42, 43, 90) to and from water, developed land, barren land, herbaceous grasslands, pasture, cultivated crops, and herbaceous wetlands (NLCD codes 11, 21, 22, 23, 24, 31, 71, 81, 82, 95). We excluded the shrub/scrub category from this change assessment because Oregon has widespread shrub/scrub ecosystems that are not considered forestland and including them would result in an overcount of land-use change, even though they may sometimes contain recently cleared and regenerating forest. Shifts among forest and woody wetland codes were not counted as land-use change events. Changes were categorized as forest loss if moving from forest or woody wetland in 2001 to the listed non-forest classes in 2019, and categorized as forest gain if newly classified as forest or woody wetland in 2019. Net land-use change estimated in this way averages -31,256 ac yr^{-1} from 2001-2019 (+31,364 ac yr^{-1} forest gain and -62,620 ac yr^{-1} forest loss), which differs substantially, in both magnitude and trend, from estimates based on FIA data for the same period (+24,042 ac yr^{-1} forest gain and -19,515 ac yr^{-1} forest loss for a net change of +4,527 ac yr^{-1}; Christensen et al. 2019).

We applied the CBM-CFS3 default disturbance matrix for forest gain (afforestation) events. For forest loss (deforestation), the default CBM-CFS3 disturbance matrix assumes that 80% of cleared merchantable trees are removed for wood products. However, as described in the **Forest Management** section above, this is not an accurate assumption for Oregon forests. Therefore, we modified the deforestation disturbance matrix in consultation with our state partners to match the high harvest disturbance matrix, (85% removal of merchantable material, 15% left on site as Medium DOM).

Disturbance Event Schedule

CBM-CFS3 does not independently predict future events, but instead follows a user-determined schedule of annual disturbances for each simulation period. As described above, we gathered disturbance data for Oregon that included both disturbance types and annual acreages from 2000-

2021. We used these historical values to calibrate our model during spinup, used actual acreage values in our model from 2000-2021, and applied annual averages based on the historical period for each disturbance type from 2022-2100 (see **Table 2** for BAU event schedule values). This use of an annual average inherently excludes extreme disturbance events in our projections (especially relevant for wildfire), but is the necessary approach given available data.

Post-Disturbance Transition Rules

This final input table defines model behavior after each disturbance event. For stand-replacing events such as high harvest, CBM-CFS3 assumes by default that stand age resets to zero, all other classifiers remain the same, and the same forest type begins to grow again in the next model timestep. For events that are not stand-replacing, the model assumes that no changes occur post-disturbance aside from the movements of carbon determined by the disturbance matrix. Where these default model assumptions are inaccurate, they can be altered using transition rules, allowing for changes to new classifiers, yield curves, or stand ages, as well as regeneration delays if necessary. We defined transition rules for all disturbance events in our model, even if just to affirm the defaults, to best control model behavior.

To more accurately model carbon dynamics after certain harvest disturbances, we adopted several distinct strategies for transition rules. For thinnings in both uneven and even-aged stands, the modified yield curves mentioned in the **Volume-Age Curves and Volume-to-Biomass Conversions** section above were applied using the Thinned classifier (records transitioned from Thinned=0 to Thinned=1) to represent the anticipated temporary increase in growth from remaining trees. Following intermediate harvest disturbances with at least 50% volume removed, forest records were split where the harvested area stand age was reset to zero to simulate natural regeneration, and unharvested trees continued on their original growth and age trajectory (i.e., for an intermediate harvest at 50% removal, 50% of the stand reset to age zero and 50% continued as before). Group selection harvests were implemented with a different transition where the age of the harvested stand reset to 30-40 years younger than pre-harvest age, based on the typical three-aged nature of stands managed in this way (Huff 2014). We also utilized transition rules to implement forest loss and forest gain events.

AIDB Adjustments

In addition to collecting data to parameterize these seven input tables, we also updated the AIDB with Oregon-specific values for mean annual temperature (MAT). MAT drives decomposition dynamics in CBM-CFS3, and using default Canadian temperatures leads to inaccurate decomposition and soil carbon accumulation results for Oregon. To find Oregon MAT values, we aggregated mean monthly temperature from the PRISM Climate Group (PRISM Climate Group 2024; Daly et al. 2008) into annual values and calculated annual averages for 2000-2021. Then using the *raster* package in R (Hijmans 2010), we applied a forest area mask from our forest type group classifier raster to extract MAT for forested areas only (to filter out higher temperatures from urbanized and desert areas). Statewide forestland MAT values from 2000-2021 ranged from 7.64°C to 9.99°C. We applied these annual MAT values for the period from 2000-2021, and used an average MAT value (8.66°C) for the period from 2022-2100.

Comparison of BAU Scenario and Growth Removals and Mortality Methodology

One of the more unexpected results from this assessment of forest carbon dynamics is a large discrepancy between average net ecosystem carbon flux as estimated from the BAU scenario, and a previously published estimate of forest carbon flux for Oregon (Christensen et al. 2019). The data from Christensen et al. (2019), which are based on growth, removals, and mortality (GRM) of remeasured trees in FIA plots, indicate that from 2001-2016, Oregon forests were a net carbon sink, with an average forest carbon flux of -31.4 $TgCO_2e\ yr^{-1}$. Over the same period, the BAU scenario suggests that forests were a net carbon source, with an average net ecosystem carbon flux of 12.7 $TgCO_2e\ yr^{-1}$. While it is not

unexpected that two different methodologies would lead to different outcomes, the magnitude of the difference is noteworthy. We will examine several possible causes for this discrepancy in the text below, while keeping methodological details to the minimum required to understand the difference between methods. For a full description of methodology, including citations for component models used within the GRM approach, refer to Chapter 3 of Christensen et al. (2019). For a full description of the methodology underlying the BAU scenario, including a description of model parameterization, see the preceding **Appendix** sections. For a full description of the CBM-CFS3 model, which was used in the BAU scenario, see Kurz et al. (2009) and Kull et al. (2019).

Both the BAU scenario and the GRM approach utilize FIA data to estimate starting carbon stocks; however, there are critical differences in each approaches' methodology which may lead to differences in the size of these pools. A common thread of difference between approaches is that estimates in GRM are based on direct plot-level observations, which are then scaled up to represent the full forest, while in the BAU scenario an area-based forest inventory is generated which is then read into the model for simulation of carbon stocks. For example, in the GRM approach, estimates of aboveground live-tree woody carbon are based on plot-level observations of stand volume, which are converted to biomass (assumed to be 50% carbon) using regional FIA equations. The BAU scenario also uses a similar volume to biomass conversion (also assuming that biomass is 50% carbon); however, this conversion is applied to inventory records that have been "grown" to their current size within the model. CBM-CFS3 uses a growth and yield-based structure, where a series of yield curves (**Figure S1**) are used to estimate stand volume at a given age. So, to estimate stand volume, which is then converted to biomass, the user must first supply the model with a starting forest inventory (in ha), stratified by relevant classifiers (e.g., Forest Type Group; **Table S1**) and mean stand age. Then based on the assumed volume of these stands at a given age, an estimate of biomass and thus aboveground live-tree woody carbon is produced.

Both methodologies have a similar approach for estimating belowground live-tree woody carbon, calculating this carbon pool as a proportion of aboveground live-tree woody carbon. The GRM approach applies a species-group specific ratio to estimate carbon in roots >2 mm in diameter. The BAU scenario utilizes CBM-CFS3's default root biomass ratios, which are differentiated by hard and softwood, and contain an additional ratio for calculating fine roots (<2 mm) as a proportion of total root carbon. The GRM approach also calculates carbon in aboveground and belowground understory vegetation (including live trees < 1 inch in diameter), as a function of forest type and stand age. Understory vegetation was not estimated in the BAU scenario, as CBM-CFS3 is only designed for estimating carbon in trees, and does not account for diameter distributions of trees in an inventory record. However, the allometry equations used in CBM-CFS3 mean that at younger age classes, inventory records first begin accumulating carbon in foliage and non-merchantable carbon pools (contributing to total aboveground live-tree woody carbon) before allocating carbon to merchantable carbon pools at older age classes.

Estimation of DOM and soil carbon pools are an area of large divergence between the GRM method and the BAU scenario. In the GRM method, carbon in standing dead trees is estimated similarly to aboveground live-tree woody carbon, but with reductions applied for breakage of tops and limbs, loss of bark, and decay parameters applied to roots. Further, aboveground down woody debris is estimated from transect-intercept measurements, and wood is binned into coarse (≥ 3 inches intersect diameter) and fine (≥ 0.25 to < 3 inches diameter) groups, with appropriate wood density and decay class reduction factors applied when converting biomass to carbon. Carbon contained in the forest floor (litter and duff) is estimated as a function of plot location, elevation, forest type group, live tree carbon, and climate. Finally, soil organic carbon stocks (to a 1-meter depth) are derived from model estimates calibrated on data from soil cores on FIA plots and other national soil datasets. Unlike in the GRM approach, where some DOM pools are estimated based on plot-level observations, in the BAU scenario, all DOM and soil carbon pools are simulated as a function of site history. To begin, each inventory

record is initialized in CBM-CFS3 via a spin-up process. In this process, all carbon pools begin at zero, and each inventory record is grown to the stand replacement age for its historical disturbance type (assumed to be wildfire with a return interval of 150 years for all records) and then disturbed. This pattern of growth and disturbance repeats until the slow above and belowground DOM carbon pools are within 0.1% of each other at the end of two successive rotations. The model then simulates a final pass of growth, this time using the last disturbance type and age at last disturbance (both estimated from FIA data) as a guide for how and when to disturb the records. Finally, the records are grown up to their current age (in 2000) as specified in the forest inventory. In this way, there are no jumps or discontinuities between historical records and model simulations. During these growth and disturbance passes, carbon is accrued in above and below-ground live woody carbon (as described above) and subsequently passed to DOM and then soil carbon pools according to hard and softwood specific turnover rates, or in the case of disturbance, in a proportion corresponding to that disturbance's disturbance matrix (**Table S2 and S3**). Carbon is also transferred between DOM pools, from DOM to soil pools, and is lost to the atmosphere from DOM and soil pools according to decomposition and transfer equations. These equations are governed by modeled mean annual temperature (MAT; set at 8.66°C for the model spin-up) and site condition (assigned the model default for "Montane Cordillera"). Once initialized to represent conditions in 2000, the model was run forward with annual patterns of growth, disturbance, turnover, and decomposition simulated to reflect change in carbon stocks in each year.

Although there are discrepancies in how forest carbon is grouped or categorized between the GRM approach and the BAU scenario, we nonetheless can try and compare these groups to assess where they are similar or different (**Figure S2**). Total carbon stocks (GRM = 11.88 $PgCO_2e$, BAU = 10.31 $PgCO_2e$), are lower for the BAU scenario than as estimated via the GRM approach, with the largest differences in aboveground live tree carbon stocks (GRM = 3.81 $PgCO_2e$, BAU = 3.31 $PgCO_2e$) and soil carbon stocks (GRM = 5.78 $PgCO_2e$, BAU = 3.92 $PgCO_2e$; **Figure S2**). Forest floor carbon is higher as estimated in the BAU scenario (GRM = 0.43 $PgCO_2e$, BAU = 1.62 $PgCO_2e$) as is total dead tree carbon (GRM = 0.37 $PgCO_2e$, BAU = 0.45 $PgCO_2e$; **Figure S2**). Non-living carbon (dead trees and roots, down wood, forest floor, and soil) as a percentage of total carbon is also higher for the BAU scenario (63%) than the GRM estimation (60%).

These differences in carbon stocks, and critically the ratio of living to non-living carbon, may reflect some of the carbon flux differences observed during the period between 2001 and 2016. In the GRM estimation, life tree carbon (including foliage and roots), standing dead trees, and forest floor carbon all exhibit annual increases. Dead tree roots, understory (including roots), down woody material, and soil carbon, each decline over this period; however, these carbon losses are smaller than the carbon gain associated with the other categories, leading to a net increase in total carbon stocks. These dynamics suggest a growing forest, with moderate rates of turnover and mortality, and reductions in DOM either from management action or increased decomposition. Over the same period in the BAU scenario, dead tree carbon (including roots) and carbon in down wood each increased, while live tree carbon (including foliage and roots), forest floor carbon, and soil carbon each declined, leading to a net decrease in total carbon stocks.

In the BAU scenario, these dynamics suggest a clear trend in carbon shifting from more durable pools (live trees and soil) into less durable carbon pools (dead trees and down wood). These dynamics may be the result of management or disturbance outpacing growth, or an increase in the rate of mortality across the forested landscape. In addition, forest floor carbon, which is the most labile of the carbon pools, initially increases (from 2001-2012) before declining through 2021, which suggests that transfers to and subsequent losses from this pool account for a not insignificant proportion of the losses in the live tree carbon pools. When these changes in carbon stocks are examined in terms of annual fluxes, annual

loss of carbon from litter decomposition accounts for an average of 52% of the total gross carbon emissions each year (+111.6 $TgCO_2e\ yr^{-1}$), more than decomposition of down wood (+25.5 $TgCO_2e\ yr^{-1}$), decomposition of soil carbon (36.8 $TgCO_2e\ yr^{-1}$), losses of carbon to disturbance emissions (2.9 $TgCO_2e\ yr^{-1}$), and losses of carbon to harvest (38.6 $TgCO_2e\ yr^{-1}$) combined (**Report Figure 6a**).

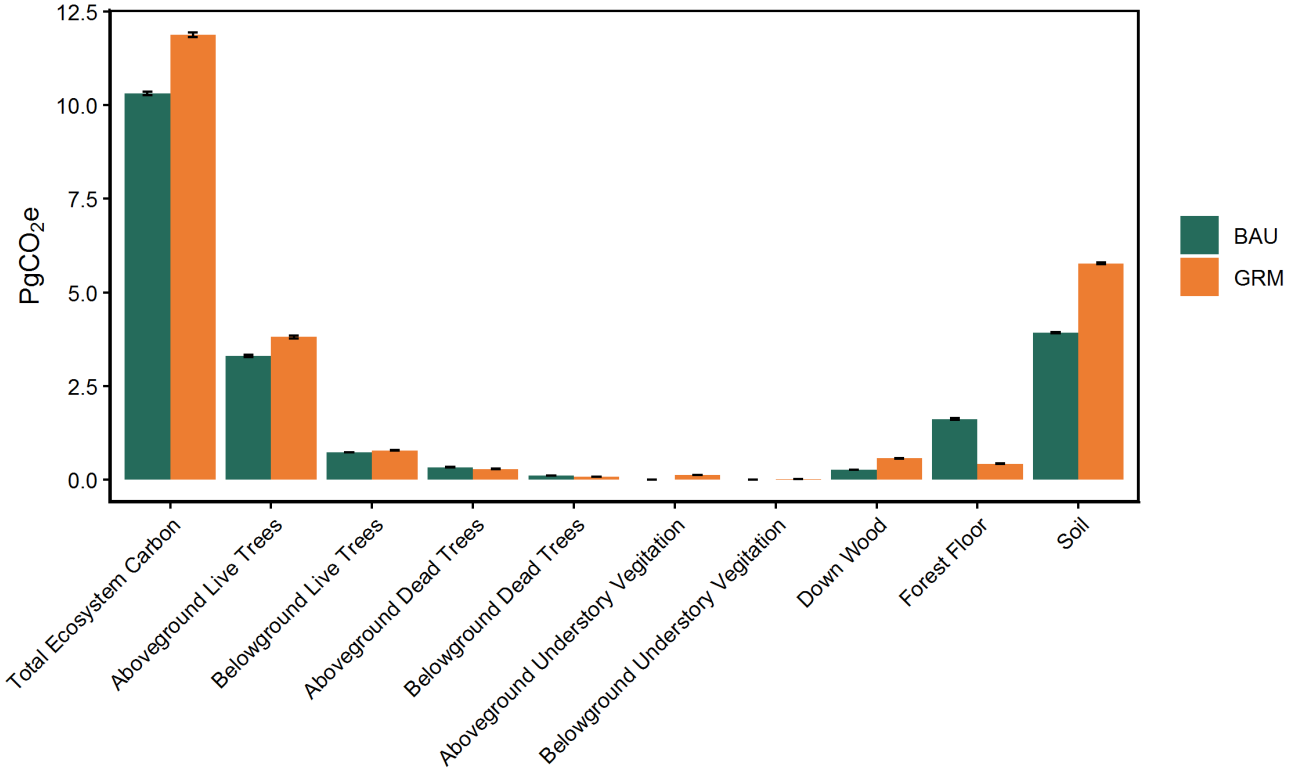

Figure S2. Comparison of average carbon stocks (2007-2016; $PgCO_2e$) as simulated in our BAU scenario and as estimated from the Growth Removal and Mortality (GRM) measurement approach as reported in Christensen et al. (2019) Table 4.13a. BAU carbon stocks were grouped into categories from the in the GRM approach as follows: Aboveground Live Trees = Softwood Merchantable Carbon + Softwood Foliage + Softwood Other + Hardwood Merchantable Carbon + Hardwood Foliage + Hardwood Other; Belowground Live Trees = Softwood Course Roots + Softwood Fine Roots + Hardwood Course Roots + Hardwood Fine Roots; Aboveground Dead Trees = Softwood Stem Snags + Softwood Branch Snags + Hardwood Stem Snags + Hardwood Branch Snags; Below Ground Dead Trees = Belowground Fast DOM + Belowground Very Fast DOM; Down Wood = Medium DOM; Forest Floor = Aboveground Fast DOM + Aboveground Very Fast DOM + Aboveground Slow DOM; Soil = Belowground Slow DOM. Error bars for the BAU scenario represent the standard deviation of the annual (2007-2016) estimate for each category. Error bars for the GRM methodology represent the standard error as reported in Table 4.13a in Christensen et al. (2019).

Some of this large loss of carbon from the forest floor and soils may be due to the decay and decomposition dynamics incorporated into CBM-CFS3. As mentioned before, CBM-CFS3 utilizes Q_{10} equations to relate decomposition rates to MAT. These equations, developed for the first version of CBM-CFS in the mid 1980's, may not be entirely appropriate to represent decomposition dynamics in Oregon, where MAT is substantially higher than it was when the model was parameterized. MAT also increases over the period from 2000-2021 (ranging from 7.64°C to 9.99°C), contributing to further increases in emissions from this carbon pool.

Another factor which may be contributing to elevated emissions from forest floor carbon is the size of the forest floor carbon pool relative to total ecosystem carbon. From 2007-2016 forest floor carbon constituted just 3% of total carbon stocks as estimated with the GRM methodology, whereas when estimated in the BAU scenario, forest floor carbon accounted for 16% of total carbon stocks over this same period (**Figure S2**). This large ratio of forest floor carbon may be the result of transfers (losses) of

carbon from the live tree carbon pool, which can occur either via direct inputs like litterfall or through the breakdown of material in other "slower" carbon pools like down wood. However, even from the initialization of the simulation in 2000, forest floor carbon accounted for 15% of total ecosystem carbon stocks, suggesting that the litterfall and turnover dynamics and spin-up process in CBM-CFS3 may also be contributing to elevated DOM pools observed in the BAU scenario when compared to the GRM estimations. When this large starting carbon pool (which may be in a state of equilibrium during the spin-up) is subject to an increase in MAT, as experienced during the period between 2000-2021, large fluxes of carbon are expected.

Another major difference between the GRM methodology and the BAU scenario, not yet discussed, is how each methodology applies or accounts for disturbance and management. In the GRM methodology, disturbances are quantified at the plot level by assessing a change in forest condition classification. This system allows FIA crews to code up to three management treatments, and up to three natural disturbances during each observation, meaning that a change in carbon stocks between time periods can be attributed to multiple overlapping disturbance types. In the BAU scenario, disturbances are applied in the model based on a spatial analysis of maps of historical management, natural disturbance, and land use change. Because CBM-CFS3 is spatially referenced, rather than spatially explicit, disturbances are applied stochastically (in the case of natural disturbances or land use change events), or according to a set of age or carbon-based sort rules (in the case of management disturbances) to all inventory records with matching classifier values (e.g., Forest Type Group, Ecoregion; **Table S1**) and mean stand age. For every disturbance type there is a corresponding disturbance matrix, which dictates the relative proportion of carbon which is to be transferred between pools as the result of a disturbance (**Table S2** and **S3**).

These differences highlight the fact that, in the GRM methodology, changes in carbon stocks and carbon fluxes are attributed to patterns of disturbance, while in the BAU scenario patterns of disturbance drive changes in carbon stocks and carbon fluxes. The GRM methodology also allows for the same disturbance agent (e.g., fire) to have a differential impact across multiple plots, proportional to the change in carbon stocks which has actually been observed in the forest. In an equivalent example from the BAU scenario, all fire (at a given severity level) will have an equivalent relative impact on each inventory record, with the only differences in disturbance impacts resulting from the absolute level of carbon stored in each carbon pool at the onset of the disturbance. This more "generic" approach to disturbances used in the BAU scenario is required for forward projections in CBM-CFS3, where the actual impact of any one disturbance on carbon stocks cannot be known a-priori. Nonetheless, this approach does introduce uncertainty into the BAU scenario, especially where quantification of the exact management practice(s) being undertaken is difficult to determine, or the total area disturbed is difficult to ascertain. Both challenges are compounded for assessment of private lands, where management tracking and reporting (e.g., FERNS, ODF Smoke Management Reports) is a relatively new requirement, and there is no required internal or external verification of activity completion.

Because of these challenges, the disturbances represented in the BAU scenario between 2000-2021 are simply an approximation (though one we have a high degree of confidence in) of the disturbance related carbon flux which has occurred, rather than a more robust direct observation, as is the case for the GRM methodology. Based on our analysis of the difference in per-acre aboveground live woody carbon flux attributable to growth, removals, and mortality (**Report Figure 7**) we believe the two methodologies represent similar dynamics on a per-acre basis. However, differences in estimated disturbance area between the methodologies, in particular a possible overestimate of disturbance in the BAU scenario, may be leading to the larger loss in total aboveground live woody carbon as observed in the BAU scenario.

In addition, when management actions deviate from our estimated norms (**Table S2** and **S3**) movements of carbon as simulated in the BAU scenario may differ from observations. This may be especially true for carbon in shorter residency carbon pools (e.g., forest floor and down wood), which, unlike removals of carbon from harvest, we are not able to compare to external harvest inventory reports (e.g., Morgan et al. (2019)) for verification. It is quite possible that our disturbance matrices for certain disturbance types may be overestimating the movement of carbon from live woody carbon pools to non-living carbon pools (e.g., forest floor carbon) contributing to the increase in these carbon stocks, and emissions from these carbon pools relative to the GRM estimation. This may be particularly pertinent for harvest removals where we assume that almost 100% of the non-merchantable carbon cut is left on site to either decay or be pile burned (see also the **Harvested Wood Volume** section below). Estimates of carbon in piles are not included in the GRM methodology, which may help to partially explain the larger ratio of forest floor carbon to total carbon (**Figure S2**) in the BAU scenario, and subsequent flux of carbon from these pools.

A third consideration associated with the difference in management and disturbance between approaches is the difference between an annual estimate, as is the case in the BAU scenario, and decadal observations, as is the case in the GRM methodology. The inclusion of independent natural disturbance events and disturbance matrices on annual timesteps allows the BAU scenario to simulate the impacts of smaller, non-mortality causing disturbance events (e.g., insect and disease defoliation, low-severity fire, or abiotic disturbance events) in a more immediate way. In such an event, the forest floor or down wood carbon pool may temporarily increase due to a loss of foliage or small branches; however, these pools may return to pre-disturbance levels within a few years. Likewise, the live woody carbon pools may temporarily decline or exhibit a slower rate of growth in response to these disturbances. Because the BAU scenario operates at an annual timestep, it is capable of capturing carbon fluxes associated with these events (e.g., the increase and decrease of down wood or forest floor pools). However, the GRM methodology which utilizes a decadal observation timeline and interannual smoothing may mask or miss the immediate impacts of these events if there is no change in carbon stocks between time periods.

One final major source of divergence between the BAU scenario and the GRM approach is their estimation of net change in forest area due to land-use change. For the BAU simulation, we estimate land-use change from a time-series comparison of the National Land Cover Database (Dewitz and USGS 2021) in 2001 versus 2019. For the GRM approach, land-use change trends were estimated directly from FIA data (Christensen et al. 2019). Net land-use change as parameterized in the BAU scenario was -31,256 ac yr^{-1} from 2001-2019 (+31,364 ac yr^{-1} forest gain and -62,620 ac yr^{-1} forest loss). Net land-use change as parameterized in the GRM approach was +4,527 ac yr^{-1} from 2001-2016 (+24,042 ac yr^{-1} forest gain and -19,515 ac yr^{-1} forest loss). This difference, both in sign and magnitude, leads to a net loss of carbon from land-use change in the BAU scenario (+3.9 TgCO2e yr^{-1}), while the GRM approach estimates a net gain of carbon from land use change (-0.9 $TgCO_2e$ yr^{-1}). While these numbers are small relative to the overall difference in carbon flux (GRM = -31.4 $TgCO_2e$ yr^{-1}, BAU = 12.7 $TgCO_2e$ yr^{-1}), they nonetheless contribute to the divergence and provide another area where methodological reconciliation could prove helpful for future assessments of forest carbon.

Given the information presented above, we believe that the differences in forest carbon flux between our BAU estimates and the GRM method are most likely due to differences in DOM (particularly forest floor) and soil carbon dynamics (**Figure S2** and **Report Figure 6a**), rather than an inherent error or misestimation of forest carbon dynamics in our CBM-CFS3 based modeling approach. Both our BAU scenario and the GRM approach utilize FIA data to estimate starting carbon stocks; however, the method of estimation, the relative starting size of each pool (**Figure S2**), and the permanence or lability of these stocks can and do have a large influence on annual forest carbon flux. In addition, contrasting

trends in land use change, and differences in the area of management and disturbances also contribute to differences in total forest carbon flux, even if the per-acre fluxes are aligned (**Report Figure 7**). Although our results are different from those presented in Christensen et al. (2019), we have full confidence in the validity of our modeling approach. In addition, any difference in model outcome from prior work will be carried throughout all of our scenarios and portfolios, meaning that among scenario comparisons are still a useful exercise for determining the mitigation potential of different forest management and wood utilization approaches.

Harvested Wood Products Model Methodology

The harvested wood products model (CBM-HWP-OR), built using the ANSE framework, requires data inputs on 1) harvested wood volume; 2) exports; 3) mill efficiency and use of mill residues; 4) primary product ratios; 5) additional wood product streams; 6) domestic end-use consumption and half-lives; and 7) product retirement and landfills. Data sources and assumptions for each are described below. Data inputs and results were processed using Excel and R, with models run using the ANSE software (Microsoft 2016b; R Core Team 2020; CFS 2024).

Harvested Wood Volume

Because carbon makes up approximately half of the dry weight of wood, much of the carbon that is harvested from the forest ecosystem continues to be stored in harvested wood products (HWP). The CBM-HWP-OR tracks carbon entering the forest products sector, including where it goes, its path to get there, and how long it spends in different pools before ultimately being retired (**Report Figure 4**). The CBM-HWP-OR is a closed system, meaning that all carbon that enters the HWP stream is accounted for either as a carbon stock (i.e. in products in use or inert in landfills) or an eventual emission into the atmosphere; there is no additional or lost carbon over time. From a carbon accounting perspective, it is most relevant to know what percent of harvested carbon is stored or emitted at any given time; as such, rather than track specific carbon molecules over time, the model has been parameterized to proportionally allocate carbon mass according to distinct harvest classification (input type), as it moves through the HWP stream. For example, a certain proportion of merchantable timber entering the stream will first be exported; a proportion of that remains domestically will go toward commodity production, with a certain proportion of that carbon going toward mill residues, where some will be burned, and some will go toward additional commodity production.

Input data on carbon entering the HWP stream in each year of our simulation came from two sources. Carbon entering the stream starting in 2000 came directly from harvest disturbances in CBM-CSF3, equal to the amount of carbon transferred to HWP in disturbance matrices. Carbon entering the stream between 1950 and 1999 representing *inherited* or *historical carbon* (i.e., carbon entering the HWP stream before the start of our BAU scenario) was calculated using estimates of annual Oregon harvest volumes from USDA Forest Service (Dillon and Morgan 2023; Simmons et al. 2021; Morgan et al. 2019) and University of Montana Bureau of Business and Economic Research (BBER 2022). To convert harvest volumes to units of carbon, we calculated an average bark expansion factor from Miles and Smith (2009) for species typically harvested in Oregon according to Simmons et al. (2021), and applied this to harvest volumes (which do not include bark) from BBER (2022) and Morgan et al. (2019). We then used conversion factors based on Smith et al. (2006) to convert from product volumes such as board feet to metric tons of carbon. These carbon conversions were adjusted using wood-type (i.e., hardwood or softwood) specific gravities based on species typically harvested in Oregon, which we calculated from FIA data (USDA Forest Service 2021a).

With input harvest volumes converted to units of carbon, we then partitioned these inputs as a percentage of harvested carbon allocated to each of five model input flows: bark residue, utilized biomass, industrial roundwood, residential fuelwood, and direct to landfill (**Table S4**). Each of these

flows has unique rules and utilization pathways within the CBM-HWP-OR model, as discussed below. To govern this partitioning of carbon, we first split carbon inputs from CBM-CFS3 into merchantable and logging residue categories. This was necessary, as after consultation with state partners and industry professionals, it was determined that wood from tops, limbs, and stumps is not commonly utilized in Oregon. However, our disturbance matrices use the same removal proportion for stemwood, which is assumed to be 100% merchantable, and "other" wood, which includes tops, limbs, and stumps. As such, we needed to calculate a post-hoc correction to account for the biomass which was removed in our ecosystem model, but ultimately not utilized for products in the HWP model. Again, this was only necessary for carbon inputs from CBM-CFS3 (2000-2100); *historical carbon inputs* (1950-1999) represent actual removals reported at mills, so we assume 100% of this was merchantable.

To determine the fraction of removed wood which was merchantable, we first split harvest inputs by source, with the assumption that any harvested course woody debris (stem and branch snags) would be allocated 100% toward the merchantable category. Harvests of live biomass (stemwood and other) were further divided into hardwood and softwood categories, and then further subdivided into branch and bole+bark categories. This latter division was determined based on a weighted average of the forest type group specific allometric proportions as calculated for our forest type groups using the equations from Boudewyn et al. (2007), with parameters modified for this study (see the **Volume-Age Curves and Volume-to-Biomass Conversions** section above). We assumed that 100% of the branch category (for both hardwood and softwood) should be considered not utilized. For the bole+bark category, we used a report of logging utilization in Oregon and Washinton (Simmons et al. 2016), to estimate that 3.5% of this category (for both hardwood and softwood) should be treated as not utilized. Then based on the mass of carbon in the utilized and not utilized categories, we estimated a removal specific utilization percentage. We then compared this percentage back to the assumed percentage of biomass left on site after each harvest type to determine the amount of the total cut wood which is already not being utilized. For example, the high harvest disturbance matrices assume that 90% of the above ground biomass is cut, and 85% is removed, meaning 5.556% (5%/90%*100) of the cut biomass has already been left on site after harvest and thus not utilized. In cases where our removal specific utilization percentage was greater than the disturbance specific percentage of biomass left on site, we took the difference and assumed this percentage would constitute the percentage of harvested biomass which was logging residue (removed but not utilized), with the remaining precent assume to be merchantable (removed and utilized). We then summed the annual hardwood and softwood merchantable carbon (biomass and course woody debris) and logging residue carbon (biomass only) for division into our five model input flows.

Carbon in the logging residue category was further divided and allocated into either the residential fuelwood, or direct-to-landfill model flows. Because pile burns follow an average of 2.85% of harvest, and because pile burns consume 50% of the available medium DOM pool (**Table S3**), we allocated 1.452% of the carbon in the logging residue category toward the residential fuelwood model flow, which sees full combustion of all allocated carbon (99% CO_2, 1% CH_4). The remaining 98.575% of the carbon in the logging residue category was allocated to the direct to landfill model flow, where this carbon was treated as a paper-like product (56% decomposable fraction, 14.5-year landfill half-life).

Carbon in the merchantable category was further divided and allocated into the bark residue, utilized biomass, and industrial roundwood model flows. Because CBM-CFS3 harvest removals include carbon in bark, we first split out a bark proportion of merchantable wood, based on mill residue data from Donahue, Morgan, and Dillon (2021), and the average annual proportion of mill residue to primary timber production for hard and softwoods from BBER (2022). Based on these values, 9.61% of hardwood merchantable carbon, and 9.98% of softwood merchantable carbon is bark, with the remaining 90.39% and 90.02% as wood. This wood proportion was further partitioned into the

industrial roundwood and utilized biomass flows to represent roundwood used for products and roundwood used for industrial fuel, respectively. Based on mill survey data from BBER (2022), we estimate that 0% of hardwood and 0.1% of softwood is allocated toward utilized biomass.

Because the overall proportion of total harvest entering each of the five model input flows is first dependent on the proportion of harvest which is merchantable or logging residue, values are calculated dynamically for each year and scenario. In the CBAU scenario, for example, an average of 7.32% of harvested hardwood material, and 4.68% of harvested softwood material is considered logging residue; however, these values vary by ± 4.1 % and 2.3% respectively. Average values for the percentage of carbon allocated to each of the five model flows are provided in **Table S4**.

Table S4. Carbon flow splits for input of harvested wood in the CBM-HWP-OR model. The values shown in this table are an average of inputs (2000-2100) for the CBAU using BAU HWP assumptions. Percentages may not sum to 100% due to independent rounding.

Wood Type	Proportion of Harvested Volume Partitioned into Model Input Flows				
	Bark residue	Utilized biomass	Industrial roundwood	Residential fuelwood	Direct to landfill
Hardwood	8.907%	-	83.773%	0.104%	7.215%
Softwood	9.512%	0.095%	85.712%	0.067%	4.614%

Exports

We calculated HWP exports at two stages: raw roundwood exports before commodity production, and commodity exports after production. We used Oregon roundwood export data from the US International Trade Commission trade database (USITC 2024) to determine the proportions of harvested roundwood exported, and destination countries for these exports. Based on these data, Oregon exported on average 0.02% and 16.79% of its hard and softwood industrial roundwood (respectively) harvested between 2015 and 2019 (**Report Table 3**). We relied on the FAOSTAT statistical database (FAO 2024) to determine the proportions of commodities produced from exported roundwood, categorized as fuel, paper, or wood commodities (**Figure S3**). Destination countries for these exports were binned into three regions based on their weighted-average HWP half-life (**Table S5**; FAO 2024; Pingoud et al. 2006). We assumed all exported logs were stripped of their bark prior to shipment so no bark was exported; instead, we modeled it as a domestic product stream.

Table S5. Export destination country bins based on product-weighted average HWP half-life.

Export Region	Half-Life Range	Average Half-Life	Major Countries
1	0-5 years	1 year	Cambodia, Bangladesh, Guatemala, Nicaragua
2	5-15 years	9 years	China, Taiwan, Brazil, Mexico, Italy, Spain
3	15-30 years	20 years	Canada, Germany, UK, Malaysia, Japan

We used data from Howard and Liang (2019) for US-level commodity exports and found that an average of 26% of softwood commodities and 33% of hardwood commodities were exported annually from 1965-2017. We utilized national numbers here rather than state-specific ones due to a lack of data on intrastate trade and subsequent difficulty determining which commodities were traded within the US rather than internationally. Commodity exports were aggregated into a single commodity export region and were subject to international HWP half-lives (**Report Table 3**).

Mill Efficiency and Use of Mill Residues

We assumed that all harvested industrial roundwood not exported entered domestic commodity pools, either as primary products (see below) or mill residues. Mill residues have different uses than other primary products, so they need to be tracked separately in CBM-HWP-OR. We used mill efficiency data (Morgan et al. 2019) to estimate mill residues as a proportion of total harvest volume after export for domestic HWP. We found that in 2014 Oregon's mills had an average mill efficiency of 56.52% for hardwoods and 54.73% for softwoods, meaning that the remaining material – 43.48% and 45.27% of total harvest after export for hardwoods and softwoods, respectively – becomes mill residue during the commodity production process. We differentiated between softwood and hardwood inputs, as these wood types differ in their exports and commodities produced, as well as their associated product half-lives and displacement factors (described below). We then assigned mill residues to four commodity pools using proportions from Metcalf (1965), Manock, Choate, and Gedney (1968), Schuldt and Howard (1974), Howard and Hiserote (1976), Howard (1984), Howard and Ward (1988; 1991), Ward (1995; 1997), Ward, Lettman, and Hiserote (2000), Brandt et al. (2006), Gale et al. (2012), Simmons et al. (2016), and Morgan et al. (2019): pulpwood, composite panels, bioenergy, and other industrial uses (see **Report Table 3** and **Figure S3** for proportions for softwoods and hardwoods).

Primary Product Ratios

As noted above, CBM-HWP-OR works by allocating carbon mass proportionally through HWP streams using annualized and regionalized parameters and inputs. These proportions come from *primary product ratios*, which partition harvest volume inputs into various commodities based on their relative historical production. Upon entering the CBM-HWP-OR model, a certain amount of industrial roundwood carbon was immediately partitioned to roundwood exports as described above. We then apportioned the remaining carbon from industrial roundwood into four domestic commodity pools and four mill residue uses (as noted above) following primary product ratios for Oregon from Metcalf (1965), Manock, Choate, and Gedney (1968), Schuldt and Howard (1974), Howard and Hiserote (1976), Howard (1984), Howard and Ward (1988; 1991), Ward (1995; 1997), Ward, Lettman, and Hiserote (2000), Brandt et al. (2006), Gale et al. (2012), Simmons et al. (2016), and Morgan et al. (2019), (**Report Table 3**, **Figure S3**). Again, we differentiated between softwood and hardwood inputs.

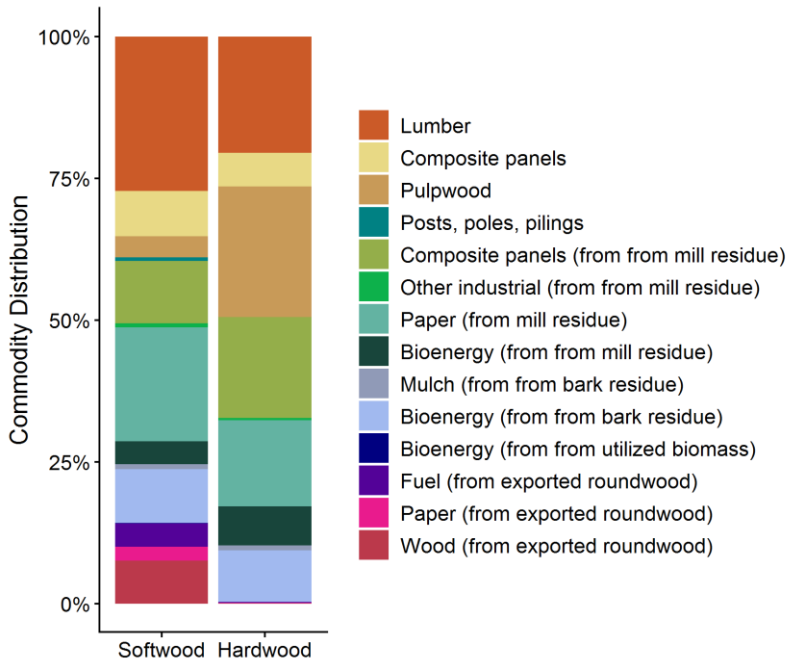

Figure S3. Average production ratios for commodities produced in Oregon, differentiated between softwood and hardwood inputs.

To account for carbon losses during the manufacture of these primary products, we incorporated end-loss and manufacture efficiency data from Row & Phelps (1996), Franklin Associates (1998), and Skog & Nicholson (2000). We modeled efficiencies of 92.5% for lumber, 90.22% and 91.6% for hardwood and softwood composite panels respectively, 98% for poles, and 95% for pulp products. We allocated

any end-loss carbon that occurs when products are placed into their end-use (7.5% for lumber, 9.78% and 8.4% for hardwood and softwood composite panels, 2% for poles, 5% for pulp) directly to landfills.

Additional Wood Products Streams

Aside from the model flows related to industrial roundwood, our CBM-HWP-OR model also includes additional wood products streams for residential fuelwood, bark residue, utilized biomass, and direct-to-landfill material, informed by data from Donahue, Morgan, and Dillon (2021), BBER (2022), and our state partners. Carbon allocated to industrial bioenergy from utilized biomass was assumed to be emitted immediately, consistent with all fuel sources in our model, and therefore did not pass through other product streams before reaching the atmosphere. We did not calculate product substitution for scenarios with additional industrial bioenergy from utilized biomass relative to CBAU – as described below, product substitution was calculated for produced commodities only. Bark residues, including bark stripped from exported roundwood, were mostly used for bioenergy (91.53%) with a small proportion going toward mulch and landscaping products (8.36%), and just 0.1% going unused. Because we used the direct-to-landfill stream for unutilized logging residue, we assumed this material would decompose at a rate similar to the in-forest decomposition rate, and thus assigned this material the landfill characteristics of paper (see **Product Retirement and Landfills** section below). Likewise, we used the residential fuelwood stream to represent pile burning of unutilized logging residue, and as such assumed full combustion of all allocated carbon with an emissions profile similar to pile burns in CBM-CFS3 (99% CO_2, 1% CH_4), though CBM-HWP-OR does not track CO production.

Domestic End-Use Consumption and Half-Lives

After calculating exports, mill residues, and primary products from annual roundwood harvest volumes, we determined end-uses for those products and their associated half-lives. We used end-use product half-lives from Row & Phelps (1996), Skog & Nicholson (1998, 2000), and Smith et al. (2006) and product use data from Metcalf (1965), Manock, Choate, and Gedney (1968), Schuldt and Howard (1974), Howard and Hiserote (1976), Howard (1984), Howard and Ward (1988; 1991), Ward (1995; 1997), Ward, Lettman, and Hiserote (2000), Brandt et al. (2006), Gale et al. (2012), Simmons et al. (2016), and Morgan et al. (2019) to calculate softwood- and hardwood-specific half-lives for all commodities currently produced in Oregon, weighted by wood product market share for each product following the IPCC approach (Pingoud et al. 2006). We assume that all residential fuelwood, and residues or utilized biomass used for bioenergy will be combusted in the same year the carbon enters the HWP model and therefore has an in-use half-life of zero years. We also relied on IPCC defaults from Pingoud et al. (2006) for half-lives for international wood and paper.

Where our scenarios included innovative wood product streams and uses, we calculated new half-lives for these products. We estimated a half-life for mass timber and mass plywood by assuming all mass timber and mass plywood material goes to construction end uses and applying the appropriate half-life from Row & Phelps (1996), Skog & Nicholson (1998, 2000), and Smith et al. (2006). For mass timber, we differentiated half-lives by softwood (85.5 years) and hardwood (73.3 years) materials. For mass plywood, we assumed a common half-life of 84.1 years, regardless of wood type. We assumed a biochar half-life of 100, on the conservative end of literature ranges (Zhang et al. 2022; Li and Tasnady 2023), in consultation with our state partners. See **Report Table 3** for half-life assumptions for both domestic and international product use.

Product Retirement and Landfills

Finally, we estimated product retirement proportions for each commodity in use, dividing retired products between landfills, waste incineration, and recycling streams based on values from 1960-2018 (EPA 2023a, 2023b). Recycled products were moved back into the appropriate commodity pool and stayed there according to the half-life determined for that commodity (see **Report Figure 3** for

recycling pathways modeled). Waste incineration pathways (applicable only to paper) were assumed to result in immediate emissions to the atmosphere.

To accurately model landfill dynamics, we utilized Oregon specific data on biodegradable proportions of landfilled material (Morgan et al. 2019) to determine that 23% of landfilled wood and 56% of landfilled paper could eventually emit carbon to the atmosphere through decomposition. We assumed the remainder of landfilled carbon was inert and would not decompose. We then applied domestic landfilled material half-lives data, also from Morgan et al. (2019), to these decomposable fractions; half-lives were assumed to be 29 years for wood and 14.5 years for paper. International landfilled product half-lives, from IPCC (Towprayoon et al. 2019), were modeled at 26.5 years for wood and 13.5 years for paper. Finally, based on these landfill half-lives we applied methane generation (k) rates of 0.0239 m^3 yr^{-1} for wood and 0.0478 m^3 yr^{-1} for paper. We assumed that 67.4% of generated methane was flared or recovered for energy (creating emissions of CO_2 rather than methane) and 32.6% was unrecovered based on data reported in the 2015 US National Inventory Report Annex I (EPA 2015). CBM-HWP-OR reports all landfill emissions in metric tons of CO_2e.

Leakage and Product Substitution Calculation Methodology

Using HWP results from the CBM-HWP-OR model, we calculated leakage and product substitution for each scenario where harvest levels differed from CBAU. Data inputs and results were processed using Excel and R.

Leakage

For any scenario resulting in less harvest than business as usual (in this case, the CBAU scenario) in a given year, we applied a leakage factor to represent an assumed increase in out-of-state harvest activity compensating for the decrease in harvesting in-state. We assumed demand for wood (or substitute) products will remain constant despite reductions in harvest (e.g., due to continued construction demand) and assume a portion of that demand will be met via additional wood imports from increased out-of-state harvest (i.e., leakage). We assumed all remaining product demand (that which is not met by in-state harvest or out-of-state imports) will be met by product substitution (i.e., increased use of non-wood materials in place of wood). In this analysis, we applied leakage to all harvest emissions and products derived from merchantable wood, i.e. that which is allocated to the industrial roundwood, utilized biomass, and bark residue model flows.

Determination of leakage rates in the United States depends in part on the degree of assumed regional collaboration (e.g., less leakage occurs when neighboring states or regions are engaging in similar harvest reduction activities) and estimates in the literature range from 63.9% with regional collaboration (Gan and McCarl 2007) to 84.4% without (Wear and Murray 2004). Based on consultation with state partners, we applied a leakage factor of 84.4% in line with the assumption of no regional collaboration in reducing harvest levels (Wear and Murray 2004). This means that 84.4% of reduced harvest relative to CBAU was assumed to leak out-of-state and the remaining 15.6% of reduced harvest relative to CBAU was subject to additional emissions from product substitution, as noted above. In all cases, leakage was only assumed to result from reduced in-state harvest; any additional in-state harvest relative to CBAU was assumed to result in increased in-state wood use and disposal (e.g., pile burning, recycling, or landfilling) rather than reductions in out-of-state harvest.

Product Substitution

In cases where HWP commodities substitute for alternative, more emissions-intensive products (e.g., concrete or steel), the difference in embodied emissions associated with those commodities relative to CBAU is associated with displaced emissions, also referred to as substitution benefits. When additional wood products are manufactured relative to CBAU, we assume those additional products will be used

in place of alternative emissions-intensive materials and credit those scenarios with the corresponding substitution benefits, representing a reduction of atmospheric GHG emissions. Likewise, a decrease in harvest and commodity production may be associated with increased emissions (or negative substitution benefits) in cases where more emissions-intensive products are assumed to replace the less emissions-intensive wood products, as applied in the **Leakage** section above.

Substitution benefits calculations rely on assumptions made about the emissions associated with the extraction, raw material transport, and manufacture of both the wood products and the assumed alternatives. To calculate substitution benefits associated with wood product substitution, we coupled Oregon-specific production data from Metcalf (1965), Manock, Choate, and Gedney (1968), Schuldt and Howard (1974), Howard and Hiserote (1976), Howard (1984), Howard and Ward (1988; 1991), Ward (1995; 1997), Ward, Lettman, and Hiserote (2000), Brandt et al. (2006), Gale et al. (2012), Simmons et al. (2016), and Morgan et al. (2019), with US consumption rates (Howard, McKeever, and Liang 2017), product weights (C. Smyth et al. 2017), and LCA data (Bala et al. 2010; Dylewski and Adamczyk 2014; Hubbard et al. 2020; Puettmann 2020; Puettmann and Salazar 2019, 2018; Puettmann et al. 2020c, 2020b, 2020a; Athena Sustainable Materials Institute 2019; Meil and Bushi 2013), following the calculation methods developed by Smyth et al. (2017). We calculated state-specific displacement factors for saw logs (softwood: 1.604; hardwood: 2.212) and composite panels (softwood: 1.928; hardwood: 0.978), as each is associated with a different commodity and end-use mix. For mass timber and mass plywood, we used the displacement factor for glulam (0.94) as reported by Cabiyo et al. (2021). These values represent the amount of carbon reduction from other products per unit of carbon used in additional wood products (tC/tC).

Scenario Parameterization Methodology

The data sources and methodologies above largely apply for business-as-usual (BAU) scenario parameterization for the forest ecosystem and HWP models. We created our alternative management scenarios in consultation with our state partners, and some scenario parameters were given to us directly while some scenarios required additional data and assumptions to parameterize (see **Report Table 4** for all scenario parameters). Scenario assumptions and additional data sources are described below. Unless otherwise noted, scenarios use BAU HWP assumptions from the CBM-HWP-OR model.

Climate-Adjusted Business-As-Usual

In recognition of the growing influence of climate change already evident in Oregon's forests, we developed a climate-adjusted business-as-usual (CBAU) scenario which uses the same management and land-use change parameters from BAU and incorporates some projected changes in climate under RCP 8.5 from 2022-2100 (Fleishman 2023). This includes modified frequency and severity of natural disturbance events (Anderegg et al. 2022), post-fire regeneration probability (Davis et al. 2023a; 2023b), and declines in productivity due to climate mismatch (Stewart and Wright 2023). Though there are many other projected impacts of climate change on forests such as CO_2 fertilization and mortality from compounding natural disturbance (e.g., drought followed by insect or wildfire disturbance), we chose these three categories based on available data and applicability to the landscape scale of CBM-CFS3.

To modify the frequency and severity of natural disturbances (wildfire, insect, disease, and abiotic disturbances) relative to our BAU projection, we used projections of future acreage or probability of natural disturbance events from Anderegg et al. (2022). For insect, disease, and abiotic disturbances, we obtained data for projected annual insect and drought basal area mortality rates by decadal periods for FIA plot locations from Dr. Anderegg and matched them with the FIA plots used to create our forest inventory input table to obtain the relevant classifiers for our events. For wildfire we obtained the geospatial data created by Anderegg et al. (2022), and overlaid it with the raster of our model classifiers

to extract decadal mean fire probability by ecoregion and ODF District. Then, we filtered the data down to RCP 8.5 projections from four of the six available GCMs (ACCESS-ESM1-5, MIROC-ES2L, MPI-ESM1-2-LR, MRI-ESM2-0). We chose these four based on assessed performance for western North America (Mahony et al. 2022) in order to avoid the "hot model" problem (Boyles et al. 2024; Hausfather et al. 2022) that occurs when a climate model's equilibrium is outside the IPCC's "very likely" warming threshold of 2-5°C (Sherwood et al. 2020). Following these guidelines, we removed the CanESM5 model for being above the "very likely" threshold and excluded ACCESS-CM2 following Mahony et al. (2022). Having filtered the natural disturbance projections to our chosen GCMs and emissions scenario, we created multipliers for increasing disturbance area by comparing a base period (in this case, 2000-2021) to future decades. Since insect and disease events are often modeled together, we applied the insect disturbance multiplier to disease events as well. For wildfire, we only applied projected increases to moderate and high-severity events to reflect projected increases in future fire severity in the absence of changing management practices (Parks et al. 2016). See **Report Table 2** for the average modified natural disturbance acreages for the CBAU scenario.

The second main category of modifications to CBAU was to incorporate post-fire regeneration failure, based on data from Davis et al. (2023b) projecting the probability of at least one seedling regenerating in a 0.01 ha plot within 10 years of a high-severity wildfire under a high emissions (RCP 8.5) scenario. We obtained the geospatial data created by Davis et al (2023a) and overlaid it with the raster of our model classifiers to extract regeneration probability by forest type group and ecoregion. We then calculated the average likelihood of regeneration failure as:

$$(1 - probability\ of\ regeneration\ success) * 100$$

which we used to create new transition rules after high-severity wildfire (**Table S6**). Though these data are projected only through 2050, we applied these new transition rules for our entire projection period from 2022-2100 for consistency.

Table S6. Estimated post-fire regeneration probability (%) after high-severity wildfire by forest type group and ecoregion. Blank cells do not indicate that post-fire regeneration failure is not possible; rather, they indicate that it was not projected in Davis et al. (2023a) for a given forest type group and ecoregion combination.

Forest Type Group		Ecoregion						
TYPGRPCD	Description	Coast Range	Eastern Oregon	East Cascades Modoc	West Cascades	Klamath Mountains	Blue Mountains	Willamette Valley
180	Pinyon / juniper group	-	44%	32%	-	-	45%	-
200	Douglas-fir group	87%	67%	78%	91%	74%	72%	95%
220	Ponderosa pine group	87%	55%	48%	67%	68%	61%	92%
240	Western white pine group	-	76%	79%	80%	78%	65%	-
260	Fir / spruce / mountain hemlock group	86%	73%	77%	87%	76%	78%	96%
280	Lodgepole pine group	89%	80%	63%	90%	87%	77%	-
300	Hemlock / Sitka spruce group	90%	-	93%	96%	87%	-	95%
320	Western larch group	-	79%	79%	-	-	79%	-

Table S6, cont. Estimated post-fire regeneration probability (%) after high-severity wildfire by forest type group and ecoregion. Blank cells do not indicate that post-fire regeneration failure is not possible; rather, they indicate that it was not projected in Davis et al. (2023a) for a given forest type group and ecoregion combination.

Forest Type Group		Ecoregion						
TYPGRPCD	Description	Coast Range	Eastern Oregon	East Cascades Modoc	West Cascades	Klamath Mountains	Blue Mountains	Willamette Valley
340	Redwood group	-	-	-	-	84%	-	-
360	Other western softwoods group	-	43%	35%	51%	59%	54%	-
700	Elm / ash / cottonwood group	91%	50%	69%	92%	85%	-	94%
900	Aspen / birch group	-	65%	56%	-	83%	83%	-
910	Alder / maple group	88%	-	96%	95%	74%	-	97%
920	Western oak group	83%	43%	56%	60%	62%	-	95%
940	Tanoak / laurel group	88%	-	72%	81%	78%	-	93%
960	Other hardwoods group	85%	67%	52%	82%	64%	75%	97%
999	Nonstocked	87%	50%	49%	84%	72%	64%	96%

Lastly, we incorporated projected declines in productivity due to climate mismatch to modify our yield curves. We obtained spatial data on the average % decline in productivity (%DP) by decade from the Climate-Adapted Seed Tool (Stewart and Wright 2023). We then overlaid these data with rasters of our model classifiers to summarize average %DP by forest type group by decade (**Table S7**) and applied this as a multiplier to our yield curve values to create a set of climate-modified curves. We triggered a change to these modified yield curves using the "Climate Mod" classifier, changing from a value of Climate Mod=0 to Climate Mod=1-8 each decade beginning in 2022.

Table S7. Estimated average productivity decline (%DP) by forest type group and decade.

Forest Type Group		Decade							
TYPGRPCD	Description	2022-2029	2030-2039	2040-2049	2050-2059	2060-2069	2070-2079	2080-2089	2090-2100
180	Pinyon / juniper group	6%	16%	23%	30%	42%	51%	57%	63%
200	Douglas-fir group	5%	11%	16%	23%	33%	42%	48%	54%
220	Ponderosa pine group	7%	15%	22%	29%	40%	50%	57%	62%
240	Western white pine group	6%	11%	16%	22%	31%	40%	46%	51%
260	Fir / spruce / mountain hemlock group	7%	14%	20%	27%	38%	48%	55%	60%
280	Lodgepole pine group	7%	15%	20%	28%	39%	49%	55%	61%
300	Hemlock / Sitka spruce group	4%	10%	14%	20%	29%	38%	44%	50%

Table S7, cont. Estimated average productivity decline (%DP) by forest type group and decade.

Forest Type Group		Decade							
TYPGRPCD	Description	2022-2029	2030-2039	2040-2049	2050-2059	2060-2069	2070-2079	2080-2089	2090-2100
320	Western larch group	8%	16%	22%	30%	42%	52%	59%	64%
340	Redwood group	3%	6%	9%	13%	20%	28%	33%	40%
360	Other western softwoods group	7%	16%	22%	30%	41%	51%	57%	63%
700	Elm / ash / cottonwood group	6%	12%	17%	23%	33%	41%	48%	53%
900	Aspen / birch group	5%	13%	18%	25%	35%	44%	50%	56%
910	Alder / maple group	6%	16%	23%	31%	42%	52%	58%	63%
920	Western oak group	6%	13%	18%	25%	35%	44%	50%	55%
940	Tanoak / laurel group	4%	9%	13%	18%	27%	35%	41%	47%
960	Other hardwoods group	6%	12%	17%	24%	34%	43%	49%	55%
999	Nonstocked	6%	14%	20%	27%	38%	48%	54%	60%

Wildfire Resilience

The Wildfire Resilience scenario represents one of the biggest priorities for our state partners: increasing resilience treatments across the landscape to reduce the risk and severity of wildfire. Rather than starting with an acreage target for our Wildfire Resilience scenario, we conducted a fire resilience needs assessment for Oregon's forests to understand where fire resilience treatments are most needed and then constructed our scenarios to model initial treatment of this need over a 29-year period (2022-2050).

For our needs assessment, we utilized a map of wildfire hazard potential (WHP), an index that quantifies the potential for wildfires to both ignite and be difficult to control (Dillion et al. 2015), to determine where treatments were most needed. This map, produced as part of the 2023 Pacific Northwest Quantitative Wildfire Risk Assessment (McEvoy et al. 2024), was overlaid with our rasters of our model classifiers (Ecoregion, Forest Type Group, OWNGRPCD, Productivity Class, and RESERVCD), and geospatial datasets of critical habitat (USFWS 2020), to allow filtering of WHP areas by important ecological conditions or operational considerations. Once these datasets had been combined using the Combine tool in ArcGIS Pro, we extracted the raster attribute table into an Excel spreadsheet for final filtering and processing. We filtered our results to focus just on high and very high WHP, where treatments are most urgently needed. Overall, we found that more than 8.6 million acres of forest across Oregon are currently in need of treatment to reduce future wildfire risk and severity (**Report Table 1**).

This 8.6-million-acre total demonstrates the significant need for fire resilience treatments in Oregon's forests, but not all forest types or locations can or should be treated in the same way. Therefore, we further filtered our total needs assessment acreage based on operational constraints and common practices to identify eligible acres under various treatment approaches utilizing combinations of thinning and/or prescribed fire. All designated wilderness (reserved) areas and areas under the jurisdiction of the National Parks Service were deemed ineligible for thinning activities and were therefore limited to prescribed fire treatments only. Further, non-wilderness areas containing critical habitat were restricted to thinning treatments without biomass removal and subsequent pile burns for

surface fuel management. This same restriction was extended to non-wilderness non-critical habitat areas in the "east side" ecoregions (Eastern Oregon, Blue Mountains, East Cascades & Modoc) where market conditions mean that removal of this material is not economically viable. For private and tribal ownerships on the "east side" we assumed that 1% of the total need would be treated each year through 2050, through thinning without removal and subsequent pile burning. Finally, we assumed that private and tribal ownerships in "west side" ecoregions (Coast Range, Klamath Mountains, Willamette Valley, West Cascades) would not implement resilience treatments.

Using these filters, we found that only 7.02 million acres of forest are likely to be eligible for resilience treatments given current techniques, technologies, and policies (**Table S8**). This total includes 0.43 million acres eligible for thinning with biomass removal and follow-up prescribed fire, 4.44 million acres eligible for thinning without removal and pile burning, and 2.16 million acres eligible for prescribed fire only. While there are additional considerations such as road access, terrain steepness, proximity to a utility corridor, wildland-urban interface, and/or fire protection responsibility areas which could be used to further filter and inform prioritization and targeting of treatments, we did not use these factors in developing our modeling scenarios.

Table S8. Acres in need of and eligible for fire resilience treatments by treatment approach, ownership, and ecoregion.

Ecoregion	Ownership	Reserve Status	Critical Habitat Status	Thinning	Burn	Treatment Area
(East Side) Eastern Oregon, Blue Mountains, East Cascades Modoc	USFS, Other Federal, State/Local	Reserve	All	-	Rx burn every 20 years	1,558,245 ac (22% of total need)
		Not reserve	Not Critical Habitat	Thin without removal (30% biomass cut, 0% removed)	Pile burn within 5 years; repeat on 15-year cycle	2,261,992 ac (32% of total need)
		Not reserve	Critical Habitat	Thin without removal (30% biomass cut, 0% removed)	Pile burn within 5 years; repeat on 15-year cycle	915,944 ac (13% of total need)
	NPS	All	All	-	Rx burn every 20 years	16,789 ac (0.2% of total need)
	Private and Tribal	All	All	Thin without removal (30% biomass cut, 0% removed)	Pile burn within 5 years; repeat on 15-year cycle	535,507 ac* (8% of total need)
(West Side) Coast Range, Klamath Mountains, Willamette Valley, West Cascades	USFS, Other Federal, State/Local	Reserve	All	-	Rx burn every 20 years	583,636 ac (8% of total need)
		Not reserve	Not Critical Habitat	Thin with removal (30% biomass cut, 25% removed)	Rx burn on 15-year cycle	426,484 ac (6% of total need)
		Not reserve	Critical Habitat	Thin without removal (30% biomass cut, 0% removed)	Pile burn within 5 years; repeat on 15-year cycle (20-year cycle in Coast Range)	722,989 ac (10% of total need)
	NPS	All	All	-	Rx burn every 20 years	638 ac (<0.1% of total need)
	Private and Tribal	All	All	-	-	-

*Here we assume east side Private/Tribal landowners will treat ~1% of total need each year through 2050

We modeled this area to receive initial treatments at a steady rate over 29 years from 2022-2050, equating to an average of 242 thousand acres per year of additional fire resilience treatments above CBAU during this period. We used the commercial thin disturbance matrix to represent thinning treatments with biomass removal, and the hazardous fuels thin disturbance matrix to represent thinning without biomass removal. Both disturbance matrices assume that 30% of live biomass is cut. We also scheduled follow-up prescribed fire activities (using existing disturbance matrices for Rx fire and pile burns) in our model at a return interval determined by the original treatment type, ecoregion, and ownership (**Table S8**), driving the average activity footprint during the treatment phase (2022-2050) to roughly 562,000 acres per year. We did not include follow-up thinning after biomass removal activities, emphasizing the return of beneficial fire to the landscape as the key maintenance mechanism for our scenarios.

To simulate the effectiveness of wildfire resilience treatments on future fire intensity, we reduced the acreage of high and moderate-severity wildfire in proportion to the area treated, assuming a 90% success rate for treatment. This means that there is a nine in ten chance of treatment being deemed effective each year, and if effective it will lower the severity one level (high-severity -> moderate-severity, moderate-severity -> low-severity). However, treatment affects only severity, and thus the total fire extent (area burned) each year remains the same before and after treatment. Treated area accumulates over successive years until 2050, meaning that from 2051 onward all treatments are for maintenance of current levels of resilience and do not further reduce fire severity.

Pest Resilience

The Pest Resilience scenario was designed to address the vulnerability of forest lands across Oregon to insect and disease outbreaks, which are represented as either mortality or defoliation in CBM. Because of the diversity of insect pests, and their associated unique treatment strategies, we chose to focus only on two insect archetypes, defoliators and mortality causing insects, rather than multiple individual insect species. Risk from defoliators (represented by the risk from budworm, woolly adelgid, and tussock moth) and mortality causing insects (represented by the risk from bark beetles and engravers) was extracted from the 2018 National Insect and Disease Risk Map (NIDRM; USDA Forest Service 2018b). As with our wildfire needs assessment, we overlayed data from NIDRM with our rasters of our model classifiers (Ecoregion, Forest Type Group, OWNGRPCD, Productivity Class, and RESERVCD), and geospatial datasets of critical habitat (USFWS 2020), to allow filtering of insect risk areas by important ecological conditions or operational considerations. We binned risk data in the NIDRM (% of basal area effected) into three severity classes to align with effects in CBM (low-severity = 1-7% basal area effected, moderate-severity = 8-20% basal area effected, high-severity = 21+% basal area effected). We chose to focus just on areas at risk of moderate and high-severity disturbance, where treatments are most urgently needed. Overall, we found that more than 8.7 million acres of forest across Oregon are currently in need of treatment to reduce future risk of insect mortality, 0.94 million acres were in need of treatment to reduce future risk of insect defoliation, and a further 0.74 million acres were in need of treatment to reduce future risk of both defoliation and mortality.

Of the total of 10.4 million acres necessitating treatment, we determined that treatment was only likely on public lands, eliminating roughly 3 million acres from consideration. In addition, all designated wilderness (reserved) areas and areas under the jurisdiction of the National Parks Service were deemed ineligible, as insect resilience treatments involve thinning and removal of biomass. This brought the total treatment area down to 5.9 million acres over the course of 29 years (2022-2050), or an approximate impact of 202,000 acres treated each year.

To simplify the vast diversity of insect resilience treatment strategies, we chose to model treatment as a thinning with removal (30% biomass cut, 25% biomass removal), repeating on a 20-year cycle, and

using the disturbance matrix from the commercial thin treatment. While it may not always be economically feasible, the removal of this thinned material is nonetheless imperative, as for insect resilience treatments to be effective, slash must be appropriately treated (typically burnt or otherwise disposed of offsite) to prevent it from becoming a secondary vector of pest insects. To simulate the effectiveness of insect resilience treatments on future insect outbreaks, we reduced the acreage of high and moderate severity insect mortality and defoliation in proportion to the area treated each year, assuming a 25% success rate for treatment. This means that there is a one in four chance a treatment will be deemed effective, and if effective it will lower the severity one level (high-severity -> moderate severity, moderate severity -> low severity). Treatment affects only severity, and thus the total insect disturbance extent each year remains the same before and after treatment. Treated area accumulates over successive years until 2050, meaning that from 2051 onward all treatments are for maintenance of current levels of resilience and do not further reduce insect mortality or defoliation severity. In cases where both mortality and defoliation risk overlap, both disturbance types receive risk reduction.

For disease pests, we chose to focus on pest containment rather than resilience. We also focused on a single disease, Swiss needle cast, a defoliator which effects trees in the Douglas-fir forest type group. In Oregon, the Coast Range ecoregion is the epicenter for Swiss needle cast outbreaks, and as such we assumed that any moderate or high-severity disease defoliation impacting Douglas-fir in the Coast Range was the result of Swiss needle cast. As there is no known effective treatment for Swiss needle cast infections, we modeled the response to an outbreak as a removal of infected trees, and subsequent replacement with resilient forest type groups. The distribution of these new forest type groups was based on their current proportion in the Coast Range ecoregion (62% Alder / maple group, 38% Hemlock / Sitka spruce group). Since these new forest type groups are resilient to Swiss needle cast, this effectively reduces the susceptible area in proportion to the treatment area. Treated area each year was in proportion to the prior year's disease area. On average, 4,449 acres are treated each year.

Landscape Restoration

The Landscape Restoration scenario was designed to address post-fire reforestation and restoration needs in Oregon and was constructed with two parts. First, our state partners were interested in the carbon outcomes of addressing the post-fire reforestation backlog in the state, which we estimated to be 492,000 acres from the 2000-2021 wildfires. To model this, we created a new "Reforestation" disturbance type (with a disturbance matrix identical to afforestation) to represent site prep and reforestation activities. We then targeted this disturbance type to acres recovering from high-severity wildfire that occurred in 2000-2021, treating them over a period of 29 years from 2022-2050.

Second, we added additional post-fire salvage and reforestation activities to combat the post-fire regeneration failure added for the CBAU scenario. We created two new "Post-fire Restoration" disturbance types, one using the disturbance matrix for salvage, and the second using a disturbance matrix with no transfers of carbon. In both cases, transition rules were set to restart forest growth in the year following the restoration activities. We targeted these practices at future modeled areas of post-fire regeneration failure, allowing salvage and site prep in non-reserve areas (RESERVCD=0) and limiting activities to just replanting in reserved areas. We scheduled these events to occur within a relatively short period after the wildfire when standing timber on site would still be considered merchantable (3 years for private lands, 5 years for public lands).

For both restoration disturbance types (restoration with salvage, and restoration without salvage), we assumed reforestation occurred at low density based on research from North et al. (2022). As such we assigned a productivity class of "low" (productivity class = 2).

Net Zero Forest Loss

The two Net Zero Forest Loss scenarios were constructed to investigate the effect of reducing permanent forest loss to land-use change to net zero. That is, keeping a constant forest acreage despite some level of forest loss and forest gain each year. We parameterized these scenarios to either increase the CBAU rate of afforestation by +32,252 acres per year (+203%), in the case of Net Zero Forest Loss via Increased Afforestation, or to decrease the CBAU rate of deforestation by -32,252 acres per year (-43.9%), in the case of Net Zero Forest Loss via Decreased Deforestation. In both scenarios, the change was consistent across all disturbances such that the relative increase or decrease was proportional to the base rate of forest gain or loss in each ecoregion, forest type group, ownership, and productivity class. These modified rates began in 2022 and ran through the end of the simulation in 2100.

No Deforestation Outside of the Urban Growth Boundary

Each city within Oregon designates an urban growth boundary (UGB), the area in which a city expects to grow over a 20-year period. Development of land outside the UGB for urban uses (housing, industrial facilities, businesses, or public facilities such as utilities) is strongly restricted, effectively limiting the potential for suburban sprawl into forest and farmland. However, Oregon has experienced a net rate of forest loss from land-use change trends, based on our analysis of changes between forest and non-forest land uses (water, developed land, barren land, herbaceous grasslands, pasture, cultivated crops, and herbaceous wetlands) in NLCD between 2001 and 2019. This reduction in forest land may have occurred as previously forested lands were cleared for agriculture, or as municipalities revise and expand their UGBs. Preventing conversion of forests to non-forest land uses is a fundamental tenet of the 2021 Oregon Climate Action Commission's Natural and Working Lands Proposal (Institute for Natural Resources 2023), which recommends activities aimed at forest land conservation and preservation of forest loss.

To simulate a total prohibition on the conversion of forests to non-forests outside of the UGB, we took the 2023 UGB shapefile (State of Oregon 2023), and overlayed it on our raster of forest gain and loss from NLCD between 2001 and 2019. We then identified any forest losses that occurred outside the UGB footprint, and removed these from consideration. The remaining forest loss was aggregated by ownership, forest type group, and ecoregion, and a new average annual rate of deforestation (-64 acres yr^{-1}) was calculated, and applied to the period from 2022 – 2100. Notably, unlike the Net Zero scenarios described above, this new rate of deforestation was not proportionally distributed across the forested landscape, as it is tied to forests within the 2023 UGB.

Silvopasture

Silvopasture is the purposeful integration of low-density tree cover in pastureland that does not remove the land from productive pasture use (Ramachandran Nair 2014). This practice helps landowners diversify income streams, reduces the potential for heat stress in livestock, and can provide additional feedstock for pasture animals (Smith et al. 2022; Garrett et al. 2004). Livestock can also help manage vegetation to reduce fuel loads and provide disturbance critical for grassland health and restoration (Mazaroli and Carlisle 2023). Silvopasture is receiving attention as a potential natural climate solution (Fargione et al. 2018; Cook-Patton et al. 2020; Papa et al. 2023), but adoption in the US has so far been limited due to a lack of available information and successful case studies (Smith et al. 2022; Garrett et al. 2004). Silvopasture implementation at scale would likely require outreach and technical assistance for landowners. Since the purpose of this analysis is to examine a broad range of potential CSF pathways, we included a Silvopasture scenario to further investigate the opportunity for and climate mitigation potential of this practice in Oregon.

We used data from the Reforestation Hub (The Nature Conservancy and American Forests 2023; Cook-Patton et al. 2020) that identifies 722,920 acres of pastureland with the potential for reforestation in

Oregon. We constructed our Silvopasture scenario to establish silvopastoral systems via tree planting on all 722,920 acres at a linear rate of 24,928 ac yr^{-1} from 2022-2050. We created a new "Silvopasture" disturbance type (with a disturbance matrix identical to afforestation) to model this activity. Silvopastoral systems are typically designed for low (10-40%) canopy density and are best implemented with tree species adapted to regional conditions (Garrett et al. 2004; Ramachandran Nair 2014; NRCS 2016; Mazaroli and Carlisle 2023), so we crated a new set of growth and yield curves for each forest type in a silvopastoral system in which stand volume is 50% of its nominal value at each age class. In addition, we assigned these new silvopasture plantings the most common hardwood forest type group for each ecoregion (**Table S9**) determined from FIA data (USDA Forest Service 2021a). While some silvopasture systems can also be established by removing trees from or introducing livestock into existing forests, we chose not to model this method to prioritize maintaining current forest extent in Oregon and to illustrate the potential for adding trees to pastureland.

Table S9. Forest type groups used for Silvopasture scenario by ecoregion.

Ecoregion	Silvopasture area (ac yr^{-1})	TYPGRPCD	Description
Blue Mountains	1,752	960	Other hardwoods group
Coast Range	3,304	910	Alder / maple group
East Cascades Modoc	4,574	920	Western oak group
Eastern Oregon	3,252	900	Aspen / birch group
Klamath Mountains	2,343	940	Tanoak / laurel group
West Cascades	5,416	910	Alder / maple group
Willamette Valley	4,290	910	Alder / maple group

Altered Harvest Management

Changing harvest rotations and intensities, specifically extending the average length of rotations before harvesting, is a popular management tool and NCS strategy for increasing forest carbon storage (Fargione et al. 2018; Graves et al. 2020, 2022). However, while these practices have the potential to sequester more carbon in the forest, they introduce increased risk of elevated emissions from disturbances especially in fire-prone landscapes (Badgley et al. 2022), as well as a potential financial cost due to reduced short term revenues from timberlands, or the need to retool mills to process large-diameter logs (Anderson 2023). Variable retention cuts or uneven-aged management practices may also not be feasible in all ecoregions or forest types, especially the highly productive Douglas-fir and true fir forest systems in Oregon's coast range (Harrington et al. 2022). Nonetheless, exploring the carbon implications of altered management and rotation length is of great interest in Oregon (Oregon Global Warming Commission 2021b) given the high carbon storage potential of its forests (Fain et al. 2018), and the central role that timber harvest play in its economy (Kuusela et al. 2019).

Table S10. Culmination of mean annual increment (CMAI) values as reported in Kerr (2020). In cases where multiple species represent a single forest type group, an average of the species values was used. When a range of CMAI values was reported, the median value was used. For the nonstocked forest type group, CMAI was assumed to be 80 years.

Forest Type Group	Description	CMAI (years)
180	Pinyon / juniper group	100
200	Douglas-fir group	84
220	Ponderosa pine group	90
240	Western white pine group	100
260	Fir / spruce / mountain hemlock group	90
280	Lodgepole pine group	78

Table S10, cont. Culmination of mean annual increment (CMAI) values as reported in Kerr (2020). In cases where multiple species represent a single forest type group, an average of the species values was used. When a range of CMAI values was reported, the median value was used. For the nonstocked forest type group, CMAI was assumed to be 80 years.

Forest Type Group	Description	CMAI (years)
300	Hemlock / Sitka spruce group	90
320	Western larch group	70
340	Redwood group	90
360	Other western softwoods group	70
700	Elm / ash / cottonwood group	30
900	Aspen / birch group	30
910	Alder / maple group	67
920	Western oak group	70
940	Tanoak / laurel group	70
960	Other hardwoods group	70
999	Nonstocked	80

We constructed three scenarios to examine the relative impacts of altered harvest management. We modeled our 80-Year Rotations scenario as an increase in the modeled minimum harvest age for commercial management, raising it from 40 (private industrial), 50 (public), or 60 (private non-industrial) years to 80 years for all forest types and land ownership. Our CMAI Based Rotations scenario altered the harvest age for all forest owners to a forest type group specific culmination of mean annual increment (CMAI) value as reported in Kerr (2020; **Table S10**). Both of these scenarios apply to our high and intermediate harvest management practices. For multi-entry intermediate harvest, we also adjusted the age limitations for second cuts to reflect the change in age at first entry. Finally, our Uneven-Aged Management scenario replaces high harvest with group selection for forest type groups and land ownerships in ecoregions east of the Cascades (Eastern Oregon, Blue Mountains, East Cascades & Modoc).

Portfolios

While each individual scenario described above represents a potential CSF management tactic, these practices would rarely be implemented alone across the state. To better represent comprehensive forest climate action, we constructed three portfolios – ensembles of scenarios or practices that could be concurrently implemented throughout the state – to visualize the cumulative potential of Oregon's forests and forest sector to provide climate mitigation benefits. These were a Combined Resilience and Restoration portfolio, a combination of the Wildfire Resilience, Pest Resilience, and Landscape Restoration scenarios, a Maximum Forest Area and Carbon portfolio, a combination of the Silvopasture, 80-Year Rotations, and No Deforestation Outside of the UGB scenarios, and a Maximum Forests as Natural Climate Solutions portfolio, a combination of the Combined Resilience and Restoration and the Maximum Forest Area and Carbon portfolios. These portfolios were parameterized in the same way as their component solo scenarios, except in cases where wildfire and insect resilience treatments overlapped. In such cases we assigned the appropriate wildfire resilience treatment, assuming that it was also effective at reducing the risk of insect outbreaks. Combining multiple scenarios also allows for unique interactions between treatments (e.g., wildfire resilience and landscape restoration) which would not be possible if the scenarios were only run separately.

Alternate Wood Utilization Scenarios

We ran the Wildfire Resilience and Pest Resilience scenarios as well as the Combined Resilience and Restoration and Maximum Forests as Natural Climate Solutions portfolios with BAU wood utilization parameters and with an alternative set of parameters which we deemed the Innovative Wood Utilization scenario. For the scenarios with BAU wood utilization parameters, additional harvested material was used in the same way as in the base CBM-HWP-OR model (described in the **Harvested Wood Products Model Methodology** section above), just in larger volumes.

For the Innovative Wood Utilization scenario, we diverted additional cut biomass from fire or pest resilience treatments into innovative wood products, which after discussions with state partners, we determined more accurately reflect their potential use. This led to variable amounts of material transferred into innovative products each year, depending on how much additional material was cut and removed. 50% of this material was allocated to lumber products, an amount starting at 0.07% and increasing to 5% by 2100 was allocated to biochar, and the remaining material was allocated to bioenergy. Because biochar is not currently produced in Oregon, we created a new biochar product stream in the CBM-HWP-OR model with a 100-year half-life (Zhang et al. 2022; Li and Tasnady 2023) for both softwood and hardwood inputs, and calculated substitution benefits of zero because biochar does not displace current construction materials or energy sources. Bioenergy produced in this scenario is assumed to have a half-life of zero (i.e., immediate combustion) and zero substitution benefits because it is unlikely to displace traditional fossil fuel sources in Oregon.

In addition, we developed an Increased HWP Efficiency scenario, in consultation with our state partners, which aimed to increase the efficiency and carbon storage potential of the current product streams in Oregon's forest products sector. This scenario aligns with legislation and grant programs under development across the state (e.g., Oregon DEQ's Materials Management program and the City of Portland's Deconstruction program). For this scenario we increased the half-life of lumber used in construction by 50% by multiplying the half-life of each of the lumber sub-products (from Pingoud et al. 2006) used in construction (e.g., residential building lumber) by 1.5, thus increasing the overall lumber product half-life in the correct proportion. Updated half-lives were 62.02 years for softwood lumber and 29.24 years for hardwood lumber. Similarly, we increased the recycling rate for lumber used in construction by 25% by adjusting the recycling rate for construction lumber from 10% up to 12.5%. This caused the weighted lumber recycling rate to increase to 10.50% and 9.55% for hardwood and softwood lumber respectively. We also altered the utilization of mill residue, shifting 25% of material away from pulpwood, industrial fuel, and other industrial products and into the production of composite panels. Finally, we allocated an increasing amount of softwood roundwood (from 0.07% in 2022 to 5% by 2100) away from traditional lumber and composite panels toward mass timber and mass plywood. We created new mass timber and mass plywood product streams in the CBM-HWP-OR model with half-lives of 85.5 years for mass timber and 84.1 years for mass plywood. These half-lives were based on the assumption that mass timber and mass plywood have the same half-lives as traditional construction lumber and structural panels (Row and Phelps 1996; Skog and Nicholson 1998; 2000; Smith et al. 2006). We applied a displacement factor of 0.94 tC/tC for both mass timber and mass plywood (Cabiyo et al. 2021) based on the assumption that all mass timber would go to construction end uses. While the Increased HWP Efficiency scenario could be paired with any of the ecosystem scenarios, for simplicity we chose only to pair it with the CBAU scenario, and the Combined Resilience and Restoration, Max Forest Area and Carbon, and Maximum Forests as Natural Climate Solutions portfolios.