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

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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, Kurz, and McFarlane 2021). However, these benefits can be constrained or even negated in fire-prone ecosystems if wildfire hazard and impact on forests is not adequately addressed (Jerrett, Jina, and Marlier 2022).

Future management and policy decisions that mesh mitigation goals with adaptation to future climate conditions can maintain and strengthen the NCS capacity of forests. 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, seeking to balance carbon sequestration and storage rates throughout the forest. 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 wood 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 NCS practices for forests follow a CSF approach.

The state of California has set ambitious greenhouse gas (GHG) emissions reduction goals through Assembly Bill 32 California Global Warming Solutions Act (2006) and subsequent legislation (e.g., Senate Bill 32 (2016); Executive Order B-55-18 (2018)), requiring the state to reduce emissions to 40% below 1990 levels by 2030 and achieve net zero emissions by 2045. In 2021, California's forest sector sequestered and stored 22 million metric tons of carbon dioxide equivalent (MtCO$_2$e; USDA Forest Service 2024b), equivalent to 6% of the total GHG emissions reported in the state for that same year (CARB 2023). However, recent modeling from the California Air Resources Board (CARB) indicates that California's forests will be a net source of carbon emissions under future climate conditions, even with substantial levels of management (CARB 2022a). The state seeks to leverage the climate benefits from its 31.5 million acres of forest (USDA Forest Service 2021a) where possible, and minimize carbon losses from future climate impacts, through its influence on forest management, implementing climate-smart practices on public lands and providing technical and financial support for forest landowners.

This report is designed to guide California toward identifying promising CSF practices and to encourage the inclusion of forests and the forest products sector in state-level climate action planning. 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 substitution benefits from using wood in place of other emissions-intensive materials. We also estimate expected treatment costs, potential wood product revenue, and wood processing capacity constraints for each scenario. These results provide information about forest climate mitigation and adaptation opportunities that can integrate with and inform frequently updated statewide efforts, including the California Wildfire and Forest Resilience Task Force (Task Force) Action Plan, CARB's 2022 Scoping Plan, and the California Natural Resources Agency's (CNRA) Nature-Based Solutions Climate Targets (California Wildfire and Forest Resilience Task Force 2021; CARB 2022a; CNRA 2024).

Modeling Forest Management and Wood Utilization in California

Following previous work (Dugan et al. 2018; 2019; 2021; DeLyser et al. 2022a; 2022b; Papa et al. 2023), we assess carbon trends and management scenarios in the forest ecosystem and forest products sector for California 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 natural resource agency staff and forestry experts to understand forest management priorities, concerns, and goals in California, based on current conditions and a landscape resilience needs assessment;
2) Development of business-as-usual (BAU) 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 California, ii) a customized lifecycle harvested wood products model (CBM-HWP-CA) 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 v) economic analysis; and
4) Engagement and discussion with state agency staff to explore modeling results and consider implications for California.

Through a series of meetings with California Department of Forestry and Fire Protection (CAL FIRE) and USDA Forest Service (USFS) staff, academics, and forestry practitioners in the state, we identified several management priorities and concerns for forests in California: **understanding impacts of climate change, forest health and resilience, wildfire, forest regeneration and reforestation, wood utilization, land use and land cover**, and **harvesting practices and rotations**. From these stated priorities and policy targets, we developed 19 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

Table E1. Names, descriptions, and forest management activity acres (not including land-use change or natural disturbance) for our 19 modeled scenarios. 2022-2031 is the "treatment phase" when most modeled treatments are implemented, representing the highest level of annual activity.

	Scenario name and description	Average annual management activity, 2022-2031 (ac yr^{-1})	
		Current activity (CBAU)	New scenario activity
	Business-as-usual (**BAU**) Continuation of average historical rates of management, land-use change, and natural disturbance	280,368	-
	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	280,368	-
Forest management scenarios (run on CBAU)	**Landscape restoration** Post-fire salvage/site prep and reforestation, addressing both current backlog and projected future need	280,368	247,025
	Fire resilience Fire resilience treatments (a combination of thinning and/or prescribed fire) to reduce future wildfire severity	280,368	789,462
	Expand fire resilience treatments to mature and old-growth forest (**MOG resilience**) Expand eligibility for fire resilience treatments (a combination of thinning and/or prescribed fire) to reduce future wildfire severity in mature and old-growth forests following US Forest Service definitions	280,368	789,462
	Forest conservation Reduce the rate of permanent forest loss from land-use change	280,368	13,186
	Silvopasture Integration of low-density native tree cover in active pastureland without removing the land from pasture use	280,368	9,512
	Extended rotations Increase minimum even-aged harvest age from 50 to 80 years on all forestlands	165,504	114,864
	Altered rotations Increase minimum even-aged harvest age from 50 to 80 years on public forestlands, decrease minimum even-aged harvest age from 50 to 40 years on private and Native American forestlands	165,504	114,864
Innovative wood utilization scenarios	**Fire resilience + Biochar, MOG resilience + Biochar** Use additional biomass (non-merchantable) material cut during fire resilience treatments to create biochar	280,368	789,462
	Fire resilience + Transportation fuels, MOG resilience + Transportation fuels Use additional biomass (non-merchantable) material cut during fire resilience treatments to create transportation fuels	280,368	789,462
	Fire resilience + Mass timber, MOG resilience + Mass timber Use additional biomass (non-merchantable) material cut during fire resilience treatments to create biochar	280,368	789,462
Portfolios (combined scenarios)	Ramp up implementation (**Ramp up**) Landscape restoration + MOG resilience scenarios	280,368	1,036,487
	Ramp up + Innovative wood utilization Landscape restoration + MOG resilience scenarios with innovative wood utilization (biochar + transportation fuels + mass timber)	280,368	1,036,487
	Maximum natural climate solutions by 2045 (**Max NCS**) Landscape restoration + MOG resilience + Forest conservation + Silvopasture + Extended rotations scenarios	165,504	1,174,049
	Max NCS + Innovative wood utilization Landscape restoration + MOG resilience + Forest conservation + Silvopasture + Extended rotations scenarios with innovative wood utilization (biochar + transportation fuels + mass timber)	165,504	1,174,049

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 highlighted in other statewide efforts, including the Task Force Action Plan, CARB's 2022 Scoping Plan, and CNRA's Nature-Based Solutions Climate Targets (California Wildfire and Forest Resilience Task Force 2021; CARB 2022a; CNRA 2024). We collected historical data from 2000-2021 for model validation and used this as the basis for our forward-looking scenario projections over a 50-year period from 2022-2071. See **Report Tables 2** and **4** for full scenario descriptions and parameters.

Climate-Smart Forestry in California

Results of this study show that California forests have been a net source of carbon emissions since 2015 and will continue to be a net carbon source through 2071. Though the forest products sector is a growing carbon storage pool for the state, its contributions are not enough to counteract trends in emissions from California's forest ecosystems. These trends are partially driven by climate change and its projected effects creating larger and more severe natural disturbances and declines in forest productivity. As the area of high-severity wildfire increases, large swaths of forest are likely to experience regeneration failure and possible conversion to non-forest ecosystems, driving substantial decreases in forest area and carbon stocks and increases in projected carbon emissions from forests over the next 50 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 stabilize the forest carbon sink in California (**Box 1**). Our scenarios also illustrate the potential to deploy 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.

A key factor for success will be addressing 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 1.5 million acres; (USDA Forest Service 2024a) and for combatting future regeneration failure as high-severity wildfires expand under future climate conditions (creating reforestation need on 8.6 million additional acres from 2022-2071 as modeled in this study). This work includes salvage of commercially viable timber, site preparation techniques to prepare the landscape for safe planting efforts and reduce future fuel hazards in post-burn areas, and subsequent reforestation at low stand densities. Though not specifically modeled here, climate-informed reforestation techniques like planting climate-adapted species in variable stand structures will also be important for fostering future forests more resilient to wildfire and a changing climate (Meyer et al. 2021; North et al. 2019).

Fire resilience treatments, a combination of thinning and prescribed fire to reduce stand densities to lower than under current management and fuel loads (North et al. 2022), provide a second climate-smart approach to addressing wildfire impacts. Based on our landscape resilience needs assessment, more than 11.2 million acres of forest are currently in need of treatment to reduce future wildfire risk and severity. Conducting initial treatments in these acres quickly (such as over the 10-year period we modeled) can help restore critical resilience to the landscape before wildfires are projected to intensify in the 2040s, creating conditions where any future wildfires will likely burn at a lower severity in treated areas (Davis et al. 2024). This reduces emissions and mortality from high-severity wildfires and eases the future demand for post-fire reforestation, as fire resilience treatments help reduce the occurrence of high-severity wildfire and its associated regeneration failure across the landscape. Additionally, fire resilience treatments facilitate the reintroduction of beneficial fire to many fire-adapted ecosystems.

BOX 1. CLIMATE-SMART FORESTRY PRACTICES IN CALIFORNIA

- ✓ **Address post-fire regeneration failure** through *landscape restoration* activities such as salvage of commercially viable timber, site preparation techniques 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 wildfires** through *resilience treatments*, including thinning and prescribed fire, at a landscape scale to reduce stand densities and reintroduce beneficial fire in fire-adapted ecosystems.
- ✓ **Use additional woody material** removed from landscape restoration and resilience treatments in *innovative wood products* to reduce decomposition and pile burn emissions from leaving the material on site and gain substitution benefits from using the wood in place of more emissions-intensive materials.
- ✓ **Reduce the rate of permanent forest loss** through *landscape restoration* and *forest conservation* paired with landscape scale *resilience treatments* to reduce disturbance-related carbon losses from these areas.
- ✓ **Increase forest extent where ecologically appropriate** through *silvopasture*, the low-density integration of trees into active pastureland without removing the land from productive pasture use.
- ✓ **Increase carbon stocks while sustaining timber supply** by *extending rotations* to optimize tree growth, paired with landscape scale *resilience treatments* to reduce the risk of disturbance-related carbon losses.
- ✓ **Prepare for increasing negative impacts of climate change** and use climate-adapted species and stand structures to promote forest health and resilience and restore key ecological processes.

Both of these management approaches, modeled across millions of acres, include the cutting of large amounts of additional wood from thinning and salvage activities. Following current wood utilization trends, merchantable softwood material is likely to be removed and used in commercial wood products. However, California's forest products industry has limited commercial uses for pulpwood and small diameter material aside from bioenergy, so a large portion of tops, limbs, and non-merchantable biomass is usually piled on site after harvest, with the intention of a subsequent pile burn (Eric Huff, personal communication). This piled material does not always get burned in follow-up as intended and is often left to decompose on site instead. Hardwood removals during salvage operations are typically used for residential fuelwood and do not contribute to industrial roundwood products. In all these cases, the carbon in this wood is emitted relatively quickly to the atmosphere, contributing to the net carbon source status of the forest. With nearly 3 times the CBAU carbon removals projected to occur from our modeled resilience and restoration treatments on 7.4 million acres from 2022-2031, current wood utilization strategies will not be enough to reduce additional emissions from this activity.

We identified opportunities to reduce these additional emissions through our Innovative Wood Utilization scenarios, which call for removing the cut material from resilience and restoration treatments and using it to produce biochar, transportation fuels, and mass timber rather than leaving it to decompose or burning it on site. These wood utilization strategies help reduce emissions from additional cut material, especially when biomass that would otherwise burn or decompose is used in longer-lived products like biochar or mass timber, which lock carbon away for decades. These products also provide substitution benefits from using wood in place of more emissions-intensive materials: mass timber can substitute for concrete and steel in construction, and transportation fuels like diesel made from woody biomass can substitute for their fossil fuel-based counterparts. In both cases, using wood-based products helps avoid (or displace) emissions from the production or use of the substituted products, reducing overall carbon emissions to the atmosphere.

Beyond minimizing forest loss from wildfire, strategies like forest conservation (which we modeled as a decrease in the rate of permanent forest loss from land-use change) can also maintain forest carbon in California. So long as the conserved forest lands are not impacted by wildfire, this approach accumulates additional carbon in the landscape and helps reduce the rate of forest loss. With more forestland available, however, our results show that without also undertaking resilience treatments on the conserved acres, emissions from wildfire and post-fire regeneration failure increase relative to CBAU – highlighting the importance of addressing wildfire impacts in addition to other climate-smart strategies. Not doing so leaves forests vulnerable to future climate and wildfire impacts and destabilizes the future climate mitigation potential of forests in the state.

This same principle holds true for practices that increase forest carbon stocks on the landscape, such as extending rotations and silvopasture. Extended rotations can optimize tree growth and accumulate more carbon in the forest ecosystem between harvest cycles, which can then transfer to the HWP sector as trees are harvested. However, longer harvest cycles can introduce tradeoffs with decreasing current timber supply and incurring potential leakage of harvest activities and emissions to forests elsewhere. Extended rotations can also increase exposure to the risk of disturbance-driven losses (e.g., from wildfire), so this practice needs to be paired with landscape scale resilience treatments to minimize this risk. By contrast, silvopasture focuses on the low-density integration of trees into active pastureland (where ecologically appropriate) without removing the land from active pasture use. This practice provides initially slow rates of carbon sequestration as trees grow from seedlings, but can help accumulate more carbon on the landscape as trees mature. The low-density arrangement of trees (and assumed control of understory vegetation by grazing livestock) also facilitates improved fire resilience.

Influence of future climate

Without the quick application of large-scale climate-smart forestry practices, it will be challenging to minimize future carbon losses as California's forests are severely impacted by future climate conditions. Our results show that forests in the state have been a net carbon source since 2015, driven by large-scale insect mortality events in 2015 and 2016, enabled by preceding drought, which decreased live tree sequestration rates, increased emissions from deadwood decomposition, and contributed to increased emissions from wildfires in subsequent years (Office of Environmental Health Hazard Assessment 2022). Under a projected future climate and business-as-usual management as represented by the CBAU scenario, forests will become even more of a net source of carbon emissions as natural disturbances, declining productivity, and post-fire regeneration failure intensify across the landscape. **This drives substantial decreases in forest area (-48%, a loss of 15 million acres) and carbon stocks (-50%, a loss of 4.7 billion metric tons of carbon dioxide equivalent, or GtCO$_2$e) while roughly doubling carbon emissions from forests from 2022-2071 (Table E2).**

These losses are largely due to the combination of more frequent high-severity wildfire and regeneration failure following roughly 82% of those high-severity events (based on our analysis of data from Davis et al. 2023a). Together, these dynamics mean that more acres of forest are exposed to a double whammy of wildfire and natural regeneration failure, while also emitting carbon from snags and other dead organic matter (DOM) on site after the fire. Insect disturbances and mortality events are projected to ramp up during the 2030s, followed by greater wildfire acres in the 2040s and beyond – an echo of the trends observed in 2015 and 2016 (Office of Environmental Health Hazard Assessment 2022). By 2060, decomposition emissions from lands in a state of post-fire regeneration failure outpace emissions from wildfires, highlighting the growing influence of these areas on net forest carbon trends. Any surviving forest in the CBAU simulation experiences declining productivity due to climate adaptation mismatch, which occurs because climate conditions are changing more rapidly than trees can adapt. This mismatch causes forests to grow more slowly or experience higher rates of mortality because they are now poorly adapted to their current climate (Stewart and Wright 2023). This decreasing productivity, down roughly 28% from 2022-2071 according to our analysis of data from Stewart and Wright (2023), further depresses carbon accumulation and contributes 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 69% of their forest area from 2022-2071 (decreasing from 14.8 to 4.5 million acres) and 74% of their carbon stocks (decreasing from 4.5 to 1.2 GtCO$_2$e) over the same period. USFS lands are also projected to accumulate 9 million acres of failed post-fire regeneration by 2071, which is twice the area of surviving forest on USFS lands in the same year. This drives net ecosystem carbon emissions on USFS lands to be 63% higher than under BAU in 2071. Overall, USFS lands make up roughly 70% of the total forest area and carbon stocks lost under the CBAU scenario and about 51% of the change in net ecosystem carbon flux (**Box 2**).

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 a carbon gain to the ecosystem) and positive numbers represent a net carbon source (more carbon in the atmosphere and a carbon loss or emission from the ecosystem).

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 CO$_2$ sequestered from the atmosphere and captured as carbon in forests and wood products (a net carbon sink or gain to the forest sector) and positive values indicate CO$_2$ emitted to the atmosphere from forests and wood products (a net carbon source or emissions from the forest sector).

Private and Native American lands also experience substantial impacts under the CBAU scenario: -29% forest area (decreasing from 12.5 to 8.8 million acres) and -27% carbon stocks (decreasing from 3.6 to 2.7 GtCO$_2$e) from 2022-2071, with 2.8 million acres of post-fire regeneration failure and 192% higher net ecosystem carbon emissions in 2071. Though this change is seemingly high percentage wise, emissions from private and Native American forests are still less than half of those from USFS lands in 2071. Declines in productivity and consistently higher emissions from natural disturbances relative to BAU drive this trend. Private and Native American lands account for 23% of overall CBAU losses of forest area and carbon stocks, and 37% of increased net ecosystem carbon flux from the scenario.

Forests in the Sierra/Cascades and Klamath/Interior Coast Ranges ecoregions will also be heavily impacted by projected future climate conditions. These two 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. The Sierra/Cascades ecoregion loses 56% of its forest area (decreasing from 14.8 to 6.5 million acres) and 64% of its carbon stocks (decreasing from 4 to 1.5 $GtCO_2e$) from 2022-2071 under CBAU, accumulating 7.5 million acres of land that have failed to regenerate post-fire and leading to 84% higher net ecosystem carbon emissions at the end of the scenario. In addition to the wildfire and regeneration failure impacts, the forest types in this ecoregion are largely projected to experience higher than average productivity declines (28.7% for the Sierra/Cascades vs 27.7% on average), further contributing to these climate change impacts. Overall, the Sierra/Cascades ecoregion accounts for roughly 55% of the total forest area and carbon stocks lost under the CBAU scenario, and about 62% of the change in net ecosystem carbon flux.

The Klamath/Interior Coast Ranges ecoregion also experiences strong climate change impacts under the CBAU scenario, losing 68% of forest area (decreasing from 8 to 2.6 million acres) and 66% of carbon stocks (decreasing from 2.7 to 0.9 $GtCO_2e$) from 2022-2071, with 4.2 million acres of post-fire regeneration failure and 54% higher net ecosystem emissions by 2071. Forest types in the Klamath/Interior Coast Ranges experience slightly lower than average productivity declines under future climate conditions (26.9% vs 27.7%), minorly tempering these projected climate change impacts. This ecoregion makes up 36% of overall CBAU losses of forest area, 38% of losses in carbon stocks, and 18% of increased net ecosystem carbon emissions from the scenario.

The benefits of expanding climate-smart forestry in California

When implemented concurrently across the landscape, the CSF practices in Box 1 can accomplish up to a **14% decrease in average annual emissions** from California's forests relative to CBAU over the next 50 years (**Table E2**). Represented by the Max NCS + Innovative Wood Utilization portfolio (which includes the Expand Fire Resilience to Mature and Old-Growth Forests (MOG Resilience), Landscape Restoration, Extended Rotations, Forest Conservation, and Silvopasture scenarios; **Table E1**), climate-smart forestry can help make significant progress towards the state's forest restoration goals (California Wildfire and Forest Resilience Task Force 2021) and natural climate solutions targets (CNRA 2024). Though forests will not be able to act as a carbon sink to offset emissions from other sectors, CSF practices can reduce net forest carbon emissions and confer other important landscape benefits.

Though forests in all scenarios remain a net carbon source from 2022-2071, the relative magnitude of California's annual *net carbon balance* (**Box 2**) is fairly consistent across scenarios after the pulse of resilience and restoration treatment removals modeled from 2022-2031 (**Table E2**). This means that **even with large-scale restoration treatments, associated removals, and wood product dynamics, carbon trajectories are not made worse by this activity so long as biomass cut during these treatments is utilized in some way** (as demonstrated by the Max NCS + Innovative Wood Utilization portfolio). Landscape conditions will stabilize following these treatments, based on reductions in forest loss and carbon stock loss achieved by this portfolio: forest area declines just 8% (2.5 million acres) rather than 48% (15 million acres) under CBAU, and forest carbon stocks decrease by 20% (1.9 $GtCO_2e$) instead of 50% (4.7 $GtCO_2e$) from 2022-2071. Though *net ecosystem carbon flux* (**Box 2**) is higher than CBAU during resilience and restoration treatments (an average of 47.1 $MtCO_2e\ yr^{-1}$ vs 23 $MtCO_2e\ yr^{-1}$ under CBAU), this is an expected behavior given the additional thinning and prescribed fire activities.

Once the 10-year treatment pulse has passed, net ecosystem carbon flux drops below CBAU levels and stays there (averaging 23.7 $MtCO_2e$ yr^{-1} from 2046-2071 vs 27.9 $MtCO_2e$ yr^{-1} under CBAU). This stabilized carbon flux in our results suggests that the landscape restoration and fire resilience treatments included as CSF practices in Box 1 can effectively reduce the risks and impacts of high-severity wildfire and other natural disturbances. Post-fire regeneration failure may still occur but at a much lower rate thanks to decreased high-severity wildfire and increased reforestation activities, adding up to 2.3 million acres by 2071 for the Max NCS + Innovative Wood Utilization portfolio instead of 12.7 million acres under CBAU.

Table E2. Comparison of forest area (million acres), ecosystem carbon stocks ($MtCO_2e$), net carbon balance ($MtCO_2e$ yr^{-1}), and cumulative net carbon balance ($MtCO_2e$) in 2022 vs 2071 for our 19 modeled scenarios. Net carbon balance includes net ecosystem 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	Forest area (million ac)		Ecosystem carbon stocks ($MtCO_2e$)		Average net carbon balance ($MtCO_2e$ yr^{-1})		Cumulative net carbon balance ($MtCO_2e$)	
		2022	2071	2022	2071	2022-2031	2046-2071	2022-2071	% change from CBAU
	BAU	31.5	28.9	9,455.5	8,391.8	10.5	10.1	501.2	-61%
	CBAU	31.3	16.3	9,364.4	4,693.2	20.7	27.7	1,299.6	-
Forest management scenarios (run on CBAU)	Landscape restoration	31.3	24.5	9,387.3	6,454.6	23.4	28.6	1,360.2	5%
	Fire resilience	31.4	23.5	9,392.4	6,318.0	32.9	27.7	1,435.5	10%
	MOG resilience	31.4	23.5	9,389.2	6,281.5	33.5	27.7	1,444.6	11%
	Forest conservation	31.3	17.5	9,368.1	4,973.0	20.2	26.7	1,244.3	-4%
	Silvopasture	31.3	16.5	9,377.7	4,728.5	20.9	27.3	1,288.8	-1%
	Extended rotations	31.3	16.3	9,377.2	4,713.8	20.7	27.4	1,284.8	-1%
	Altered rotations	31.3	16.3	9,370.4	4,688.6	20.7	27.7	1,299.1	0%
Innovative wood utilization scenarios	Fire resilience + Biochar	31.4	23.5	9,392.4	6,318.0	30.5	27.7	1,411.9	9%
	Fire resilience + Transportation fuels	31.4	23.5	9,392.4	6,318.0	31.4	27.7	1,420.3	9%
	Fire resilience + Mass timber	31.4	23.5	9,392.4	6,318.0	28.1	27.6	1,382.4	6%
	MOG Resilience + Biochar	31.4	23.5	9,389.2	6,281.5	30.8	27.7	1,418.1	9%
	MOG Resilience + Transportation fuels	31.4	23.5	9,389.2	6,281.5	31.8	27.7	1,427.5	10%
	MOG Resilience + Mass timber	31.4	23.5	9,389.2	6,281.5	28.3	27.6	1,387.7	7%
Portfolios (combined scenarios)	Ramp up	31.4	26.8	9,394.9	6,963.6	33.5	27.0	1,425.7	10%
	Ramp up + Innovative wood utilization	31.4	26.8	9,394.9	6,963.6	25.6	26.4	1,324.5	2%
	Max NCS	31.4	28.9	9,401.0	7,485.3	32.2	24.1	1,302.3	0%
	Max NCS + Innovative wood utilization	31.4	28.9	9,401.0	7,485.3	25.2	23.9	1,223.7	-6%

Innovative wood utilization further improves this carbon trajectory, as wood cut during resilience and restoration treatments is used to create a mix of biochar, transportation fuels, and mass timber rather than emitting carbon from burning and decomposition. In the case of the Max NCS portfolio, the creation of innovative wood products helps reduce net forest and HWP carbon emissions by 22% during the resilience treatment period from 2022-2031, avoiding the emission of 70.2 $MtCO_2e$, nearly 3 years' worth of net emissions from California's forest sector over this period.

Our results demonstrate that these CSF practices, including fire resilience treatments, can help protect valuable mature and old-growth (MOG) forests in California and return beneficial fire to many fire-adapted ecosystems. Under the CBAU scenario, MOG forest area is projected to increase by 0.2 million acres from 2022-2071, while the Max NCS + Innovative Wood Utilization portfolio allows MOG forest area to grow by 1.6 million acres. Average stand age increases from 134 years to 149 years from 2022-2071 under the Max NCS + Innovative Wood Utilization portfolio, a reversal of the trend observed under CBAU (with an average stand age of 133 years in 2022 vs 104 years in 2071). This increase in average stand age and MOG area shows that the fire resilience and restoration treatments included in this portfolio—which we model as a light (non-commercial) thinning followed by prescribed fire in old-growth forests—are effective at reducing future losses from wildfire, including in critical MOG forests which are increasingly vulnerable to wildfire and climate change impacts (Anderson et al. 2024; Shive et al. 2021; Potter 2023). These practices create a more balanced distribution of age classes, which, along with a diversity of species and heterogenous forest structure, is a key factor in fostering ecosystem resilience and providing essential forest co-benefits such as wildlife habitat, carbon sequestration and storage, and wood products (Ferrare, Sargis, and Janowiak 2019; Seidl et al. 2016; Vangi et al. 2024; Shifley and Thompson 2011; USDA Forest Service 2023b).

The Max NCS + Innovative Wood Utilization portfolio also illustrates the compounding benefits of concurrent action on the landscape. The individual components of this portfolio sum to smaller climate mitigation benefits than the portfolio itself, adding up to a higher cumulative net carbon balance (meaning higher emissions) of 124.6 $MtCO_2e$ above CBAU levels from 2022-2071 from the sum of all individual components versus 2.7 $MtCO_2e$ above CBAU for the Max NCS portfolio, and this without including the emissions reductions achieved from innovative wood products. When innovative wood utilization is included, the Max NCS + Innovative Wood Utilization portfolio has an even lower cumulative net carbon balance, meaning lower emissions, of -76 $MtCO_2e$ relative to CBAU from 2022-2071 (**Table E2**). This points to interactions between these component scenarios that amplify their positive benefits. For example, the resilience treatments implemented in the MOG Resilience scenario (one component of the Max NCS portfolio) help to reduce wildfire severity, moving from 349,373 acres per year ($ac\ yr^{-1}$) of high-severity wildfire under CBAU to 143,220 $ac\ yr^{-1}$ in the MOG Resilience scenario. This management-driven decrease in high-severity wildfire essentially cancels out the climate-driven increase in high-severity wildfire used to create the CBAU scenario (216,010 $ac\ yr^{-1}$). Post-fire regeneration failure is driven by high-severity wildfire, so fewer acres of high-severity fire lead to fewer acres of regeneration failure and fewer acres needing the salvage and reforestation treatments of the Landscape Resilience scenario (another component of the Max NCS portfolio). Though not directly modeled here, these reforestation treatments can also be designed with climate-adapted species in variable and low-density stand structures (Meyer et al. 2021; North et al. 2019) to help make future forests more resilient to wildfire, reducing the need for the resilience treatments in the MOG Resilience scenario. Modeled together, as in the Max NCS portfolio, this creates a powerful positive feedback loop that strengthens the restoration and resilience benefits of each scenario beyond what can be accomplished by individual activities alone. Though scenarios such as Forest Conservation and Extended Rotations result in a lower cumulative net carbon balance (meaning lower emissions) than CBAU, they do not provide the restoration and resilience benefits that are so needed across the state.

The Max NCS + Innovative Wood Utilization portfolio provides the only comprehensive modeled pathway to achieve lower emissions than CBAU over the next 50 years (Table E2).

Other Considerations

The difference in impact between our scenarios comes in part from the relative scale of activity (**Table E1**). Resilience and restoration treatments on millions of acres have a larger influence on carbon trajectories and stability than practices affecting only thousands of acres. The timing of these treatments in also important: 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, insect mortality events will increase in the 2030s, followed by greater wildfire acres from the 2040s onwards. **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 treated and an acceleration of the timeline over which these treatments are carried out – for example, treating all lands that currently need fire resilience or reforestation (an operational total of 9.2 million acres, filtered down from 12.7 million acres total) over a 10-year period as in our Max NCS + Innovative Wood Utilization portfolio. This aligns well with the timelines of California's restoration and net-zero goals aiming to reach full implementation by 2045 (California Wildfire and Forest Resilience Task Force 2021; CARB 2022a; CNRA 2024).

However, this pace and scale of action requires forest management capacity that is still developing within California. In 2021, for example, resilience treatments (fuel reductions, prescribed fire, and prescribed grazing) were implemented on 402 thousand acres of forest within the state and reforestation (site preparation and tree planting or seeding) occurred on 76 thousand forest acres (Emily Brodie, personal communication). Notably, this rate is higher than we modeled in our CBAU scenario based on historic treatment levels, indicating that capacity is already ramping up. In 2023, this rate increased to 487 thousand acres of resilience treatments and 78 thousand acres of reforestation – an improvement in accomplishments but still shy of the treatment levels included in our Max NCS + Innovative Wood Utilization portfolio (a peak of 818 thousand ac yr^{-1} for resilience treatments during the treatment phase and up to 172 thousand ac yr^{-1} of reforestation). Building this capacity is critical not only for addressing current treatment needs, but also for having the ability to respond to future needs and especially surge years like the 2020 wildfire season. 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 the gap (Dobrowski et al. 2024).

The resilience and restoration treatments central to California's climate-smart strategies may be costly, requiring up to $1.8 billion annually as these treatments are implemented as determined in this analysis. Depending on timber market conditions, wood product revenues could offset 31% to 94% of these costs; however, a significant portion of these forest resilience activities will likely require alternative funding sources. Additionally, processing capacity for industrial roundwood and utilized biomass would need to expand significantly, with sawmill capacity nearly doubling and biomass utilization capacity more than doubling to manage the increased harvest volume.

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 California. In some cases, we make assumptions that can influence our overall results – for example, we assume based on existing science that fire resilience treatments effectively reduce future fire severity on 90% of treated acres, which in turn drives model dynamics of high-severity wildfire and post-fire regeneration failure. 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 the innovative wood utilization pathways modeled, where we project a 10-year period of resilience treatments to meet ecological needs and assume additional material can be utilized by industries that do not yet exist in California. Though we acknowledge that a 10-year procurement timeline may be too short for certain new products and facilities, our results demonstrate that investing in new industries for products like mass timber, transportation fuels, and biochar to utilize additional harvested wood is key to minimizing carbon losses in the state.

The practices listed in Box 1 are considered climate-smart because they balance both carbon storage and sequestration rates with forest health and resilience. California 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, other public, private, and Native American lands, coordinating resilience and restoration treatments across both public and private forests with these land managers will be key. Enabling Indigenous land stewardship, integrating Indigenous Knowledge, and developing a robust research, monitoring and adaptive management process can improve our ability to foster forest resilience under future uncertainty. The cost of inaction is significant, leaving forests vulnerable to future climate and wildfire impacts and destabilizing the future climate mitigation potential of forests in the state – so the question of restoring forest resilience in California is not a matter of if, but how soon.

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, 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).

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 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 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, Kurz, and McFarlane 2021). However, these benefits can be constrained or even negated in fire-prone ecosystems if wildfire hazard and impact on forests is not adequately addressed (Jerrett, Jina, and Marlier 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 2022, US forests captured and stored nearly 793 million metric tons of carbon dioxide ($MtCO_2e$), enough to offset 17% of carbon emissions from fossil fuels in that same year (EPA 2024). 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 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 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, seeking to balance carbon sequestration and storage rates throughout the forest. 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 wood 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 California

The state of California has set ambitious greenhouse gas (GHG) emissions reduction goals through the Assembly Bill 32 California Global Warming Solutions Act (2006) and subsequent legislation (e.g., Senate Bill 32 (2016); Executive Order B-55-18 (2018)), requiring the state to reduce emissions to 40% below 1990 levels by 2030 and achieve net zero emissions by 2045. In 2021, California's forest sector sequestered and stored 22 $MtCO_2e$ (USDA Forest Service 2024b), equivalent to 6% of the total GHG emissions reported in the state for that same year (CARB 2023). However, recent modeling from the California Air Resources Board (CARB) indicates that California's forests will be a net source of carbon emissions under future climate conditions, even with substantial levels of management (CARB 2022a). The state seeks to leverage the climate benefits from its 31.5 million acres of forest (USDA Forest Service 2021a) where possible, and minimize carbon losses from future climate impacts, through its influence on forest management, implementing climate-smart practices on public lands and providing technical and financial support for other forest landowners.

Spurred by the urgent threat of climate change, California and other US states are striving to develop policies and programs that lower greenhouse gas 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 California 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 California 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. We also estimate expected treatment costs, potential wood product revenue, and wood processing capacity constraints for each scenario. These results will provide information about forest climate mitigation and adaptation opportunities that can integrate with and inform statewide efforts, including the California Wildfire and Forest Resilience Task Force (Task Force) Action Plan, CARB's 2022 Scoping Plan, and the California Natural Resources Agency's (CNRA) Nature-Based Solutions Climate Targets (California Wildfire and Forest Resilience Task Force 2021; CARB 2022a; CNRA 2024). By leveraging this work with a related study being conducted for Oregon and other regional collaboratives like the Pacific Northwest Research Station Carbon Initiative (USDA Forest Service 2023a), California 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), we assess carbon trends and management scenarios in the forest ecosystem and forest products sector for California 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 California, based on current conditions and a landscape resilience needs assessment;

2) Development of business-as-usual (BAU) 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 California, ii) a customized lifecycle harvested wood products model (CBM-HWP-CA) built using the Abstract Network Simulation Engine (ANSE) framework, 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 v) economic analysis; and

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

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 (J. E. 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. These elements combine as forests sequester carbon and store it away in trees each year to represent the forest's climate mitigation potential. Forests that sequester and store more carbon than they release from decomposition, respiration, 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 critical comprehensive look at not only the forest ecosystem dynamics at play, but also forests' interactions with land-use change, the forest products sector in terms of emissions from wood products 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 (J. E. 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 California and

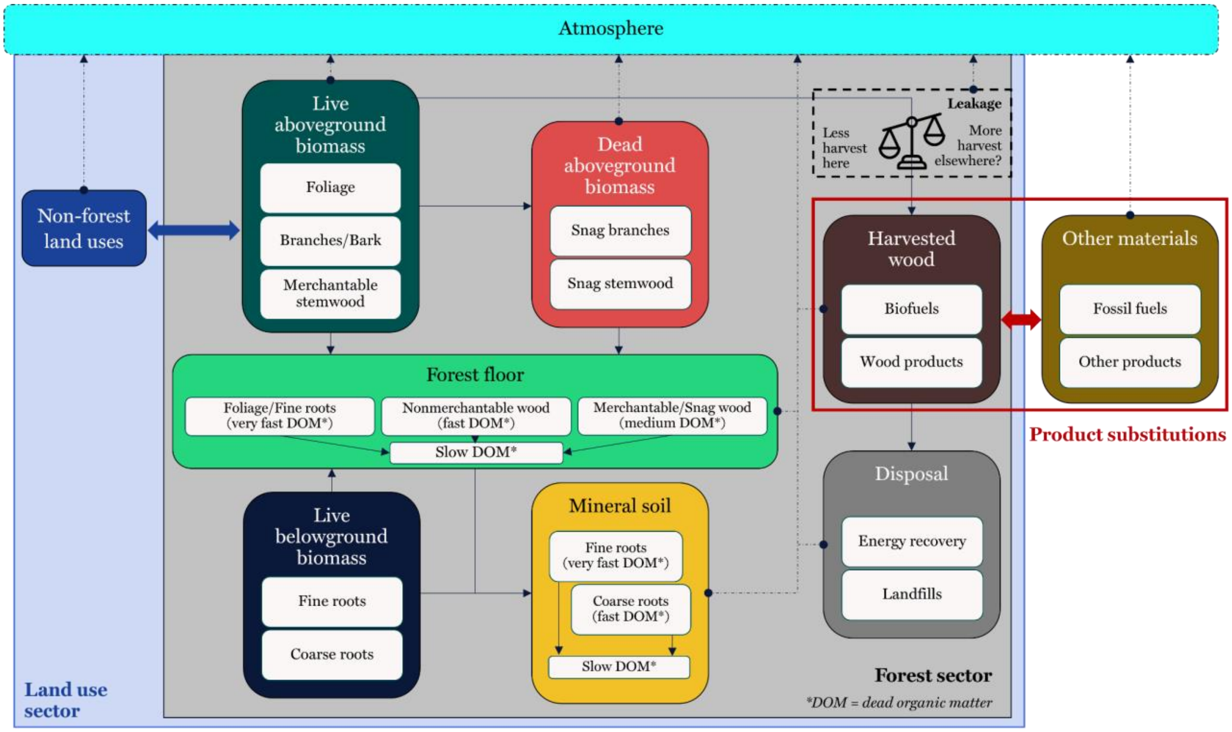


Figure 1. Simplified systems view of land uses and sectors influencing forest carbon stocks and sequestration. The forest sector (gray box) shows the forest carbon pools and transfers used in the CBM-CFS3 and CBM-HWP-CA models. For DOM (dead organic matter) pools, "very fast", "fast", "medium", and "slow" 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.

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 between these 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-CA 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 climate solution 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; Foster et al. 2024), the United States (Dugan et al. 2018; 2019; 2021; DeLyser et al. 2022a; 2022b; Papa et al. 2023), 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 California forests. We used CBM-CFS3 for this study at the request of CAL FIRE 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 Oregon (DeLyser et al. 2022a; 2022b; Papa et al. 2023). 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 used forest product regions and ecoregions for our spatial reference classifiers (**Figure 3**; see **Appendix** for full list of classifiers used in this project).

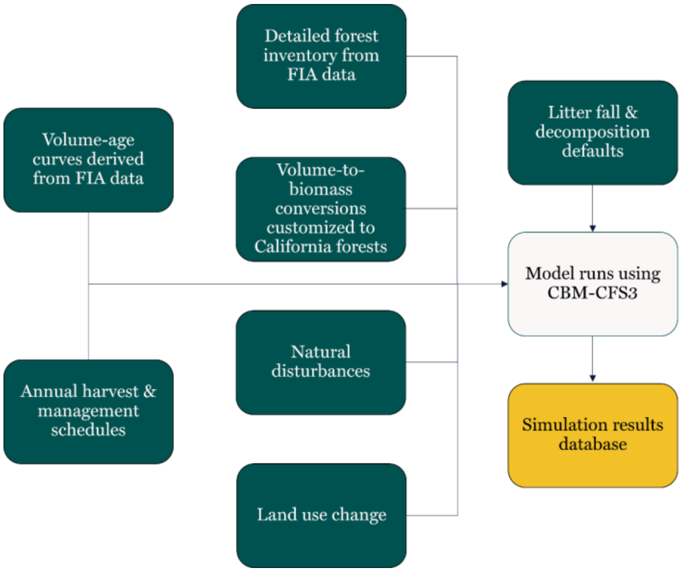


Figure 2. Modeling inputs and process for CBM-CFS3. Adapted from Kull et al. 2019.

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 critical step accounts for evident differences in growth and yield for various classifiers (especially those like forest type and ecoregion) in California, 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 accurately represent California tree species. Finally, CBM-CFS3 uses default equations to simulate dynamics between soil, dead organic matter, and forest processes like litter fall and decomposition (Kurz et al. 2009).

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. Historic forest management data for 2000-2021 come from CAL FIRE (CAL FIRE 2024a; 2024b; 2024c; 2024d), USDA Forest Service (USDA Forest Service 2021b), LANDFIRE (USGS 2016). Historic wildfire footprints and severity data come from CAL FIRE (2022), Monitoring Trends in Burn Severity (MTBS 2020), and Rapid Assessment of Vegetation Condition after Wildfire Program (RAVG 2021). We use disturbance footprints and severity information for insects, disease, and abiotic disturbances from National Insect and Disease Detection Surveys (USDA Forest Service 2019). We use data from the National Land Cover Database (NLCD; Dewitz and USGS 2021) to assess historic land-use change trends. The disturbance

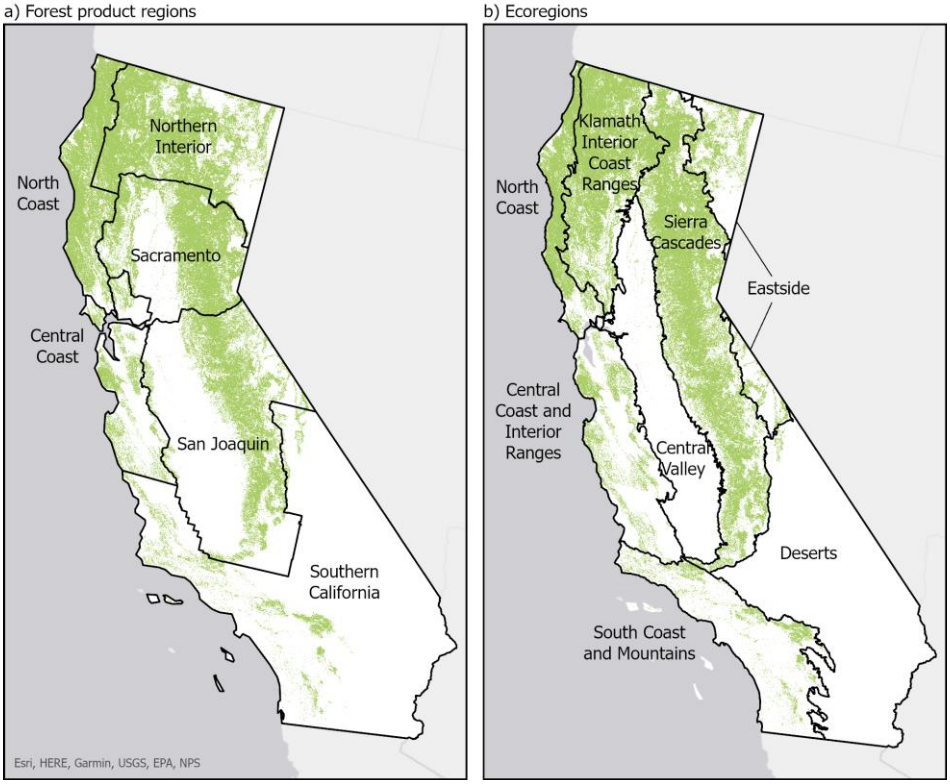


Figure 3. Maps of forest cover (shown in green) with spatial reference classifiers for a) forest product regions and b) ecoregions for California. Forest product regions are from Standiford et al. (2020) and Ecoregion (created by CAL FIRE based on Bailey's ecosystem section) from the California Forest Carbon Plan (Forest Climate Action Team 2018; CAL FIRE 2016).

matrices used for this study have been customized to California forest conditions and practices. See **Table 2** in the **Developing Modeling Scenarios** section for BAU ecosystem disturbance parameters and the **Appendix** for more information on data and assumptions used in model parameterization.

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-CA 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 sector associated with HWP from both historic 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-CA 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 California products and markets.

Some *disturbance events* (particularly, though not exclusively, harvest events) in CBM-CFS3 transfer carbon to the wood products sector, providing annual wood removal volumes in units of carbon which in turn become the primary data input for the CBM-HWP-CA model. These carbon inputs are partitioned into various HWP streams based on current practices in the forest products sector in California (**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 California roundwood. All remaining industrial roundwood carbon is allocated toward domestic commodity production, with a certain proportion going toward

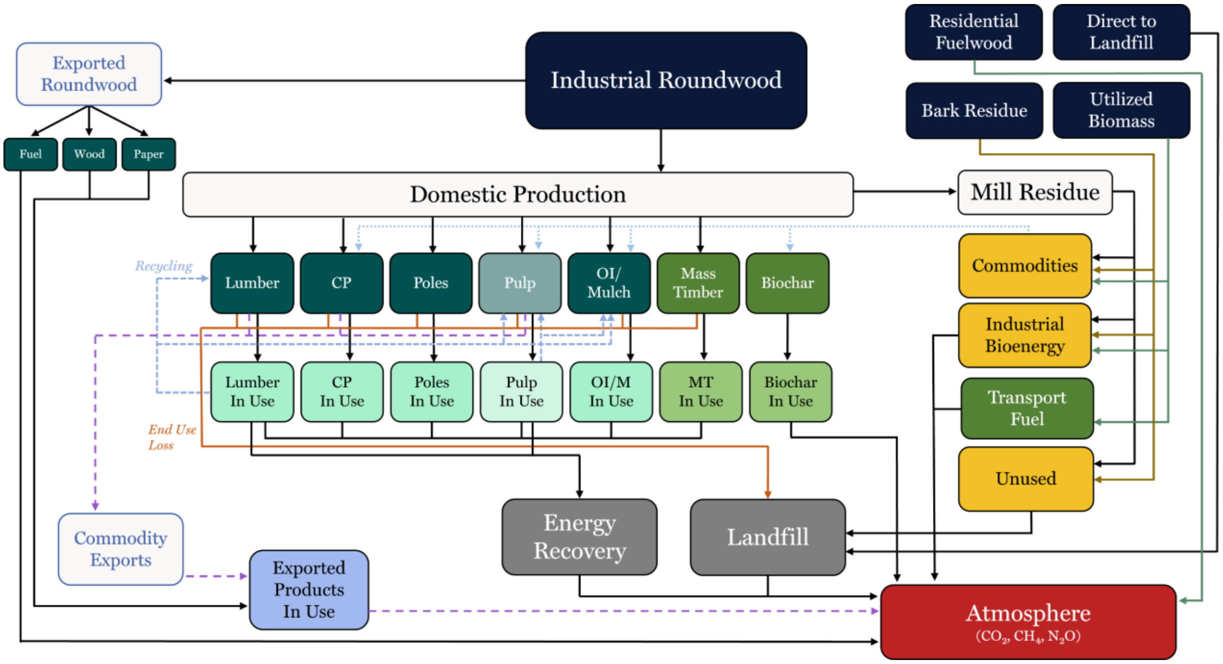


Figure 4. Pathways for carbon in harvested wood products in CBM-HWP-CA model used for analysis of the fate of harvested carbon in California. CP stands for composite panels; OI stands for other industrial products. Pulp and Pulp In Use categories are included as historic products but are no longer produced in California. Mass Timber, Biochar, and Transport Fuel categories are included for alternative wood utilization scenarios and do not represent current active industries in California.

mill residues that either become fuel, feed into additional commodity production, or go unused. Other wood product streams include residential fuelwood, bark residue, and utilized biomass (which includes tops, limbs, and other nonmerchantable biomass cut and removed during management activities). For these streams, we assume immediate combustion via fuel sources for the majority of carbon, though less so for bark, as 39% of this material ends up as mulch. 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 10% for wood and 50% for paper), meaning the remaining material will not decompose or emit carbon to the atmosphere during our model timeframe. Unique to the CBM-HWP-CA model, some removals, namely hardwood material and residues from permanent forest conversion, enter a separate wood product stream going directly to landfills and decomposing at a rate similar to landfilled paper. We also assume that hardwood material cut during salvage is used exclusively as residential firewood.

For any scenario resulting in less harvest than BAU 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. In this analysis, we apply leakage only to harvest emissions and products derived from industrial roundwood, including lumber, composite panels, and uses of roundwood bark and mill residue. Given that most pulpwood cut in California is pile burned or goes directly into fuelwood and landfills, it is not reasonable to assume that reductions in in-state pulpwood harvest would incur leakage from outside the state. On average, 90% of harvested material is included in the "leakable" industrial roundwood category, and we apply a leakage factor of 80% to this material, meaning that 80% of reduced roundwood harvest relative to BAU is assumed to leak out-of-state and the remaining 20% of reduced harvest relative to BAU 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 BAU 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 BAU is associated with *displaced emissions*, also referred to as *substitution benefits*. When additional wood products are manufactured relative to BAU, 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 lumber, composite panel, transportation fuels, 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-CA model, we use state-specific harvest, commodity, and trade data from USDA Forest Service (Marcille et al. 2020; Dillon and Morgan 2023), University of Montana Bureau of Business and Economic Research (BBER 2022), US International Trade Commission trade database (USITC 2021), and Howard & Liang (2019). We rely on the FAOSTAT statistical database

(FAO 2021) 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 California 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. We assume a half-life of zero for transportation fuel, as we do for all fuel sources. Displacement factors associated with wood product substitution come from 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 state-specific estimates from California Air Resources Board (2022b) for methane generation (k) and landfill half-lives, and IPCC defaults for the fraction of degradable organic carbon which decomposes and international landfill half-lives (Towprayoon 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.

Economic Analysis

We developed a simple framework to estimate several important economic metrics for each of our modeled scenarios, including expected treatment costs, potential wood product revenue, and processing capacity constraints.

We consider three components of treatment costs: the cost of labor and machinery necessary to manage a given acre of forest, the costs of transporting any harvested wood to a nearby processing facility, and any potential stumpage payments to landowners for the value of their standing timber. When HWP removals occur in our model, we assume that costs are incurred across all three categories, with the exception of removals on USFS lands, where we assume zero stumpage costs. This reflects expectations that management on USFS lands will follow a service-type contract rather than a timber sale program. For management activities where no biomass is removed (such as prescribed fire), we assume that only labor and machinery costs apply, with no costs associated with moving biomass to a landing or transporting it to a processing facility. We also assume that in these situations, landowners are not paid a stumpage fee. We refer to the treatment costs collectively as pre-fire treatment costs. See **Appendix** for unit cost assumptions for each of these categories.

Reforestation costs following wildfire are another major cost category in our modeling exercise. We use data from CAL FIRE's California Forest Improvement Program (CAL FIRE 2023) to estimate costs per acre. These include any tree planting (including seedling acquisition), site preparation and slash disposal, and herbicide treatment. If salvage logging occurs post-fire, we account for both the additional management costs, including transport to a processing facility, and offsetting revenue from salvaged material. In reality, many landowners do not have the financial resources to conduct salvage logging operations and in years with large salvage volumes due to wildfire, nearby mills may not have the capacity to process all of this material. See **Appendix** for additional cost assumptions.

In instances where harvested material is removed, we calculate the potential revenue of selling industrial roundwood and utilized biomass into harvested wood product markets. In reality, delivered log and biomass prices vary considerably across time, geography, species, and size class. We model three delivered log and biomass price scenarios, representing weak, average, and strong timber markets, in order to provide a range of plausible revenue outcomes. Combining these revenues with treatment costs provides an approximation of net cost and a plausible estimate of the remaining funding needed to implement various forest health restoration scenarios. We also calculate the capacity gap between existing mill and biomass facility processing infrastructure and projections of HWP volumes to understand how much additional processing capacity might be needed across the state to enable utilization of material harvested from resilience and restoration treatments. See **Appendix** for calculation details.

Identifying Forest Management Priorities

Through a series of meetings with CAL FIRE and US Forest Service (USFS) staff, academics, and forestry practitioners in the state, we identified several management priorities and concerns for forests in California. 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. As much as possible, we also integrated and aligned with priorities highlighted in other statewide efforts, including the Task Force Action Plan (2021) and CARB's 2022 Scoping Plan (2022a). Though CNRA's Nature-Based Solutions Climate Targets (2024) were released after our modeling process was completed, our identified priorities also align well with CNRA's forest-related target categories (see **Appendix** for a comparison). We used this information 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 California include:

- **Understanding impacts from climate change.** Climate change impacts are already apparent in California's forests, driving successive drought, insect mortality events, and escalating wildfires (Thorne, Wraithwall, and Franco 2018; CARB 2022a). 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, Fettig, et al. 2023; Turco et al. 2023). CSF in California will have to be centered on adapting to and mitigating future climate impacts, and understanding those impacts is critical to success.

- **Forest health and resilience.** Forests in California are much more dense than their historic conditions with more frequent fire regimes (North et al. 2022) and widespread insect and disease mortality. This density both decreases overall forest health and increases the risk of adverse disturbance impacts. These impacts extend to mature and old-growth (MOG) forests typically thought to be fire resilient, with an estimated loss of 13-19% of the giant sequoia old-growth population from wildfires in 2020 and 2021 (Shive et al. 2021). Oak woodlands are battling conifer encroachment, which alters the structure and composition of this culturally and ecologically important ecosystem (Cocking, Varner, and Engber 2015).

  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 (e.g., MOG forests). Two main concerns for forest health and resilience (wildfire and forest regeneration and reforestation) are further examined below.

- **Wildfire.** Current stand densities, fuel loading, and changes in climate are increasing vulnerability of forests to catastrophic wildfires, resulting in widespread carbon losses (CARB 2022a). Wildfire risk is also a pressing concern for communities all throughout California, in terms of potential GHG emissions, community health and vulnerability, and erosion and water resource impacts (Jerrett, Jina, and Marlier 2022; Carreras-Sospedra et al. 2024; Hino and Field 2023; Sankey et al. 2017). As such, the Task Force Action Plan (2021) calls for an increase in fuel reductions and other restoration treatments to reach an annual rate of 1 million acres per year by 2025. Modeling for CARB's 2022 Scoping Plan (2022a) identified a need for 2.3 million acres of treatment per year in order to meet statewide emissions goals by 2045.

  While these targets encompass all of California's natural and working lands, forests will be a key ecosystem for these fire resilience treatments. To understand the scale of the ecological need for these treatments, we conducted a landscape resilience needs assessment for all forest types (including those typically considered to be non-commercial such as oak woodlands and pinyon-juniper) based on previous models of wildfire hazard potential (WHP) for California (Vogler et al. 2021). WHP is an index that quantifies the potential for wildfires to both ignite and be difficult to control, making it a useful metric for identifying areas where fire resilience treatments are most urgently needed. We found over 11 million acres in need of treatment at high or very high WHP, with 60% of this need (6.78 million acres) on forestland owned and managed by federal agencies and 24% (2.75 million acres) on Native American and non-industrial private lands (**Table 1**). Not all these acres will be eligible or accessible for treatments; see **Appendix** for needs assessment methodology and eligible acre estimates.

Table 1. Acres in need of fire resilience treatments in California by ownership category and ecoregion.

Ecoregion	Ownership Category							
	USFS	BLM	NPS	Other federal	State / local	Private industrial	Native American and private non-industrial	All
North Coast	7,576	28,151	4,464	677	29,536	109,836	187,011	**367,252**
Klamath / Interior Coast Ranges	2,199,309	130,277	258	6,704	26,333	448,847	866,058	**3,677,785**
Sierra / Cascades	2,730,737	183,784	207,660	15,255	67,368	847,648	1,072,248	**5,124,701**
Eastside	371,568	125,067	-	605	3,390	72,196	115,166	**687,992**
Central Coast and Interior Ranges	170,612	40,144	8,300	29,937	58,186	1,587	380,593	**689,359**
Central Valley	-	111	-	10	59	-	3,898	**4,079**
Deserts, South Coast and Mountains	487,733	23,192	415	3,639	44,386	-	122,543	**681,907**
All	5,967,535	530,725	221,097	56,828	229,257	1,480,115	2,747,517	**11,233,075**

Fire resilience treatments in forests are generally considered to include combinations of thinning (either mechanically or by hand) and/or prescribed fire, though the CARB Scoping Plan includes other harvest or management activities as well. Recent research in the Sierra

Nevada indicates that historical stand conditions maintained by frequent low-severity fire were far less dense than current conditions and even densities achieved through typical forest thinning and fuel reduction activities (North et al. 2022). 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). This interaction needs further study, both to clarify the relationship between treatments and fire risk and to quantify the carbon tradeoffs of these activities over the short and long term. Understanding the carbon dynamics related to wildfire risk and resilience treatments is a high priority for state policy and planning efforts, especially given the scale of the issue.

- **Forest regeneration and reforestation.** Forests in California 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 reforestation (Davis et al. 2023b; Stevens-Rumann and Morgan 2019; Donato et al. 2009). Preliminary analysis from early 2024 estimates that 1.5 million acres of public land in California are currently in need of reforestation (USDA Forest Service 2024a). With wildfire occurrence and severity projected to increase due to climate change acting on degraded forest conditions, acres of post-fire regeneration failure are likely to increase, especially if high-severity patches grow in size and leave more forestland too far from a viable seed source (Davis et al. 2023b). Already, fires between 2018 and 2021 resulted in 668,000 acres of high severity fire patches greater than 40 acres in size with limited natural seed source (Mason, Bruce & Girard, Inc. 2023).

  Our analysis of data from Davis et al. (2023a) projects that an average of 82% of forest could fail to regenerate following high-severity wildfire under future climate conditions in a high-emissions pathway (RCP 8.5) in California. Therefore, addressing the current 1.5 million acre reforestation backlog and reducing the probability of future regeneration failure critical to maintaining forest in California (Dobrowski et al. 2024). 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 utilization.** Wood utilization is another piece of the wildfire resilience puzzle, especially finding a use and a market for additional woody material being removed from the forest during fire resilience treatments across millions of acres. Given the current structure of California's wood products industry, small-diameter and residual materials currently have limited commercial use beyond bioenergy, and are therefore often left on site with the intention of subsequent pile burning. This is not a feasible strategy for the scale of resilience treatments that are needed, so California's forestry community is exploring alternative wood utilization strategies that simultaneously support the development of new wood products markets in the state (such as biochar, transportation fuels, or mass timber) and incentivize treatments at the necessary scale (Cabiyo et al. 2021). Finding ways to support and sustain a market for these new products will be critical, balancing ecological needs and urgency with long-term procurement contracts and infrastructure siting constraints, among other considerations.

- **Land use and land cover.** California experiences 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. Though it is unclear to what degree these conversions are unpermitted, reducing illegal forest conversion and degradation is included in

CNRA's Nature-Based Solutions Climate Targets (2024). Activities aimed at forest land conservation and afforestation, such as through silvopasture (the low-density planting of trees in active pasture without disrupting its pastureland use), can slow or counteract rates of forest loss to land-use change and positively benefit forest land use and land cover. Silvopasture can often be done with native hardwood species like oaks (Mazaroli and Carlisle 2023; McCreary 2009), which may align with CNRA's target of oak woodland reestablishment in strategic and ecologically appropriate locations.

- **Harvesting practices and rotations**. With 31.5 million acres of forest in California, harvesting practices have the potential to influence large portions of the landscape. Many NCS assessments identify carbon benefits from extending rotations, which is also an allowed activity under CARB's U.S. Forest Project Offset Protocol (Fargione et al. 2018; CARB 2015). However, extended rotations may come at a cost in fire-prone landscapes (Badgley et al. 2022). Through engagement with stakeholders in this project, some private industrial land managers indicated that they are considering shortening their rotations in response to growing wildfire risk. Exploring changes in rotation length, which could currently affect about 115,000 acres of annual management, is of interest in the state given the potential tradeoffs between additional carbon storage and losses from wildfire.

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 California'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 19 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 California. 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 historic 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 2024a; 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 2000-2071, capturing historical management and disturbance events from 2000-2021 and proceeding with 50-year projections (2022-2071) of BAU based on historical averages (**Table 2**). Though modeling efforts often extend to 2100, we opted for a shorter model period due to growing uncertainties in future climate, policy, and market dynamics when nearing end-of-century. BAU activities include both annual averages of management and disturbance acres and average treatment or disturbance severity. Note that this approach assumes the same acreage and intensity of disturbance each year, which does not allow for interannual variability (i.e., big fire, pest outbreak, or harvest years). BAU wood utilization, discard and decay parameters (including landfill methane) are based on historical averages between 2000-2019 (**Table 3**). See the **Systems-Based Forest Carbon Modeling** section for data sources and **Appendix** for methodology and additional scenario details.

Climate-Adjusted Business-As-Usual Scenario

In recognition of the current and growing influence of climate change in California'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 forest management, wood utilization, and land-use change parameters from BAU and incorporates some projected climate change impacts on forests under Representative Concentration Pathway (RCP) 8.5 from 2022-2071. RCP 8.5 is representative of the upper range of the current high trajectory of global emissions and is recommended by the California Governor's Office of Planning and Research as a conservative approach to climate mitigation planning (Climate Nexus 2019; Cal-Adapt 2024).

The CBAU scenario includes modified frequency and severity of natural disturbance events, post-fire regeneration failure, and declines in productivity. We projected substantial changes in future high-severity wildfire (+216,010 acres per year, or ac yr^{-1}) and moderate-severity insect mortality events (+630,132 ac yr^{-1}), among other natural disturbance changes (**Table 2**) based on state-specific and regional analyses using a range of climate models (Westerling 2018; Cal-Adapt 2018; Parks et al. 2016; Anderegg et al. 2022). Our analysis of data from Davis et al. (2023a), which determines the likelihood of conifer regeneration within 10 years of a high-severity wildfire, projects that an average of 82% 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., 0.82 acres out of 1 acre burned would not regenerate) and applied this to all high-severity burns modeled from 2022-2071. 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, but it allows us to illustrate the potential impacts on California'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, such as a change from conifer to oak-dominated systems as projected for California (Thorne et al. 2016). 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 -28% productivity due to future climate mismatch. We modeled this as a percentage reduction in growth (based on forest type group) from 2022-2071.

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 13 of our remaining 17 scenarios by changing CBAU parameters at the beginning of our 50-year projection period (i.e., starting in 2022), representing potential changes in future management decisions or disturbance events. These scenarios relate to one specific practice or objective, where one CBAU practice is changed or a new practice is added and the rest of CBAU remains the same. This allows us to examine the specific influences of each altered or new management practice on forest carbon dynamics and evaluate their relative power as CSF and NCS actions. These 13 alternative scenarios cover a broad range of forest management and wood utilization practices, grouped into five categories representing similar management priorities and objectives: 1) post-fire landscape restoration; 2) wildfire resilience; 3) land use and land cover; 4) changing harvest rotations; and 5) innovative wood utilization. See **Table 4** for scenario parameters, including changes from CBAU, and **Appendix** for additional scenario development details.

General concerns about forest health and resilience as discussed in the **Identifying Forest Management Priorities** section above are represented across two categories (post-fire landscape restoration and wildfire resilience), to align with the specific targets and needs identified for post-fire reforestation and wildfire resilience treatments, respectively. In keeping with the state's goal to increase the pace and scale of forest health projects (California Wildfire and Forest Resilience Task Force 2021), initial treatments in post-fire landscape restoration and wildfire resilience scenarios were modeled over a 10-year timeframe (a "treatment phase" from 2022-2031) before transitioning into maintenance mode (from 2032-2071).

The post-fire landscape restoration category contains one scenario (Landscape Restoration) focused on addressing current and future reforestation need after high-severity wildfire. We used the 1.5-million-acre backlog estimate (USDA Forest Service 2024a) to set acreage targets for addressing current need within 10 years, modeling a combination of site preparation and reforestation at low stand densities on these acres. To address future reforestation needs as they occurred in this scenario, we modeled active reforestation treatments, including salvage to prepare the landscape for safe planting efforts and to reduce future fuel hazards to planted stands, followed by reforestation at low stand density. We targeted these treatments at all future high-severity wildfire acres. Modeled acreage targets for post-fire reforestation and restoration were 247,025 ac yr^{-1} during the treatment phase (2022-2031; see **Table E1** in the **Summary and Implications for Decision Makers** section), and 186,774 ac yr^{-1} during maintenance mode (2032-2071).

The wildfire resilience category contains two scenarios, one with BAU management age restrictions (the Fire Resilience scenario) and one with expanded management eligibility for specific actions to include MOG forest (the Expand Fire Resilience to Mature and Old-Growth Forests, or MOG Resilience, scenario). We used forests identified in our needs assessment (**Table 1**) as the basis for these scenarios, setting targets to treat all eligible and accessible forest acres initially within 10 years, with follow-up treatments and maintenance occurring throughout the model period. To model these treatments, we applied a combination of mechanical thinning and follow-up prescribed fire on most forests with slopes up to 49%, hand thinning with pile burning on regular cycle on slopes 50-69%, and prescribed fire only treatments on certain ownerships, forest types and slopes. Mechanical thinning treatments were designed to reduce stand densities more than current practice (a cutting of 40% biomass rather than 30% under CBAU), given the overstocked nature of California's forests (North et al. 2022). See **Appendix** for additional treatment eligibility details. We assumed treatments to be 90% effective at reducing future wildfire severity and modeled this as a reduction of fire severity by one class (from high severity to moderate severity or from moderate to low) on 90% of treated acres. This is a conservative assumption, as some data show higher rates of treatment effectiveness (Davis et al. 2024).

We created the MOG Resilience scenario in response to the growing threat and impact of wildfire to MOG forests in California and leveraged USFS definitions to modify our model's management age restrictions accordingly to include MOG stands (Anderson et al. 2024; Shive et al. 2021). Mature stands (from 140 years up to the minimum old-growth age defined by USFS, which differs by species and productivity) were made eligible for mechanical thinning treatments in our model, while old-growth stands were made eligible for hand thin and pile burn treatments. Acreage targets did not change between these two wildfire resilience scenarios; the only difference was the expanded treatment eligibility to cover more of the landscape. Modeled acreage targets for wildfire resilience treatments are 789,462 ac yr^{-1} during the treatment phase (2022-2031; **Table E1**), and 501,225 ac yr^{-1} during maintenance mode (2032-2071).

Though conifer encroachment in oak woodlands was identified as another key resilience priority, we did not explicitly model this due to a lack of available model parameterization data. However, the expanded use of thinning and prescribed fire included in the wildfire resilience scenarios includes actions in oak woodlands that can also accomplish the goal of managing conifer encroachment, which is often treated in similar ways (Cocking, Varner, and Engber 2015).

Following CARB's 2022 Scoping Plan and CNRA's Nature-Based Solutions Climate Targets timeline (CARB 2022a; CNRA 2024), alternative management practices in scenarios related to land use and land cover and changing harvest rotations were extended through at least 2045 to represent sustained action towards and beyond these goals. Both scenario categories contain two scenarios, each representing differing approaches to addressing overarching concerns about land-use change. The land use and land cover category includes the Forest Conservation and Silvopasture scenarios. The Forest Conservation scenario aims to reduce permanent forest loss to land-use change (i.e. conserve forestland), adjusting the BAU rate of forest loss we calculated by comparing NLCD data (Dewitz and USGS 2021) from 2001 and 2019. We model this forest conservation action by decreasing forest loss in a compound way (by an additional 2,397 ac yr^{-1}) from 2022-2045 until reaching a new equilibrium equal to the rate of forest gain (5,109 ac yr^{-1}) in 2045 to create a state of no net forest loss from land-use change from 2045-2071. We developed the Silvopasture scenario to assess the potential for establishment of new silvopastoral systems, which we modeled as the low-density planting of native trees in pastureland without removing the land from active pasture use. We set acreage targets for this scenario by identifying the potential for planting trees in pasture from the Reforestation Hub (The Nature Conservancy and American Forests 2023) and modeling a linear rate of implementation (9.512 ac yr^{-1}) from 2022-2045.

The changing harvest rotations category includes the Extended Rotations and the Altered Rotations scenarios. Under the Extended Rotations scenario, the minimum harvest age for all forest types and forest owners was raised from 50 years to 80 years, thereby extending rotations by roughly 30 years. The Altered Rotations scenario includes this same rotation extension on all public lands and instead implements a shortened rotation length (from 50 years to 40 years) on private and Native American lands in response to concerns about wildfire risk to timber shared with us during our stakeholder engagement process. For both scenarios, these actions were modeled to begin immediately in 2022 with no phase-in period on all 114,865 ac yr^{-1} of even-aged management (**Table 2**). While the changing harvest rotations scenarios are not designed to capture the full nuance of management objectives and techniques for all forest owners and forest types throughout the state, they do illustrate and compare the choices and tradeoffs forest owners are facing.

We developed wood utilization scenarios focused on three innovative HWP pathways (biochar, transportation fuels, and mass timber) that are not currently widely produced in California. As discussed in the **Identifying Forest Management Priorities** section above, innovative wood products are most discussed in the context of fire resilience treatments as a better use for additional woody material cut during this management practice (rather than leaving or burning it on site). Therefore, we combined our wood utilization scenarios with the wildfire resilience scenarios, demonstrating the differential impact of using the additional merchantable and submerchantable wood removed by fire resilience treatments to create various innovative HWP. All other individual scenarios were modeled with BAU wood utilization assumptions.

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 final 4 scenarios were constructed as *portfolios* – ensembles of scenarios or practices that could be concurrently implemented throughout the state – to visualize the cumulative potential of California's forests and forest sector to provide climate mitigation benefits. These portfolios centered around two objectives: 1) ramping up implementation of post-fire landscape restoration and wildfire resilience treatments, in the spirit of the Task Force Action Plan (2021); and 2) maximizing NCS action by 2045 through pursuing all potential avenues simultaneously, contributing to the natural and working lands goals set by CARB (2022a) and CNRA (2024). We use the term "maximizing" for this scenario to denote the combination of all the NCS practices included in our model, though other NCS practices not modeled here may also be viable options in California. Each of these portfolios was modeled alone (i.e. with BAU wood utilization assumptions) and also with an innovative wood product trifecta – a combination of the three individual wood product scenarios mentioned above.

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. California BAU and CBAU ecosystem disturbance parameters. BAU values are based on historical average rates from 2000-2021. CBAU values are based on projections under RCP 8.5 from 2022-2071. 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	-	-60,247	*-31,664*	*-6,022*	*-707*	*-21,854*
Forest gain	-	5,110	*736*	*126*	*126*	*4,124*
Net trend	**-**	**-55,137**	-30,930	-5,898	-581	-17,730

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	26,287	*3,810*	*17*	*12*	*22,447*
Intermediate harvest	50% cut, 45% removed	35,581	*3,074*	*44*	*183*	*32,282*
Group selection	50% cut, 45% removed	52,997	*1,117*	*17*	*929*	*50,936*
Commercial thin	30% cut, 25% removed	41,113	*26,109*	*35*	*44*	*14,925*
Hazardous fuels thin	30% cut, no removal	3,943	*2,666*	*53*	*165*	*1,088*
Precommercial thin	10% cut, no removal	39,616	*27,409*	*17*	*74*	*10,114*
Rx fire	5% burned	25,049	*12,130*	*1,038*	*783*	*5,147*
Pile burn	50-90% consumption of pile	20,364	-	-	-	-
Salvage	90% cut, 90% removed	29,616	*4,576*	-	*10*	*25,027*
Total	**-**	**280,368**	*86,815*	*1,300*	*2,372*	*163,566*

Natural disturbances

Disturbance	Severity	BAU (ac yr^{-1})	CBAU (ac yr^{-1})	Difference (ac yr^{-1})	Historic Range (ac yr^{-1})
Wildfire	High	133,363	349,373	+216,010	2,232-939,136
	Moderate	125,938	323,370	+197,432	5,174-802,026
	Low	158,508	158,508	-	9,065-934,514
Insects	High, mortality	4,369	8,005	+3,636	0-56,369
	Moderate, mortality	723,181	1,353,314	+630,132	3,457-3,556,668
	Low, mortality	175,746	312,519	+136,773	0-1,224,336
	High, defoliation	6,264	6,264	-	0-49,062
	Moderate, defoliation	918	918	-	0-10,533
	Low, defoliation	11,796	11,796	-	0-128,793
Disease	High, mortality	96	94	-2	0-1,873
	Moderate, mortality	43,171	55,187	+12,016	31-292,091
	Low, mortality	4,630	4,459	-171	0-43,387
	High, no mortality	4,262	4,262	-	0-49,156
	Moderate, no mortality	4,948	4,948	-	0-96,668
	Low, no mortality	10,008	10,008	-	0-46,127
Abiotics	High, mortality	835	954	+120	0-18,187
	Moderate, mortality	9,082	9,535	+453	0-101,177
	Low, mortality	30	32	+2	0-663
	High, no mortality	8,223	8,223	-	0-178,096
	Moderate, no mortality	1,692	1,692	-	0-28,505
	Low, no mortality	7,443	7,443	-	0-87,744

Additional climate impacts (statewide average)

Post-fire regeneration failure on 82% of high-severity wildfire acres	28% decline in forest productivity (annual growth rates)

Table 3. California 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	65.3% of all removals	Industrial roundwood	1.6% of harvest removals
Utilized biomass	18.8% of all removals	Utilized biomass	82.6% of harvest removals
Bark residue	15.9% of all removals	Bark residue	15.9% of harvest removals
Residential fuelwood	0% of all removals	Residential fuelwood	100% of salvage removals + 50% of deforestation removals
Direct to landfill	0% of all removals	Direct to landfill	50% of deforestation removals

Roundwood exports

Softwood exports	4.1%	Hardwood exports	0%

Commodity distribution (proportion of carbon distributed to various commodities)

Softwood commodities		Hardwood commodities	
Lumber	52.2%	Lumber	1.3%
Composite panels	9.7%	Composite panels	0.2%
Posts, poles, pilings	0.7%	Posts, poles, pilings	0%
Bioenergy from mill residue	10.8%	Bioenergy from mill residue	48.4%
Composite panels from mill residue	3.1%	Composite panels from mill residue	13.9%
Other industrial uses from mill residue	5%	Other industrial uses from mill residue	20.3%
Bioenergy from bark residue	9.7%	Bioenergy from bark residue	9.7%
Mulch from bark residue	6.2%	Mulch from bark residue	6.2%
Unused bark residue	0.03%	Unused bark residue	0.03%
Fuel from exported roundwood	1.2%	Fuel from exported roundwood	0%
Paper from exported roundwood	0.5%	Paper from exported roundwood	0%
Wood from exported roundwood	1%	Wood from exported roundwood	0%

Product half-lives

Domestic use			
Softwood lumber	42.7 years	Bioenergy	0 years
Hardwood lumber	22.5 years	Softwood mass timber	85.5 years
Softwood composite panels	33.7 years	Hardwood mass timber	73.3 years
Hardwood composite panels	27.5 years	Biochar	100 years
Posts, other industrial uses	12 years	Transportation fuel	0 years
Pulp	2.6 years		
International use			
Wood, composite panels, other industrial uses, poles	30 years	Fuel	0 years
		Paper	2 years

Product retirement

Wood	90.3% landfill 9.7% recycled	Paper	26% landfill 68% recycled
		Mass timber	100% landfill

Landfills

Decomposable materials	Paper: 50% Wood: 10%	Landfilled product half-lives	Paper: 17 years Wood: 30.5 years
Methane generation rate k	0.02 $m^3\ yr^{-1}$	Exported landfilled product half-lives	Paper: 13.5 years Wood: 26.5 years
Methane release	72.8% flared 27.2% unrecovered		

Table 4. Ecosystem and wood utilization scenario parameters for California. Unless otherwise noted, scenario changes from CBAU are immediate and last for the entire simulation period (2022-2071). 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 appropriate portfolio. See **Appendix** *for assumptions and data sources.*

Forest management scenarios

Post-fire landscape restoration

Scenario name	Objective	Change from CBAU	Scenario impact, 2022-2071
Landscape restoration*^	Address current post-fire reforestation needs within 10 years	+134,880 ac yr^{-1} post-fire site prep and low-density reforestation from 2022-2031	1,348,800 post-fire acres reforested at low density
	Address future post-fire reforestation needs within 3-5 years of high-severity wildfire	+171,961 ac yr^{-1} post-fire salvage/site prep and low-density reforestation	8,598,050 post-fire acres reforested at low density

Wildfire resilience

Scenario name	Objective	Change from CBAU	Scenario impact, 2022-2071
Fire resilience	Address current fire resilience treatment needs within 10 years, then continue maintenance treatments	+523,438 ac yr^{-1} mechanical thin to reduce fuels from 2022-2031 +65,490 ac yr^{-1} hand thin to reduce fuels	8,508,892 acres thinned
		+229,405 ac yr^{-1} Rx fire (burn only, not follow-up after thinning) +54,576 ac yr^{-1} pile burn (follow-up 5 years after hand thin) +104,689 ac yr^{-1} Rx fire (broadcast burn 10-30 years after mechanical thin)	3,886,700 acres of Rx fire and pile burn
	Decrease wildfire severity in response to treatments	206,153 ac yr^{-1} moderate-severity wildfire instead of high-severity wildfire 180,043 ac yr^{-1} low-severity wildfire instead of moderate-severity wildfire	19,309,800 acres of fire at lower severity
Expand fire resilience to mature and old-growth forest*^ (MOG resilience)	Address current resilience treatment needs within 10 years, then continue maintenance treatments	*This scenario uses the same techniques and area targets as the Fire Resilience scenario*	8,508,892 acres thinned 3,886,700 Rx fire and pile burn
	Increase resilience in mature stands within 10 years	Increase age restriction for resilience mechanical thin from 140 to minimum old-growth forest age threshold as defined by USFS (varies by forest type) to make mature acres eligible for treatment	~998,730 additional acres eligible for resilience treatments
	Increase resilience in old-growth stands within 10 years	Remove age restriction for hand thin and pile burn to make old-growth acres eligible for treatment	~720,040 additional acres eligible for resilience treatments

Land use and land cover

Scenario name	Objective	Change from CBAU	Scenario impact, 2022-2071
Forest conservation^	Reduce permanent forest loss from land-use change by 2045	Compounding decrease of forest loss rate by 2,397 ac yr^{-1} until it matches forest gain rate in 2045, then hold steady	2,150,404 forest acres conserved
Silvopasture^	Increase silvopasture implementation by 2045	+9,512 ac yr^{-1} planted in silvopasture system from 2022-2045	219,000 acres planted in silvopasture system

Changing harvest rotations

Scenario name	Objective	Change from CBAU	Scenario impact, 2022-2071
Extended rotations^	Increase harvest age for all forest owners	Increase minimum harvest age from 50 years to 80 years	5,743,250 acres eligible for extended rotation lengths
Altered rotations	Increase harvest age for public forest owners, decrease harvest age for private forest owners	Increase minimum harvest age from 50 years to 80 years on public lands Decrease minimum harvest age from 50 years to 40 years on private lands	5,743,250 acres eligible for altered rotation lengths

Table 4, cont. *Ecosystem and wood utilization scenario parameters for California. Unless otherwise noted, scenario changes from CBAU are immediate and last for the entire simulation period (2022-2071). 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 appropriate portfolio. See* **Appendix** *for assumptions and data sources.*

Forest management + Innovative wood utilization scenarios

Scenario name	Objective	Change from CBAU	Scenario impact, 2022-2071
Fire resilience + Long-lived wood products	Allocate additional harvested merchantable material from treatments in Fire Resilience scenario to mass timber	+100% of additional harvested material in Fire Resilience scenario eligible for use as lumber allocated to production of mass timber	Longer half-life for mass timber than lumber Substitution benefits from using mass timber in construction
MOG resilience + Long-lived wood products	Allocate additional harvested merchantable material from treatments in MOG Resilience scenario to mass timber	+100% of additional harvested material in MOG Resilience scenario eligible for use as lumber allocated to production of mass timber	Longer half-life for mass timber than lumber Substitution benefits from using mass timber in construction
Fire resilience + Biochar	Allocate additional utilized biomass material from treatments in Fire Resilience scenario to biochar	+100% of excess utilized biomass material (after meeting operational and idled bioenergy facility capacity) in Fire Resilience scenario allocated to production of biochar	Longer half-life for biochar than biomass left or burned on site
MOG resilience + Biochar	Allocate additional utilized biomass material from treatments in MOG Resilience scenario to biochar	+100% of excess utilized biomass material (after meeting operational and idled bioenergy facility capacity) in MOG Resilience scenario allocated to production of biochar	Longer half-life for biochar than biomass left or burned on site
Fire resilience + Transportation fuels	Allocate additional utilized biomass material from treatments in Fire Resilience scenario to transportation fuels	+100% of excess utilized biomass material (after satisfying bioenergy facility demands) in Fire Resilience scenario allocated to production of transportation fuels	Substitution benefits from using bio-based transportation fuels
MOG resilience + Transportation fuels	Allocate additional utilized biomass material from treatments in MOG Resilience scenario to transportation fuels	+100% of excess utilized biomass material (after satisfying bioenergy facility demands) in MOG Resilience scenario allocated to production of transportation fuels	Substitution benefits from using bio-based transportation fuels

Forest management portfolios

Portfolio symbol and name	Objective	Change from CBAU	Scenario impact, 2022-2071
* Ramp up implementation	Increase pace and scale of post-fire landscape restoration and fire resilience treatment implementation within 10 years, then continue maintenance treatments	*This portfolio combines the Landscape Restoration and Expand Fire Resilience scenarios with CBAU management and natural disturbance not affected by other component scenarios*	9,946,850 post-fire acres reforested 12,395,592 acres treated for fire resilience
^ Max natural climate solutions action by 2045	Maximize natural climate solutions action statewide by 2045 (based on the scenarios included in this analysis, not all possible natural climate solutions in California)	*This portfolio combines the Landscape Restoration, Expand Fire Resilience, Forest Conservation, Silvopasture, and Extended Rotations scenarios with CBAU management and natural disturbance not affected by other component scenarios*	9,946,850 post-fire acres reforested 12,395,592 acres treated for fire resilience ~1,718,770 additional mature and old-growth acres eligible for resilience treatments 2,150,404 forest acres conserved 219,000 acres established in silvopasture 5,743,250 acres with extended rotation lengths (50->80 years minimum harvest age for all forest owners)

Table 4, cont. *Ecosystem and wood utilization scenario parameters for California. Unless otherwise noted, scenario changes from CBAU are immediate and last for the entire simulation period (2022-2071). 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 appropriate portfolio. See* ***Appendix*** *for assumptions and data sources.*

Forest management + Innovative wood utilization portfolios

Portfolio symbol and name	Objective	Change from CBAU	Scenario impact, 2022-2071
* Ramp up implementation + Innovative wood utilization	Increase pace and scale of post-fire landscape restoration and fire resilience treatment implementation within 10 years, then continue maintenance treatments Allocate additional utilized biomass from fire resilience treatments to innovative wood products	*This portfolio combines the Landscape Restoration, Expand Fire Resilience, Long-Lived Wood Products, Biochar, and Transportation Fuels scenarios with CBAU management and natural disturbance not affected by other component scenarios. Biochar and Transportation Fuels scenarios each take 50% of excess utilized biomass rather than 100%.*	9,946,850 post-fire acres reforested 12,395,592 acres treated for fire resilience Longer half-life for mass timber than lumber; longer half-life for biochar than biomass left or burned on site Substitution benefits from using mass timber in construction and from using bio-based transportation fuels
^ Max natural climate solutions action by 2045 + Innovative wood utilization	Maximize natural climate solutions action statewide by 2045 Allocate additional utilized biomass from fire resilience treatments to innovative wood products	*This portfolio combines the Landscape Restoration, Expand Fire Resilience, Forest Conservation, Silvopasture, Extended Rotations, Long-Lived Wood Products, Biochar, and Transportation Fuels scenarios with CBAU management and natural disturbance not affected by other component scenarios. Biochar and Transportation Fuels scenarios each take 50% of excess utilized biomass rather than 100%.*	9,946,850 post-fire acres reforested 12,395,592 acres treated for fire resilience ~1,718,770 additional mature and old-growth acres eligible for resilience treatments 2,150,404 forest acres conserved 219,000 acres established in silvopasture 5,743,250 acres with extended rotation lengths (50->80 years minimum harvest age for all forest owners) Longer half-life for mass timber than lumber; longer half-life for biochar than biomass left or burned on site Substitution benefits from using mass timber in construction and from using bio-based transportation fuels

Results and Discussion

Results of our analysis show that the forest ecosystem in California is already a net source of carbon, and though the forest products sector is a net carbon sink for the state, it is not strong enough to counteract ecosystem trends. Our results suggest there are several opportunities to dampen future forest carbon losses, especially through practices focused on addressing wildfire risks and impacts as climate change intensifies. 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 forest resilience treatments and post-fire restoration, coupled with innovative wood utilization, is a leading strategy for minimizing forest carbon losses now and in the future.

Influence of Future Climate

In both the BAU and CBAU scenarios, California's forests become a consistent net carbon source in 2015 and remain a source through 2071, represented by a net ecosystem carbon flux above zero (**Figure 5**). *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 a carbon gain to the ecosystem) and positive numbers represent a net carbon source (more carbon in the atmosphere and a loss or emission from the ecosystem).

This transition from net carbon sink to net carbon source is driven by large-scale insect mortality events, enabled by preceding drought, in 2015 and 2016, which decreased live tree sequestration rates, increased emissions from deadwood decomposition, and contributed to increased emissions from wildfires in subsequent years (**Figure 6;** Office of Environmental Health Hazard Assessment 2022). This result differs from estimates based on current FIA data (Domke, Walters, et al. 2023), which are only now beginning to show the carbon impacts of these events due to the lagged data collection timeline and interannual smoothing used for FIA population estimates. Though our model is parameterized using FIA data and has generally good alignment with FIA carbon estimates, the inclusion of independent natural disturbance events and disturbance matrices on annual timesteps allows us to forecast the impacts of these insect mortality events in a more immediate way. This also allows us to quantify the large spike of carbon emissions from wildfires in 2020 and 2021 (**Figure 6**).

Forest area and ecosystem carbon stocks decline in tandem throughout both simulations (**Figure 5**), though CBAU results show a much stronger trend of loss with -48% forest area (a loss of over 15 million acres) and -50% carbon stocks (a loss of 4.7 billion metric tons (Gt) CO_2e) from 2022-2071. This loss is largely due to the combination of more frequent high-severity wildfire and regeneration failure following roughly 82% of those high-severity events (based on our analysis of data from Davis et al. 2023a). Together, these dynamics mean that more acres of forest are exposed to a double whammy of wildfire and natural regeneration failure, while also emitting carbon from snags and other dead organic matter (DOM) on site after the fire. Insect disturbances and mortality events are projected to ramp up during the 2030s, followed by greater wildfire acres in the 2040s and beyond (**Figure 6**) – an echo of the trends observed in 2015 and 2016 (Office of Environmental Health Hazard Assessment 2022). By 2060, decomposition emissions from lands in a state of post-fire regeneration failure outpace emissions from wildfires (**Figure 6**), highlighting the growing influence of these areas on net forest carbon flux. Wildfire acres and emissions also decrease from 2060-2071 because a large enough portion of the landscape has burned and failed to regenerate that wildfires cannot continue at historic rates (i.e. there's not enough forest left in our model to burn; **Figure 6**). While this is, at least in part, a model dynamic

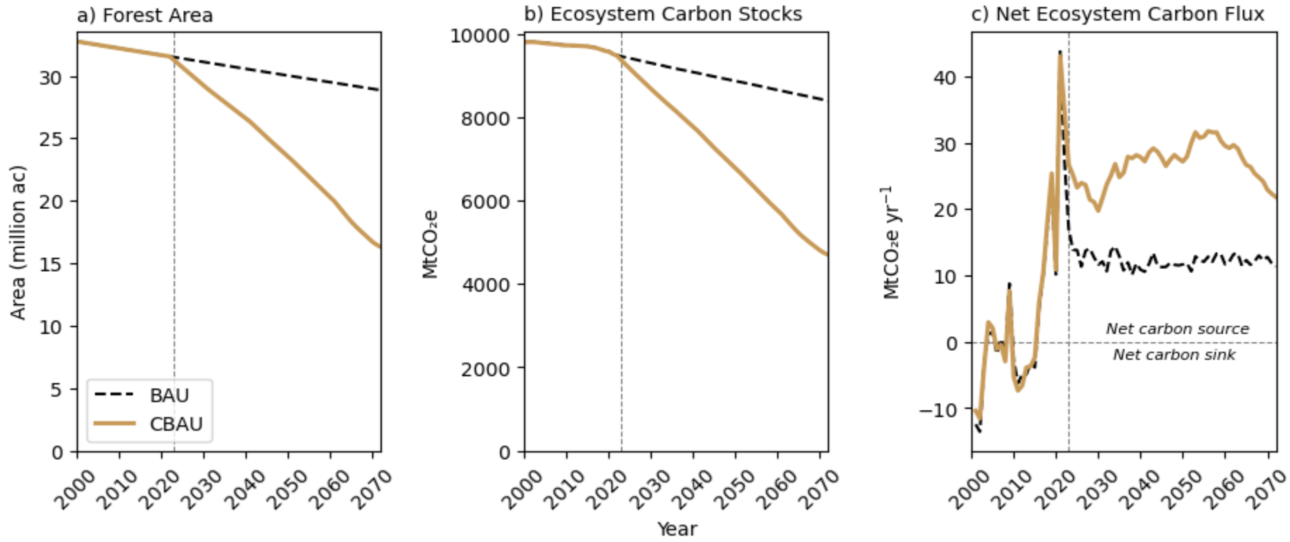


Figure 5. BAU and CBAU scenario results showing a) total forest area (million acres), b) ecosystem carbon stocks (MtCO₂e), and c) annual net ecosystem carbon flux (MtCO₂e yr⁻¹) from 2000-2071. Net ecosystem carbon flux refers to the net yearly sequestration of carbon by forests across all 14 ecosystem 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.

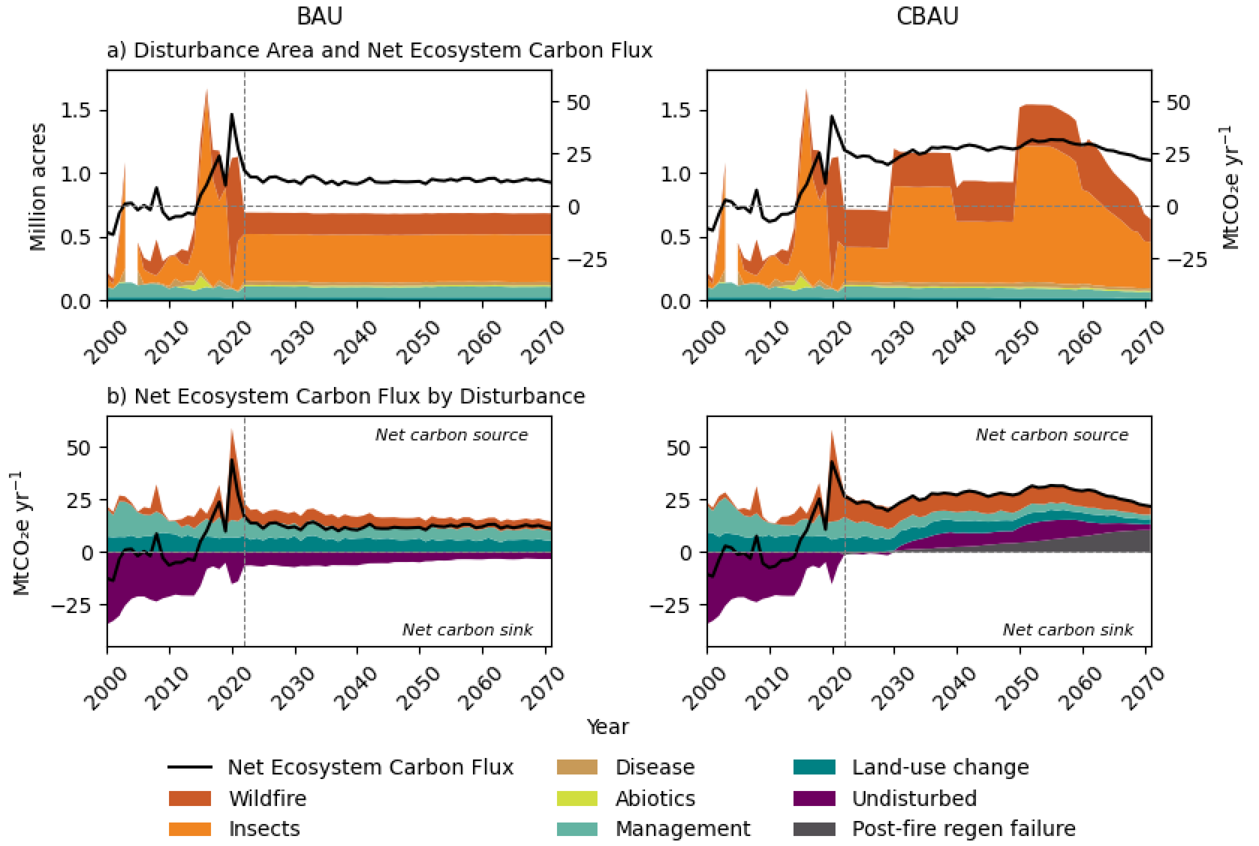


Figure 6. BAU and CBAU scenario results showing a) disturbance area (million acres) by disturbance type and net ecosystem carbon flux (MtCO₂e yr⁻¹), and b) annual net ecosystem carbon flux (MtCO₂e yr⁻¹) by disturbance type from 2000-2071. Net ecosystem carbon flux refers to the net yearly sequestration of carbon by forests across all 14 ecosystem carbon pools, after accounting for decomposition, natural disturbance emissions, and wood product transfers. In Panel b), negative numbers for net ecosystem carbon flux represent a net carbon sink and positive numbers represent a net carbon source.

(our model targets events at certain forest types each year and if that forest type is not available, the event is simply skipped), it also illustrates the growing challenge wildfires will pose to California's forests under future climate conditions.

Any surviving forest in the CBAU simulation experiences declining productivity due to climate adaptation mismatch, which occurs because climate conditions are changing more rapidly than trees can adapt. This mismatch causes forests to grow more slowly or experience higher rates of mortality because they are now poorly adapted to their current climate (Stewart and Wright 2023). This decreasing productivity, down roughly 28% from 2022-2071 according to our analysis of data from Stewart and Wright (2023), further depresses carbon accumulation and contributes to the forest's carbon source status in the future. The combination of lower productivity and increased emissions from tree mortality contributes to a higher net ecosystem carbon flux (higher emissions) even on otherwise undisturbed lands (**Figure 6**). Coupled with increasing emissions from wildfires and post-fire regeneration failures, this drives net ecosystem carbon flux to roughly double the emissions under the CBAU scenario compared with BAU (**Figure 5**). These results align with CARB's 2022 Scoping Plan (2022a), though more substantial losses are projected here (-4% carbon stocks in forests and wood products from 2022-2045 from CARB vs -23% in this study).

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 (**Figure 7**). Still, the projected transfer of carbon from the forest to the forest products sector outweighs emissions from current wood products in use and historic products (those produced prior to 2000 and either still in use or in landfills), making HWP a growing carbon storage pool for California. This trend is driven by the long-lived uses of harvested softwood material such as in lumber (**Table 3**) and the relative stability of carbon in landfilled HWP, with only 10% of wood and 50% of paper assumed to be decomposable (Towprayoon et al. 2019).

In both scenarios, softwood and hardwood removal volumes vary widely, with softwoods comprising 91% of annual removals from 2022-2071 on average. Based on historic wood utilization trends used to parameterize the CBM-HWP-CA model (see **Appendix**), the majority (65.3%) of harvested softwood

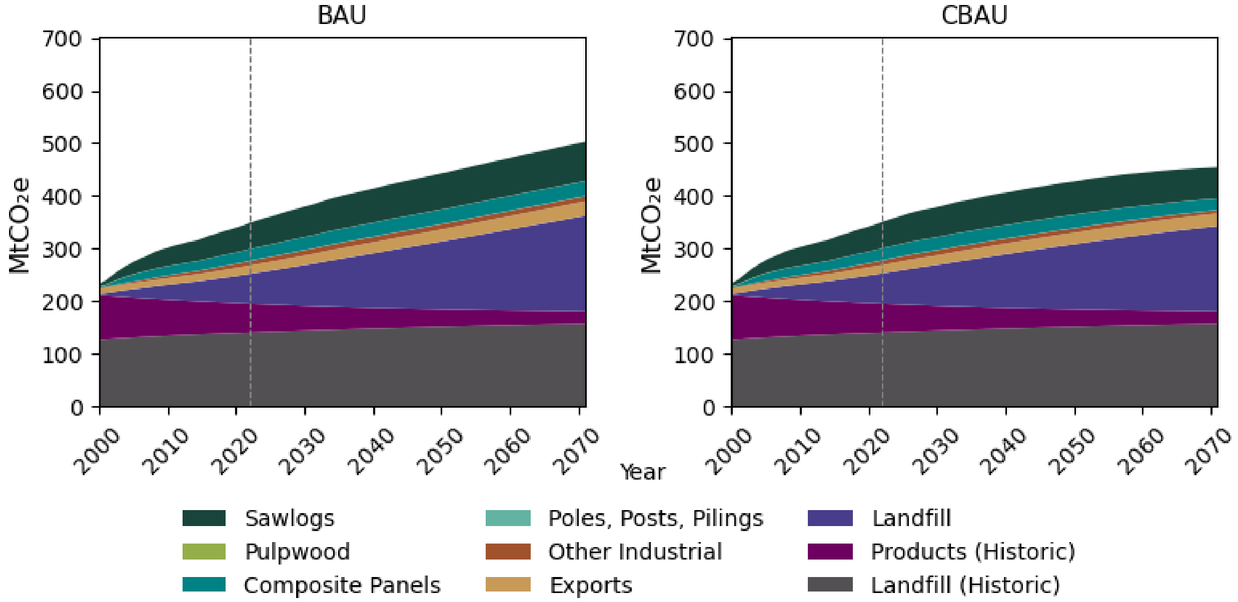


Figure 7. BAU and CBAU scenario HWP carbon stocks ($MtCO_2e$) by primary product, 2000-2071. Positive numbers denote accruing carbon stocks.

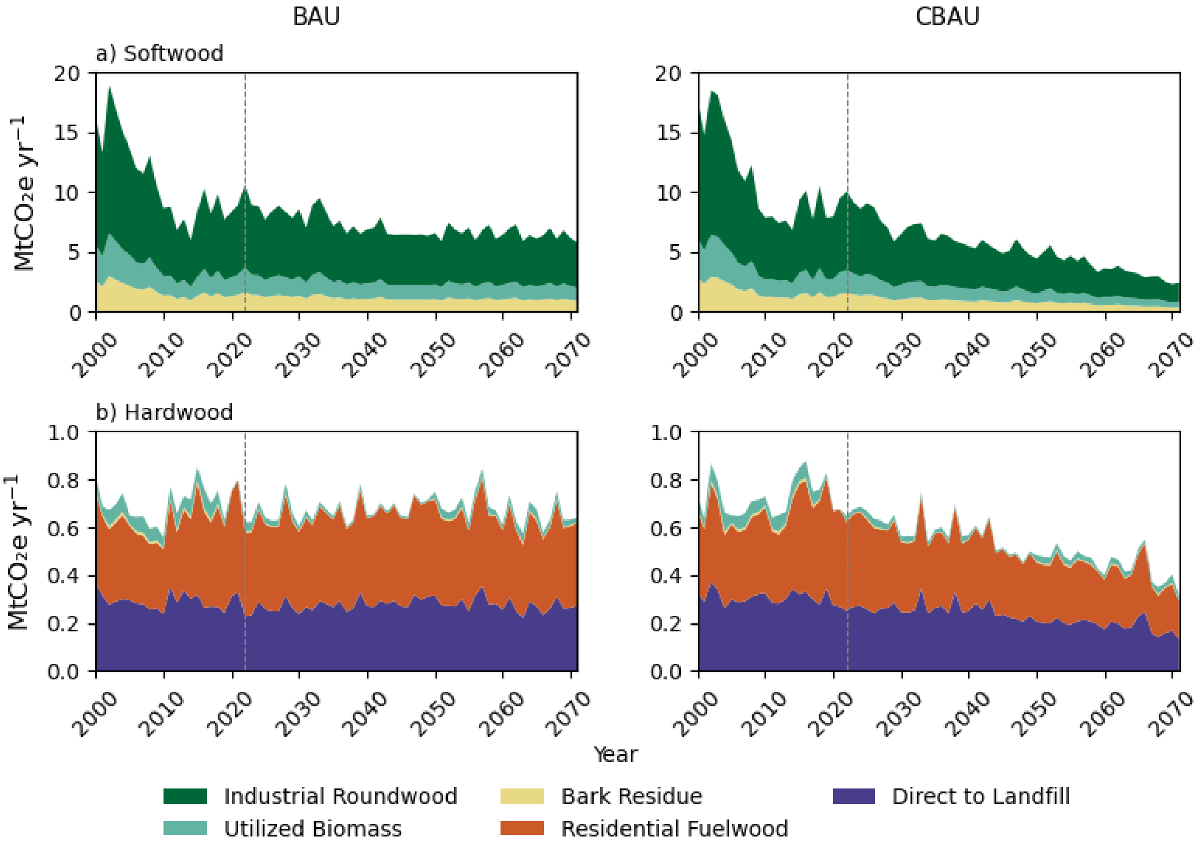


Figure 8. BAU and CBAU scenario results showing annual HWP removal distribution ($MtCO_2e\ yr^{-1}$) for a) softwoods and b) hardwoods from 2000-2071. Removals are comprised of woody material that is cut and removed from the forest and does not include any residues or other materials left on site.

under BAU goes into industrial roundwood products (**Figure 8**) such as lumber, composite panels, and poles, posts, or pilings (**Table 3**). Utilized biomass accounts for 18.8% of harvested softwood material (99.99% of which goes to bioenergy) and the remaining 15.9% of softwood removals are in the form of bark residue (which is used for bioenergy and mulch). Under CBAU, overall harvest volumes decline relative to BAU but these distributions do not change because our model assumptions for softwoods are the same. Harvested hardwood material, on the other hand, goes to different uses based on the management activities completed in each scenario. Our results show an average of 43% of hardwood harvest heading directly to landfills and 51.5% used as residential fuelwood in the CBAU scenario (**Figure 8**). These pathways stem from deforestation (land-use change) and salvage events, for which we and our state partners determined that cut wood does not enter commercial product streams. The small remaining portion of hardwood removals is distributed between utilized biomass (4.6%), bark residue (0.9%), and industrial roundwood (0.1%). These averages shift only slightly between BAU and CBAU, though once again harvested volume drops under CBAU.

In 2022, 68% (22.3 million acres) of forestland in California was younger than 140 years old, distributed among 19 forest type groups according to FIA (**Figure 9**; USDA Forest Service 2021a). This means 32% (10.4 million acres) of the landscape is already older than our BAU modeled maximum harvest age of 140 years, a proportion that increases to 59% (9.6 million acres) in 2071 for the CBAU scenario. 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. This contributes in a limited way to relatively low rates of projected removals when compared with historic trends. Note there is no state policy restricting harvest to stands younger than 140 years old; this model parameter is an indication of current practice based on FIA data and expert feedback.

MOG forest area, approximated using USFS-defined age thresholds (USDA Forest Service 2023c), increases from 7% to 14% (2.1 to 2.3 million acres) from 2022-2071 under CBAU (**Figure 9**). This is likely an undercount of true MOG area, as some definitions rely on stand- or tree-level metrics our model does not include. MOG forests are a critical component of a resilient forest landscape, though they are increasingly vulnerable to climate impacts and natural disturbances like wildfire and insect events (Anderson et al. 2024). The large percentage increases but modest acreage increases in MOG area and 140+ year old forest (which actually loses area through the model period) under CBAU reflects a shrinking denominator as the forest loss trend exhibited in **Figure 5** strengthens.

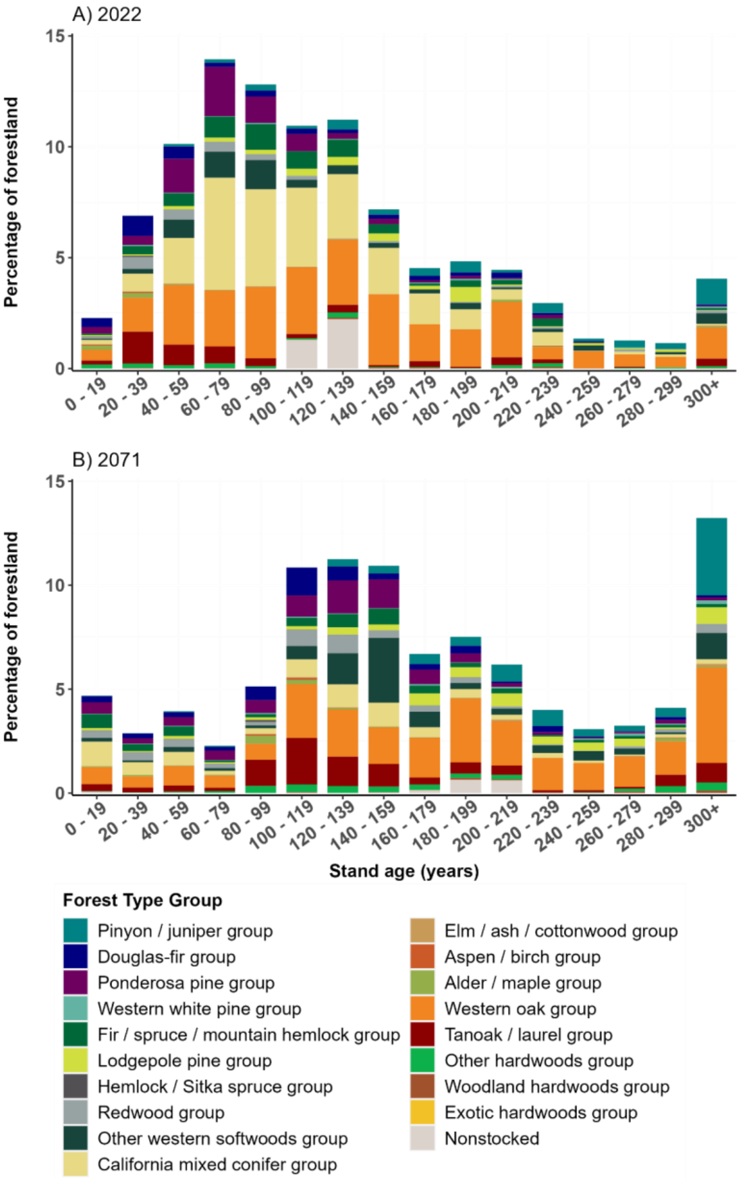


Figure 9. CBAU scenario age class distribution by forest type group in A) 2022 and B) 2071. Percentages calculated excluding post-fire regeneration failure.

This trend occurs as forests under CBAU accumulate large areas of post-fire regeneration failure, amounting to roughly 40% of today's forest landscape (12.7 million acres) by 2071. This does not include the 1.5 million acres (roughly 5% of current forest area) of public land already identified as failing to regenerate post-fire between 2000-2021 (USDA Forest Service 2024a). Not counting these areas of post-fire regeneration failure (which have a stand age of zero because they have not regenerated), only 4.7% of the landscape is in the youngest age class (0-19 years old) in 2071 (**Figure 9**). This reflects a relative lack of age class diversity across the state, limiting wildlife habitat for young-forest dependent species, compromising resilience to future climate conditions, and limiting the carbon sequestration capabilities of forests (Shifley and Thompson 2011; USDA Forest Service 2023b; Vangi et al. 2024). The severe declines in forest area and the small amount of young forest remaining by 2071 underscore the importance of addressing wildfire and post-fire regeneration challenges to minimize carbon emissions and losses.

Climate Change Impacts by Ownership Class

Results from the CBAU scenario vary greatly by ownership, mainly due to the relative number of acres in each ownership category and the influence of increasing wildfire and natural regeneration failure on those acres. Across the state, USFS is the largest forest owner, with 14.8 million acres of forestland (47% of the statewide total) in the National Forest System in 2022. Private and Native American lands make up the next largest category, with ownership of 12.5 million acres (40% of the forest landscape). The remainder of California forests are owned and managed by other federal agencies (2.9 million acres, 9% of the total) and by state/local entities (1.1 million acres, 3% of forestland).

Forests owned and managed by USFS (within the National Forest System) are projected to be most vulnerable to and affected by future climate conditions and natural disturbances, losing 69% of their area from 2022-2071 (decreasing from 14.8 to 4.5 million acres) and 74% of their carbon stocks (decreasing from 4.5 to 1.2 GtCO$_2$e) over the same period (**Figure 10**). USFS lands are also projected to accumulate 9 million acres of failed post-fire regeneration by 2071, which is twice the area of surviving forest in the same year. This drives net carbon emissions on USFS lands to be 63% higher than under

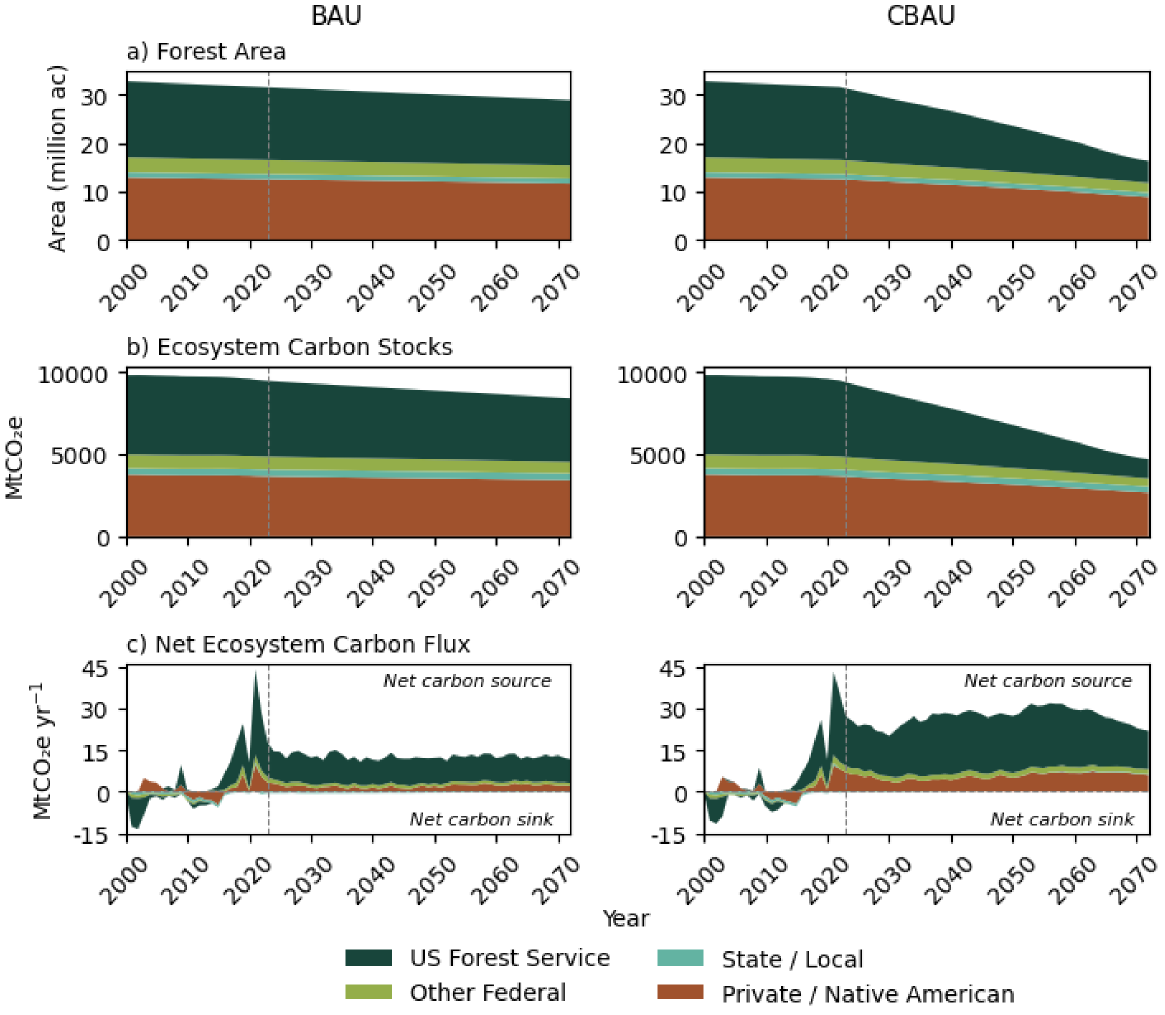


Figure 10. BAU and CBAU scenario results showing a) total forest area (million acres), b) ecosystem carbon stocks (MtCO$_2$e), and c) annual net ecosystem carbon flux (MtCO$_2$e yr^{-1}) by ownership class from 2000-2071. Net ecosystem carbon flux refers to the net yearly sequestration of carbon by forests 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.

BAU in 2071. Overall, USFS lands make up roughly 70% of the total forest area and carbon stocks lost under the CBAU scenario, and about 51% of the change in net ecosystem carbon flux.

Private and Native American lands also experience significant impacts under the CBAU scenario: -29% forest area (decreasing from 12.5 to 8.8 million acres) and -27% carbon stocks (decreasing from 3.6 to 2.7 $GtCO_2e$) from 2022-2071 (**Figure 10**) with 2.8 million acres of post-fire regeneration failure and 192% higher net emissions in 2071. Though this change is seemingly high percentage wise, emissions from private and Native American forests are still less than half of those from USFS lands in 2071 (**Figure 10**). Declines in productivity and consistently higher emissions from natural disturbances drive this trend. Private and Native American lands account for 23% of overall CBAU losses of forest area and carbon stocks, and 37% of increased net ecosystem carbon flux from the scenario.

State/local and other federally managed forests see smaller, though still negative, changes through the CBAU simulation. From 2022-2071, state/local forests lose 13% of their area (decreasing from 1.1 to 0.9 million acres), 9% of their carbon stocks (decreasing from 0.4 to 0.37 $GtCO_2e$; **Figure 10**), and arrive in 2071 with just 0.1 million acres of post-fire regeneration failure but net carbon emissions that are 221% higher than BAU. Here, the seemingly high percentage change in net emissions is affected by a small denominator: state forestlands make up a relatively small portion of the total forest area in California, and though they do shift from carbon sink to carbon source under CBAU, the magnitude of the change is only about 0.53 $MtCO_2e$ per year (5% of the total change in CBAU net emissions). State/local forests contribute just 1% to forest area and carbon stock losses under CBAU. Other federal forests experience losses of 30% of forest area (decreasing from 2.9 to 2 million acres) and 36% of carbon stocks (decreasing from 0.8 to 0.5 $GtCO_2e$) from 2022-2071 (**Figure 10**), with 0.7 million acres of forest failing to regenerate post-fire and 72% higher net carbon emissions than BAU in 2071. This equates to about 6% of overall losses of forest area and carbon stocks and 7% of the net ecosystem carbon flux increase in the CBAU scenario.

Climate Change Impacts by Ecoregion

CBAU results also vary by ecoregion (see **Figure 3** for reference map), with the Sierra/Cascades and Klamath/Interior Coast Ranges projected to experience the greatest changes in forest area, carbon stocks, and net ecosystem carbon flux (**Figure 11**). These two ecoregions experienced the highest amounts of high-severity wildfire during our BAU period (a collective average of 120,712 ac yr^{-1} from 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. The Sierra/Cascades ecoregion loses 56% of its forest area (decreasing from 14.8 to 6.5 million acres) and 64% of its carbon stocks (decreasing from 4 to 1.5 $GtCO_2e$) from 2022-2071 under CBAU (**Figure 11**), accumulating 7.5 million acres of land that have failed to regenerate post-fire and leading to a net ecosystem carbon flux 84% higher than BAU at the end of the scenario. In addition to the wildfire and regeneration failure impacts, the forest types in this ecoregion are largely projected to experience higher than average productivity declines (28.7% for the Sierra/Cascades vs 27.7% on average), further contributing to these climate change impacts. California mixed conifer forests in the Sierra/Cascades exhibit the largest losses of forest area (a loss of 84%, 3.8 million acres) and carbon stocks (a loss of 90%, or 1.3 $GtCO_2e$) from 2022-2071. Ponderosa pine also loses substantial forest area (47%, or 0.8 million acres) and carbon stocks (57%, or 0.2 $GtCO_2e$) in this ecoregion. The redwood forest type group (representing giant sequoia) in the Sierra/Cascades experiences minor decreases in forest area (a loss of 3%, or 128 acres) and carbon stocks (a loss of 1%, or 0.00003 $GtCO_2e$). Overall, this ecoregion accounts for roughly 55% of the total forest area and carbon stocks lost under the CBAU scenario, and about 62% of the change in net ecosystem carbon flux.

The Klamath/Interior Coast Ranges ecoregion also experiences strong climate change impacts under the CBAU scenario, losing 68% of forest area (decreasing from 8 to 2.6 million acres) and 66% of carbon stocks (decreasing from 2.7 to 0.9 $GtCO_2e$) from 2022-2071 (**Figure 11**), with 4.2 million acres of post-fire regeneration failure and 54% higher net emissions by 2071. Forest types in the Klamath/Interior Coast Ranges experience slightly lower than average productivity declines under future climate conditions (26.9% vs 27.7%), minorly tempering these projected climate change impacts. California mixed conifer and Western oak forests (which represent oak woodlands) in this ecoregion both exhibit large losses of forest area, totaling up to a loss of 70% (2.1 million acres) of Western oak and 89% (2.3 million acres) of California mixed conifer throughout the model period. Both forest types also lose substantial carbon stocks (70%, or 0.5 $GtCO_2e$, from Western oak and 94%, or 0.9 $GtCO_2e$, from California mixed conifer) in the Klamath/Interior Coast Ranges. Douglas-fir in this ecoregion loses 51%

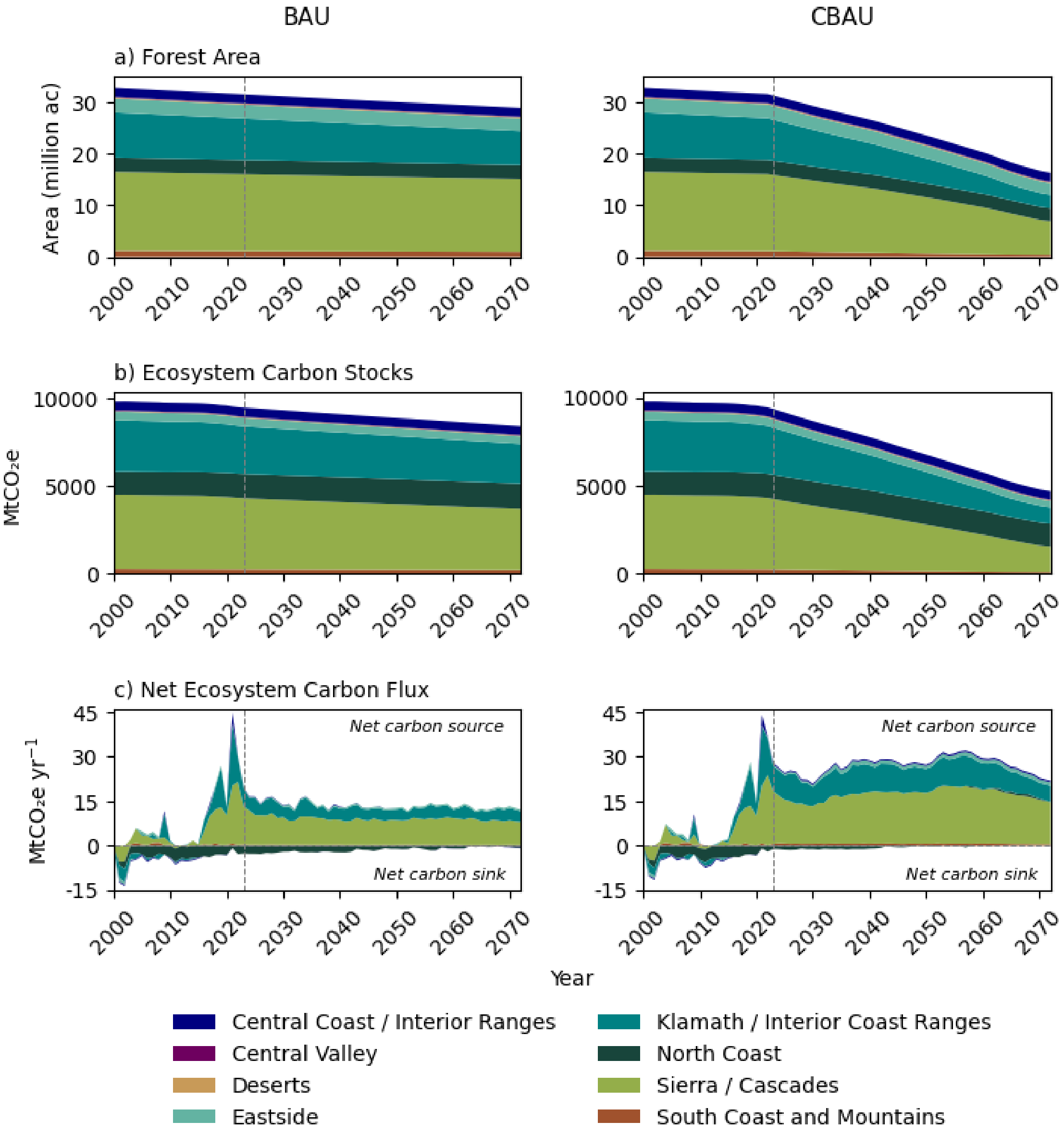


Figure 11. BAU and CBAU scenario results showing a) total forest area (million acres), b) ecosystem carbon stocks ($MtCO_2e$), and c) annual net ecosystem carbon flux ($MtCO_2e\ yr^{-1}$) by ecoregion from 2000-2071. Net ecosystem carbon flux refers to the net yearly sequestration of carbon by forests 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.

(0.3 million acres) of forest area and 55% (0.2 $GtCO_2e$) of carbon stocks from 2022-2071. The Klamath/Interior Coast Ranges make up 36% of overall CBAU losses of forest area, 38% of losses in carbon stocks, and 18% of increased net ecosystem carbon flux from the scenario.

The six other ecoregions in our model experience moderate impacts under the CBAU scenario, and of these, the South Coast and Mountains ecoregion exhibits the largest changes. In this ecoregion, forest area declines by 62% (decreasing from 1.1 to 0.4 million acres) and carbon stocks decline by 66% (decreasing from 0.2 to 0.08 $GtCO_2e$) from 2022-2071 (**Figure 11**), with 0.6 million acres of land in a state of post-fire regeneration failure and 72% higher net ecosystem carbon fluxes by 2071. Forests in this ecoregion also experience higher than average productivity declines (28.7% vs 27.7%) under CBAU, and Western oak exhibits the largest losses of forest area (89%, or 0.4 million acres) and carbon stocks (90%, or 0.1 $GtCO_2e$) from 2022-2071. The South Coast and Mountains contribute just 5% to forest area losses, 3% to carbon stock losses, and 2% to net ecosystem carbon flux increases under CBAU.

For the remaining five ecoregions, forest losses range from 0% (a consistent 0.1 million acres in the Central Valley) to 14% (decreasing from 2.7 to 2.3 million acres in the Eastside ecoregion) and carbon stock losses range from 0.2% (decreasing from 0.041 to 0.0409 $GtCO_2e$ in the Deserts ecoregion) to 21% (decreasing from 0.5 to 0.4 $GtCO_2e$ on the Eastside) from 2022-2071 under CBAU (**Figure 11**). Post-fire regeneration failure ranges from zero acres in the Deserts, Central Valley, and Central Coast/Interior Ranges ecoregions to 0.2 million acres on the Eastside. Note that a result of zero acres does not mean that forests in these ecoregions will not fail to regenerate after wildfire – rather, based on historic rates of high-severity fire and available projections of future post-fire regeneration failure (Davis et al. 2023b), our model includes minimal amounts of high-severity burns and subsequent regeneration failure in these ecoregions from 2022-2071. Net ecosystem carbon fluxes range from no change in the Deserts and Central Valley to 100% higher than BAU in the Eastside ecoregion by 2071. Forests in the Central Coast/Interior Ranges, Central Valley, and North Coast experience lower than average productivity declines (the lowest of which, a 22.6% decline, is in North Coast), while the Deserts and Eastside ecoregions see higher than average declines in productivity (up to 31.2% in the Deserts). Western oak forests consistently lose the most forest area and carbon from these ecoregions, ranging from a 2.7% loss of both (2,231 acres and 0.001 $GtCO_2e$) in the Central Valley to a 29% loss (94,191 acres and 0.03 $GtCO_2e$) on the North Coast. Redwoods in the North Coast ecoregion gain a small amount of forest area (0.6%, or 3,535 acres) and lose a small amount of carbon stocks (1.5%, or 0.1 $GtCO_2e$) from 2022-2071, while redwoods in the Central Coast/Interior Ranges ecoregion lose small amounts of both forest area (3%, or 3,880 acres) and carbon stocks (7%, or 0.01 $GtCO_2e$). Eastside pinyon/juniper forests lose just 9% (56,196 acres) of forest area and 13% (0.01 $GtCO_2e$) of carbon stocks over the model period. Collectively, these five ecoregions account for only 4% of losses in forest area and carbon stocks under the CBAU scenario and make up 18% of overall increases to net carbon emissions.

See **Appendix** for tables comparing forest area, ecosystem carbon stocks, and net ecosystem carbon flux by ownership and ecoregion for the BAU and CBAU scenarios.

Effects of Alternative Management Scenarios

Net Carbon Balance in Forests and the Forest Products Sector

From a systems perspective, California forests and forest products collectively remain a net carbon source from 2022-2071 under all scenarios modeled in this analysis, indicated by a net carbon balance greater than zero (**Figure 12**). *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 CO_2 sequestered from the atmosphere and captured as carbon in forests and wood products (a net carbon sink or a gain to the forest sector) and positive values indicate CO_2 emitted to the atmosphere from forests and wood products (a net carbon source or emissions from the forest sector).

Despite this systems-level trajectory, various scenarios illustrate the potential to slow or reverse the influences of future climate on forest ecosystems and to deploy innovative wood utilization to further improve future carbon trends. In combination, represented by our *portfolios* of concurrent management actions and wood utilization, these practices offer substantial progress toward climate-smart forestry objectives – balancing carbon sequestration and storage while improving the stability and resilience of forests in the state.

This is best represented by the Max Natural Climate Solutions Action by 2045 (Max NCS) portfolio, which includes the Expand Fire Resilience to Mature and Old-Growth Forests (MOG Resilience), Landscape Restoration, Extended Rotations, Forest Conservation, and Silvopasture scenarios. Without including the innovative wood product trifecta, this portfolio achieves a net carbon balance that is, on average, 55% higher than CBAU (equating to higher net emissions; 32.2 vs 20.7 $MtCO_2e\ yr^{-1}$) during the fire resilience treatment phase (2022-2031), 2% lower than CBAU (meaning lower net emissions; 25.4 vs 26 $MtCO_2e\ yr^{-1}$) post-treatment from 2032-2045, and 13% lower (24.1 vs 27.7 $MtCO_2e\ yr^{-1}$)

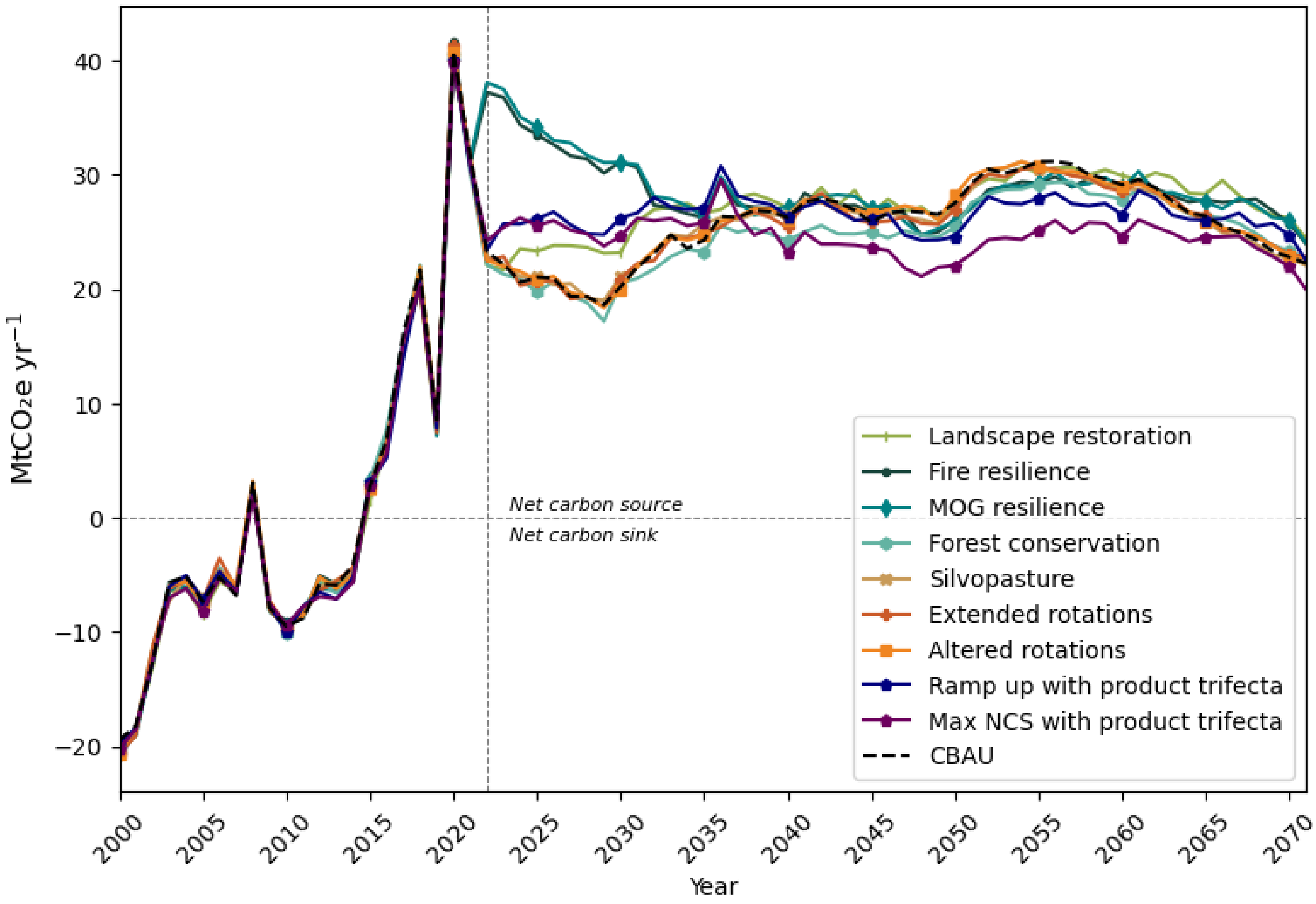


Figure 12. Annual net carbon balance for selected scenarios, 2000-2071. Net carbon balance includes net ecosystem flux in the forest, transfers to HWP, emissions from wood products in use and in landfills, substitution benefits in years where harvest is different than CBAU, and leakage in years where harvest is less than CBAU. Negative values denote carbon sequestration (a net carbon sink). Positive values denote carbon emissions (a net carbon source).

Table 5. Average annual net carbon balance for modeled scenarios during three model phases. Net carbon balance includes net ecosystem 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 for net carbon balance represent a net carbon sink and positive values represent a net carbon source. Negative values for % change from CBAU indicate lower emissions than CBAU, while positive values represent higher emissions than CBAU.

	Scenario	Average net carbon balance (MtCO$_2$e yr^{-1})						Cumulative net carbon balance (MtCO$_2$e)	
		Treatment phase (2022-2031)	% change from CBAU	Post-treatment (2032-2045)	% change from CBAU	Maintenance phase (2046-2071)	% change from CBAU	2022-2071	% change from CBAU
	CBAU	20.7	-	26.0	-	27.7	-	1,299.6	-
Forest management scenarios (run on CBAU)	Landscape restoration	23.4	13%	27.5	6%	28.6	3%	1,360.2	5%
	Fire resilience	32.9	59%	27.3	5%	5	0%	1,435.5	10%
	MOG resilience	33.5	62%	27.6	6%	27.7	0%	1,444.6	11%
	Forest conservation	20.2	-3%	24.4	-6%	26.7	-4%	1,244.3	-4%
	Silvopasture	20.9	1%	26.2	1%	27.3	-1%	1,288.8	-1%
	Extended rotations	20.7	0%	25.8	-1%	27.4	-1%	1,284.8	-1%
	Altered rotations	20.7	0%	26.1	0%	27.7	0%	1,299.1	0%
Innovative wood utilization scenarios	Fire resilience + Biochar	30.5	47%	27.3	5%	27.7	0%	1,411.9	9%
	Fire resilience + Transportation fuels	31.4	51%	27.3	5%	27.7	0%	1,420.3	9%
	Fire resilience + Mass timber	28.1	35%	27.2	5%	27.6	0%	1,382.4	6%
	MOG Resilience + Biochar	30.8	49%	27.6	6%	27.7	0%	1,418.1	9%
	MOG Resilience + Transportation fuels	31.8	53%	27.6	6%	27.7	0%	1,427.5	10%
	MOG Resilience + Mass timber	28.3	36%	27.6	6%	27.6	0%	1,387.7	7%
Portfolios (combined scenarios)	Ramp up	33.5	61%	27.8	7%	27.0	-2%	1,425.7	10%
	Ramp up + Innovative wood utilization	25.6	23%	27.4	5%	26.4	-5%	1,324.5	2%
	Max NCS	32.2	55%	25.4	-2%	24.1	-13%	1,302.3	0%
	Max NCS + Innovative wood utilization	25.2	22%	25.2	-3%	23.9	-14%	1,223.7	-6%

during the maintenance phase (2046-2071; **Table 5**). Higher emissions are expected during the treatment phase, since this portfolio includes thinning, prescribed fire, and reforestation treatments on an additional 10.4 million acres not treated in the CBAU scenario. However, net carbon balance drops quickly after treatments have been completed and the Max NCS portfolio yields fewer emissions than CBAU for the remainder of the projection period, indicating that treatments have helped recover forest carbon sequestration capacity. At the same time, forest area and carbon stocks losses are decreased substantially (see further discussion in the **Ecosystem Carbon Trends** section below), suggesting that the resilience goals of the portfolio have been achieved. These dynamics during the post-treatment period from 2032-2045 are of particular significance for California's goal of achieving net zero by 2045.

This outlook improves further when the Max NCS portfolio is paired with Innovative Wood Utilization, which calls for removing the cut material from resilience treatments and using it to produce biochar, transportation fuels, and mass timber rather than leaving it to decompose or burning it on site. This combination results in a net carbon balance that averages 22% higher than CBAU (25.2 vs 20.7 $MtCO_2e$ yr^{-1}) during the treatment phase, 3% lower than CBAU (25.2 vs 26 $MtCO_2e$ yr^{-1}) post-treatment, and 14% lower than CBAU (23.9 vs 27.7 $MtCO_2e$ yr^{-1}) during the maintenance phase (**Figure 12; Table 5**). Including the innovative product trifecta reduces the net carbon balance of the Max NCS portfolio during the treatment phase, avoiding the emissions of 70.2 $MtCO_2e$ (nearly 3 years' worth of net emissions from the forest sector) over this period.

The Ramp Up Implementation (Ramp Up) portfolio, which includes the MOG Resilience and Landscape Restoration scenarios, has a similar net carbon balance to the Max NCS portfolio. During the treatment phase, this portfolio has a net carbon balance that averages 61% higher than CBAU (33.5 vs 20.7 $MtCO_2e$ yr^{-1}) without the innovative product trifecta and 23% higher than CBAU (25.6 vs 20.7 $MtCO_2e$ yr^{-1}) when innovative wood utilization is included (**Figure 12; Table 5**). The average post-treatment net carbon balance is 7% higher for the Ramp Up portfolio compared to CBAU (27.8 vs 26 $MtCO_2e$ yr^{-1}) without innovative wood utilization, and 5% higher than CBAU (27.4 vs 26 $MtCO_2e$ yr^{-1}) with the innovative product trifecta (**Table 5**). Over the maintenance period, average net carbon balance is 2% lower than CBAU (27 vs 27.7 $MtCO_2e$ yr^{-1}) without the product trifecta and 5% lower than CBAU (26.4 vs 27.7 $MtCO_2e$ yr^{-1}) when the product trifecta is included (**Table 5**). Again, innovative wood utilization helps avoid emissions from the Ramp Up portfolio totaling 78.8 $MtCO_2e$, more than 2 years of net forest sector emissions during the treatment phase.

To better compare these portfolios with CBAU, we can assess net carbon balance in *cumulative standardized* terms, where CBAU values are subtracted from each portfolio or scenario (essentially setting CBAU to 0) and net carbon balance values are summed over the 50-year projection period to quantify the cumulative carbon sequestered or emitted for each portfolio relative to CBAU. This allows for a more direct comparison of the relative impacts of each alternative management practice on projected future carbon trends (**Figure 13**). We can also disaggregate this cumulative standardized net carbon balance into its component parts to illustrate the influence of each one on overall net carbon balance values (**Figure 14**).

Considered from this cumulative standardized perspective, the Max NCS portfolio accumulates higher emissions than CBAU during the initial treatment period, peaking in 2037 at 116 $MtCO_2e$ and decreasing steadily to 2.7 $MtCO_2e$ at the end of the model period (**Figure 14**). The Max NCS + Innovative Wood Utilization portfolio performs notably better, reaching a maximum of 44 $MtCO_2e$ in 2037, equalizing with CBAU cumulative net carbon balance (crossing zero in **Figure 13**) in 2050, and dropping to -76 $MtCO_2e$ in 2071 (**Figure 13**). This final cumulative value indicates that over the 50-year model period, this portfolio captures an additional 76 $MtCO_2e$ (leading to 6% lower emissions) compared with CBAU while also delivering on other CSF objectives to be discussed below. Without innovative wood utilization, the Max NCS portfolio has a higher net carbon balance than CBAU for the entire model period, driven by relatively large emissions during the treatment period when CBAU net carbon balance dips temporarily (**Figure 12**). The differential between Max NCS and CBAU during this period is more than future forest growth can overcome, affected as it is by declining productivity, leading a cumulative standardized net carbon balance greater than zero for the Max NCS portfolio in 2071. Innovative wood utilization can substantially decrease emissions during the treatment period, making the Max NCS portfolio with the product trifecta the only portfolio or scenario modeled to result in reduced cumulative emissions relative to CBAU by the end of the model period.

The impact of innovative wood utilization is clear when the net carbon balance components are disaggregated – the Max NCS portfolio with the innovative product trifecta provides larger product substitution benefits across all model periods (a larger green bar in **Figure 14**; -103.3 $MtCO_2e$ for Max NCS + Innovative Wood Utilization vs -39.6 $MtCO_2e$ for Max NCS without innovative wood utilization in 2071), most of which come from additional mass timber and transportation fuels substituting for more emissions-intensive building materials and fuel sources, respectively. This portfolio also incurs lower HWP emissions (a smaller orange bar in **Figure 14**; 84.8 vs 100 $MtCO_2e$ in 2071) from using additional residues for biochar, which has a much longer half-life than alternative uses like bioenergy, and using additional merchantable material for mass timber, which has a longer half-life than lumber (**Table 3**). The specific tradeoffs between these innovative wood products will be further discussed in the **Wood Products Carbon Dynamics** section below.

The Ramp Up portfolio exhibits similar differences with and without innovative wood utilization, though with a higher cumulative net carbon balance (more net emissions) than the Max NCS portfolios

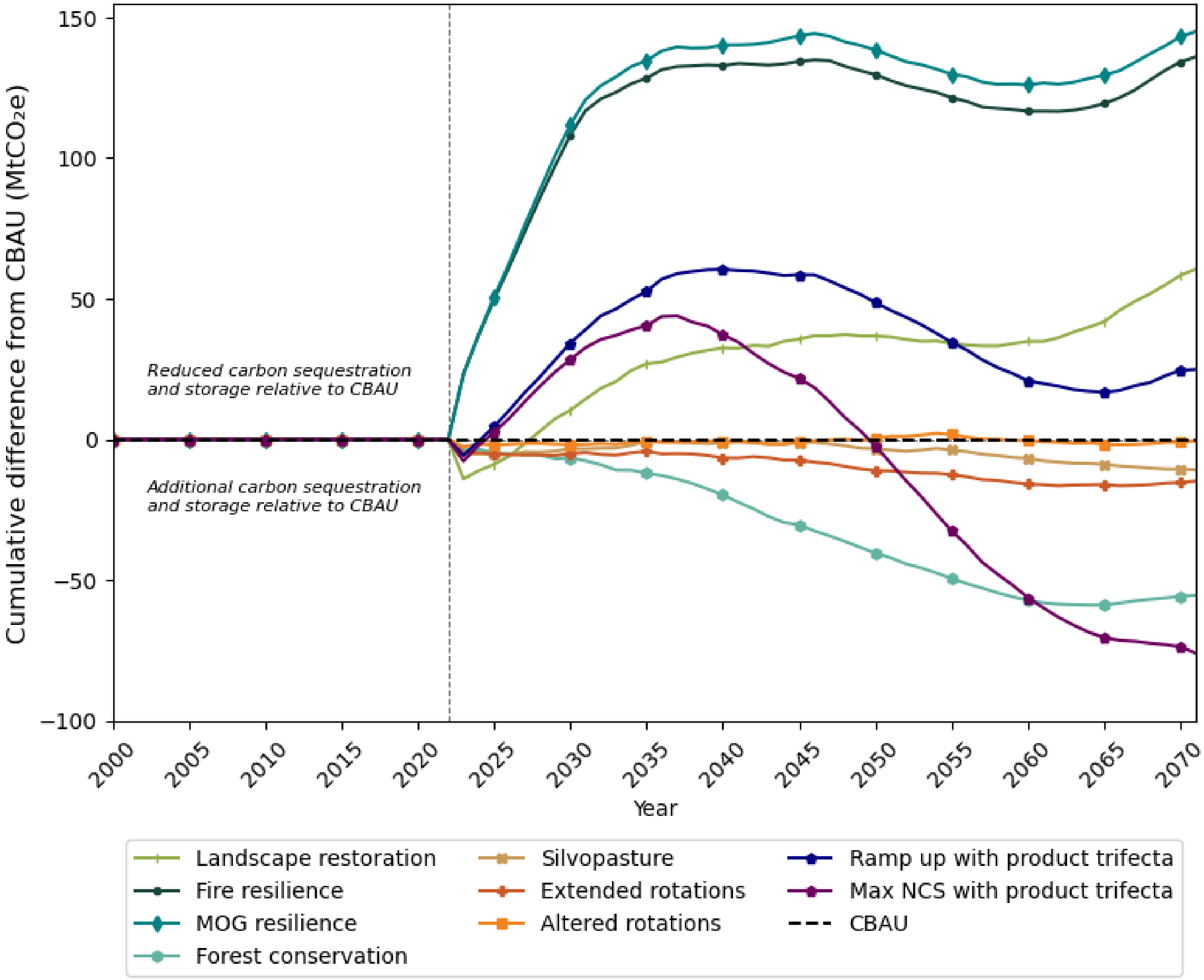


Figure 13. Cumulative standardized net carbon balance for selected scenarios, 2000-2071. Net carbon balance includes net ecosystem flux in the forest, transfers to HWP, emissions from wood products in use and in landfills, substitution benefits in years where harvest is different than CBAU, and leakage in years where harvest is less than CBAU. Negative values denote additional carbon sequestration and storage relative to CBAU. Positive values denote reduced carbon sequestration and storage relative to CBAU.

Figure 14. Snapshot of cumulative standardized net carbon balance (MtCO$_2$e) and component parts for all scenarios at the end of the treatment period (2031), end of the post-treatment period and target year for California's net-zero targets (2045), and end of the model period (2071). Scenarios are listed from left to right in descending order of net carbon balance in 2071 (from higher emissions to lower emissions). Net carbon balance includes net ecosystem 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 additional carbon sequestration and storage relative to CBAU. Positive values denote reduced carbon sequestration and storage relative to CBAU.

in both cases. By itself, the Ramp Up portfolio accumulates less carbon than CBAU until 2040, reaching a cumulative maximum at 144.9 MtCO$_2$e in that year (data not shown). This maximum is more than halved (60.4 MtCO$_2$e) when the innovative product trifecta is included (**Figure 13**). From 2040 into the 2060s, the Ramp Up portfolio has a lower annual net carbon balance than CBAU (**Figure 12**), so the cumulative net carbon balance drops over this period to a minimum of 111.6 MtCO$_2$e in 2063 for the Ramp Up alone and 16.8 MtCO$_2$e in 2065 for the Ramp Up + Innovative Wood Utilization portfolio (**Figure 13**). After this point until the end of the model period in 2071, the cumulative net carbon balance for both Ramp Up portfolios increases again, indicating higher emissions than CBAU during this period. This is mostly due to the decrease in wildfire emissions during the last 10 years of the CBAU scenario, as discussed in the **Influence of Future Climate** section. The Ramp Up portfolio includes practices that help restore millions of acres of forest so they survive the amplifying future wildfires included in the CBAU scenario, meaning those acres are still forested (and therefore able to be targeted by wildfire events in our model) from 2060-2071. In the CBAU scenario, these forests no longer exist and therefore cannot be burned in our model, allowing CBAU net carbon balance to drop during this period. Therefore, rather than the Ramp Up scenario resulting in additional emissions at the end of our simulation (annual net carbon balance actually decreases slightly during the last decade of the model), this increase in cumulative standardized net carbon balance is due to the drop in CBAU emissions.

The influence of innovative wood utilization exerts a similar influence on the Ramp Up scenario via greater cumulative product substitution benefits (-103.3 vs -54.5 $MtCO_2e$) and fewer HWP emissions (144.6 vs 162.2 $MtCO_2e$) by 2071 from the innovative product trifecta (**Figure 14**).

The difference between the Ramp Up and Max NCS portfolios highlights the contributions of the Extended Rotations, Forest Conservation, and Silvopasture scenarios, since they are included in the Max NCS portfolio but not the Ramp Up portfolio. Together, these scenarios help reduce net emissions by an additional -123.4 to -100.8 $MtCO_2e$ compared to CBAU (the difference between the Max NCS and Ramp Up portfolios), depending on whether innovative wood utilization is or is not included, respectively (**Figure 14**). This is a stronger impact than the sum of each scenario's individual cumulative standardized net carbon balance (a total of -80.9 $MtCO_2e$ by 2071), indicating that implementing these practices concurrently across the landscape in addition to fire resilience and post-fire restoration provides more climate mitigation benefits than taking these actions in isolation.

By themselves, these scenarios have a modest impact on emissions from California's forests and forest sector, in part owing to a smaller scale of implementation than the resilience and restoration treatments (**Figure 15**). They can, however, also help defray the early emissions from those resilience and restoration treatments embodied by the Ramp Up portfolio that occur during the treatment phase. Under the Forest Conservation scenario, the net carbon balance averages 3% lower than CBAU (20.2 vs 20.7 $MtCO_2e\ yr^{-1}$) from 2022-2031, 6% lower than CBAU (24.4 vs 26 $MtCO_2e\ yr^{-1}$) from 2032-2045, and 4% lower than CBAU (26.7 vs 27.7 $MtCO_2e\ yr^{-1}$) from 2046-2071 (**Figure 12; Table 5**). The Silvopasture scenario yields an average net carbon balance 1% higher than CBAU (20.9 vs 20.7 $MtCO_2e\ yr^{-1}$) from 2022-2031, 1% higher than CBAU (26.2 vs 26 $MtCO_2e\ yr^{-1}$) from 2032-2045, and 1% lower than CBAU (27.3 vs 27.7 $MtCO_2e\ yr^{-1}$) from 2046-2071 (**Figure 12; Table 5**).

Both scenarios focus on land use and land cover but affect a different number of acres (870 thousand acres of forest conservation vs 219 thousand acres of silvopasture; **Table 4**), which explains the difference in their scale of impact. They also address different aspects of land use and land cover concerns: the Forest Conservation scenario requires a decrease in the rate of permanent forest conversion from land-use change, which inherently conserves existing forests and carbon stocks. From these actions, the scenario incurs additional emissions relative to CBAU due to lower HWP transfers and associated leakage (69.6 and 52.4 $MtCO_2e$, respectively, by 2071; **Figure 14**). However, the additional carbon sequestered and stored in the forest (-137.8 $MtCO_2e$ by 2071) and decreased HWP emissions from less bioenergy and landfill disposal (-41.5 $MtCO_2e$ by 2071) outweigh these additional emissions, helping the Forest Conservation scenario reduce emissions by -55.3 $MtCO_2e$ relative to CBAU by 2071 (**Figure 14**). By contrast, the Silvopasture scenario focuses on integrating trees at low density into pasturelands where ecologically appropriate, so carbon accumulates more slowly in the scenario as trees grow from seedlings. Even with this slower rate of carbon accumulation, the Silvopasture scenario does yield a cumulative net carbon balance of -10.8 $MtCO_2e$ lower (i.e. 10.8 $MtCO_2e$ more sequestered and stored in the forest ecosystem) than CBAU in 2071 (**Figure 14**).

Changing harvest rotations also results in modest changes to CBAU carbon trajectories. The Extended Rotations scenario (which increases minimum harvest age from 50 to 80 years for all forest owners) provides a net carbon balance that averages the same as CBAU (20.7 $MtCO_2e\ yr^{-1}$) from 2022-2031, 1% lower than CBAU (25.8 vs 26 $MtCO_2e\ yr^{-1}$) from 2032-2045, and 1% lower than CBAU (27.4 vs 27.7 $MtCO_2e\ yr^{-1}$) from 2046-2071 (**Figure 12**). Under the Altered Rotations scenario, which increases minimum harvest age from 50 to 80 years on private lands and decreases harvest age from 50 to 40 on private lands, the net carbon balance averages the same as CBAU (20.7 MtCO$_2$e yr^{-1}) from 2022-2031, <1% higher than CBAU (26.1 vs 26 MtCO$_2$e yr^{-1}) from 2032-2045, and the same as CBAU (27.7 MtCO$_2$e yr^{-1}) from 2046-2071 (**Figure 12**), leading to a cumulative net carbon balance of -0.5 MtCO$_2$e relative to CBAU by 2071 (**Figure 13**). The Extended Rotations scenario behaves largely as expected, accumulating additional carbon in the forest ecosystem and reducing HWP emissions (-37.9 and -15.5 MtCO$_2$e, respectively) but increasing leakage and product substitution (12 and 0.3 MtCO$_2$e, respectively) emissions by reducing harvest and associated HWP transfers by 26.2 MtCO$_2$e in total by 2071 (**Figure 14**). Overall, this scenario reduces emissions by -14.8 MtCO$_2$e (1%) compared with CBAU by 2071 (**Figure 13**). The Altered Rotations scenario has very little impact on net carbon balance, with cumulative emissions from growth, harvest, substitution, and leakage in 2071 changing less than ±4 MtCO$_2$e relative to CBAU (**Figure 13**). One interpretation of this result is that emissions reductions from extending rotations on public lands offset additional emissions from more frequent harvest on private lands, which some landowners are considering because of higher wildfire risks to timber. While this scenario doesn't lead to higher emissions than CBAU, it also does little to reduce CBAU emissions.

Much larger landscape impacts occur in the MOG Resilience and Landscape Restoration scenarios, which have already been discussed in tandem as part of the Ramp Up portfolio. These scenarios have by far the largest footprint of the scenarios we modeled, with 8.5 million total acres treated for fire resilience under the MOG Resilience scenario and 7.7 million total post-fire acres reforested in the Landscape Restoration scenario (**Figure 15**). Under the MOG Resilience scenario, net carbon balance averages 62% higher than CBAU (33.5 vs 20.7 MtCO$_2$e yr^{-1}) during the treatment period from 2022-2031, 6% higher than CBAU (27.6 vs 26 MtCO$_2$e yr^{-1}) post-treatment from 2032-2045, and the same as CBAU (27.7 MtCO$_2$e yr^{-1}) during the maintenance phase from 2046-2071 (**Figure 12; Table 5**). The Fire Resilience scenario, which includes the same treatments as the MOG Resilience scenario but uses CBAU age restrictions that disqualify MOG forests from resilience treatments, has a similar net carbon

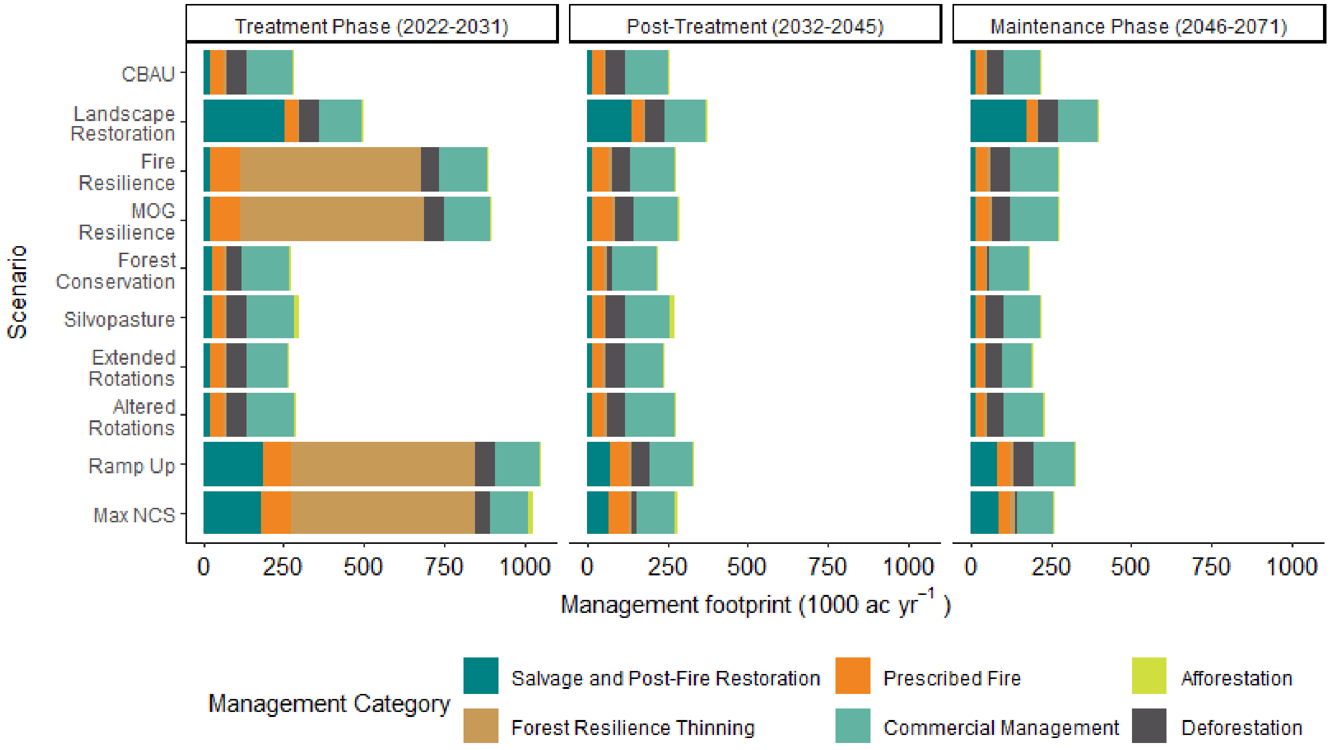


Figure 15. Actual management footprint results (accomplishments, not targets) by management category for modeling scenarios during three model phases.

balance throughout the model period: 59% higher than CBAU (32.9 vs 20.7 $MtCO_2e$ yr^{-1}) during the treatment period from 2022-2031, 5% higher than CBAU (27.3 vs 26 $MtCO_2e$ yr^{-1}) post-treatment from 2032-2045, and the same as CBAU (27.7 $MtCO_2e$ yr^{-1}) during the maintenance phase from 2046-2071 (**Figure 12; Table 5**). Both scenarios have a higher cumulative net carbon balance (meaning higher cumulative emissions) than CBAU by 2071 (145 $MtCO_2e$ for MOG Resilience and 136 $MtCO_2e$ for Fire Resilience), the highest of any individual scenarios (**Figure 13).**

This dynamic is expected, given the millions of acres of additional thinning and prescribed fire treatments modeled to reduce future wildfire severity. Net carbon balance is higher for the MOG Resilience scenario because the expanded treatment eligibility allows more treatments to occur as scheduled, averaging 84% completion of target acres during the treatment period compared with 80% for the Fire Resilience scenario (data not shown). The higher emissions from these scenarios trade off against better forest area and carbon stocks trends (discussed in the **Ecosystem Carbon Trends** section below). Innovative wood utilization can again help improve this carbon trajectory, reducing cumulative net emissions by variable rates depending on which product is created from the additional removed biomass. Unlike the portfolios, the MOG Resilience and Fire Resilience scenarios were run with each innovative product individually to better demonstrate the effects of individual changes to innovative wood utilization pathways. Results for these products are discussed in the **Wood Products Carbon Dynamics** section below.

The Landscape Restoration scenario yields an average net carbon balance 13% higher (meaning higher emissions) than CBAU (23.4 vs 20.7 $MtCO_2e$ yr^{-1}) during the treatment period from 2022-2031, 6% higher than CBAU (27.5 vs 26 $MtCO_2e$ yr^{-1}) post-treatment from 2032-2045, and 3% higher than CBAU (28.6 vs 27.7 $MtCO_2e$ yr^{-1}) during the maintenance phase from 2046-2071 (**Figure 12**), leading to a cumulative net carbon balance 60.5 $MtCO_2e$ higher than CBAU by 2071 (**Figure 13**). This is also not unexpected, as this scenario includes additional salvage of commercially viable timber and site preparation techniques to prepare the landscape for safe planting efforts and reduce future fuel hazards in post-burn areas before reforestation. Combined with MOG Resilience values, these two scenarios sum to 205.5 $MtCO_2e$ higher emissions than CBAU in 2071 – a value that is much higher than the final cumulative net carbon balance for the Ramp Up portfolio (126 $MtCO_2e$; **Figure 14**).

The difference between the cumulative emissions from these two scenarios performed in isolation from each other versus in tandem with each other points to the interactions between these scenarios that amplify their positive benefits. The resilience treatments implemented in the MOG Resilience scenario help to reduce wildfire severity, moving from 349,373 ac yr^{-1} of high-severity wildfire under CBAU to 143,220 ac yr^{-1} in the MOG Resilience scenario. This result depends in part on our assumption that MOG Resilience treatments are effective at reducing high and moderate severity by one class on 90% of treated acres (a conservative assumption given science that shows higher rates of treatment effectiveness; Davis et al. 2024). This management-driven reduction in high-severity wildfire essentially cancels out the climate-driven increase in high-severity wildfire used to create the CBAU scenario (216,010 ac yr^{-1}; **Table 2**). Post-fire regeneration failure is driven by high-severity wildfire, so fewer acres of high-severity fire lead to fewer acres of regeneration failure and fewer acres needing the salvage and reforestation treatments of the Landscape Resilience scenario. Though not directly modeled here, these reforestation treatments can also be designed with climate-adapted species in variable and low-density stand structures (Meyer et al. 2021; North et al. 2019) to help make future forests more resilient to wildfire, potentially further reducing the need for the resilience treatments in the MOG Resilience scenario. Modeled together, as in the Ramp Up and Max NCS portfolios, this creates a powerful positive feedback loop that strengthens the restoration and resilience benefits of each scenario beyond what can be accomplished alone.

Though percentage differences between scenario net carbon balances may be large, the relative magnitude of California's annual net carbon balance is fairly consistent across scenarios after the pulse of resilience and restoration treatment removals from 2022-2031 (**Figure 12**). This means that even with large-scale restoration treatments, associated removals, and wood product dynamics, carbon trajectories are not made worse by this activity so long as biomass cut during these treatments is utilized in some way (as demonstrated by the Max NCS + Innovative Wood Utilization portfolio). Landscape conditions and stability will be improved following these treatments, based on reductions in forest loss and carbon stock loss achieved by many scenarios as discussed in the **Ecosystem Carbon Trends** section below. Furthermore, scenarios that do not address wildfire impacts, either through restoration or risk reductions, exhibit early emissions reductions relative to CBAU but later emissions increases as wildfires, post-fire regeneration failure, and productivity declines worsen across the landscape (**Figure 12**). This leaves forests vulnerable to future climate and wildfire impacts and destabilizes the future climate mitigation potential of forests in the state.

Ecosystem Carbon Trends

Under all scenarios modeled in this analysis, California forests lose area and carbon stocks from 2022-2071 (**Figure 16**). However, various scenarios provide opportunities to minimize these trends and create a more stable forest ecosystem. The Max NCS portfolio performs best of all in this regard, minimizing forest area loss to only 8% (2.5 million acres) rather than 48% (15 million acres) under CBAU and keeping forest carbon stock losses to 20% (1.9 $GtCO_2e$) instead of 50% (4.7 $GtCO_2e$) under CBAU from 2022-2071 (**Figure 16**). Net ecosystem carbon flux impacts are more variable, mirroring the net carbon balance trends discussed above. The Max NCS portfolio has a net ecosystem carbon flux that averages 104% higher than CBAU during the treatment phase from 2022-2031 (equating to higher net emissions; 47.1 vs 23 $MtCO_2e\ yr^{-1}$), 9% lower than CBAU (meaning lower net emissions; 24.9 vs 27.3 $MtCO_2e\ yr^{-1}$) post-treatment from 2032-2045, and 15% lower (23.7 vs 27.9 $MtCO_2e\ yr^{-1}$) during the maintenance phase from 2046-2071 (**Figure 16**).

Though this portfolio does not accumulate additional ecosystem carbon relative to CBAU by 2071 (**Figure 14**), it does confer other benefits in line with climate-smart forestry. The positive fluxes during the treatment phase are not all emissions to the atmosphere, as large volumes of harvested wood (up to 276% higher than CBAU) are transferred to the wood products sector from these treatments (**Figure 14**), leading to net emissions reduction benefits discussed in the **Wood Products Carbon Dynamics** section below. After the 10-year pulse of treatment activity, net carbon flux under the Max NCS portfolio stabilizes, suggesting that the landscape restoration and fire resilience treatments included in the portfolio have effectively reduced the risks and impacts of high-severity wildfire and other natural disturbances. Post-fire regeneration failure still occurs but at a much lower rate, adding up to 2.3 million acres by 2071 for the Max NCS portfolio instead of 12.7 million acres under CBAU. Associated emissions from this regeneration failure are also much lower than CBAU (1.6 vs 10.5 $MtCO_2e\ yr^{-1}$ in 2071), as are emissions from land-use change (0.3 vs 2.5 $MtCO_2e\ yr^{-1}$ in 2071) thanks to the forest conservation activities included in this portfolio (**Figure 17**).

The Ramp Up portfolio also provides notable forest area and carbon stock improvements over CBAU, keeping forest loss at 15% (4.7 million acres) and carbon stock loss at 26% (2.4 $GtCO_2e$) from 2022-2071 (**Figure 16**). Net ecosystem carbon fluxes average 117% higher than CBAU during the treatment phase (50 vs 23 $MtCO_2e\ yr^{-1}$), 7% higher than CBAU (29.1 vs 27.3 $MtCO_2e\ yr^{-1}$) post-treatment, and <1% higher (28 vs 27.9 $MtCO_2e\ yr^{-1}$) during the maintenance phase (**Figure 16**). Post-fire regeneration failure in the Ramp Up portfolio decreases the most of any portfolio or scenario modeled, accumulating on 84% fewer acres (12.7 vs 2.1 million acres) by 2071 and reducing cumulative emissions from regeneration failure by 84% compared with CBAU (218.3 vs 35.3 $MtCO_2e$ total in 2071; data not shown).

The Fire Resilience and MOG Resilience scenarios perform similarly to each other since they include the same practices and acreage targets, reducing forest loss to 25% (a loss of 7.9 million acres) and carbon stock loss to 33% (a loss of 3.1 GtCO$_2$e) over the simulation period (**Figure 16**). Average net ecosystem carbon flux for the Forest Resilience scenario is 108% higher than CBAU during the treatment phase (47.9 vs 23 MtCO$_2$e yr^{-1}), 1% lower than CBAU (27 vs 27.4 MtCO$_2$e yr^{-1}) post-treatment, and 1% lower (27.6 vs 27.9 MtCO$_2$e yr^{-1}) during the maintenance phase. For the MOG resilience scenario, these numbers increase slightly: 115% higher than CBAU during the treatment phase (49.5 vs 23 MtCO$_2$e yr^{-1}), <1% lower than CBAU (27.2 vs 27.4 MtCO$_2$e yr^{-1}) post-treatment, and 2% lower (27.5 vs 27.9 MtCO$_2$e yr^{-1}) during the maintenance phase (**Figure 16**). Total wildfire acres for these scenarios are not significantly different from CBAU (recall that we did not model a decrease in fire acres, but instead a decrease in fire severity as a result of fire resilience treatments), but cumulative wildfire emissions decrease by 2% (374.1 vs 366.9 MtCO$_2$e) for the Fire Resilience scenario and 3% (374.1 vs 362.4 MtCO$_2$e) for the MOG Resilience scenario by 2045 (data not shown). Post-fire regeneration failure decreases by 58% relative to CBAU (12.7 vs 5.3 million acres) by 2071 for both scenarios, reducing cumulative emissions from regeneration failure by 73% (218.3 vs 59.4 MtCO$_2$e) for the Fire Resilience scenario and by 74% (218.3 vs 57.5 MtCO$_2$e) for the MOG Resilience scenario by 2071 (data not shown). Though the differences between these two scenarios are minor overall, they do indicate the effect of expanding eligibility for resilience treatments to include MOG forests – slightly higher emissions during the treatment phase, as more acres are able to be treated (**Figure 15**), and slightly lower emissions by the end of the model period as more of the landscape enters a more stable condition. Coupled with a consistent age class distribution for both scenarios with a higher average forest age than

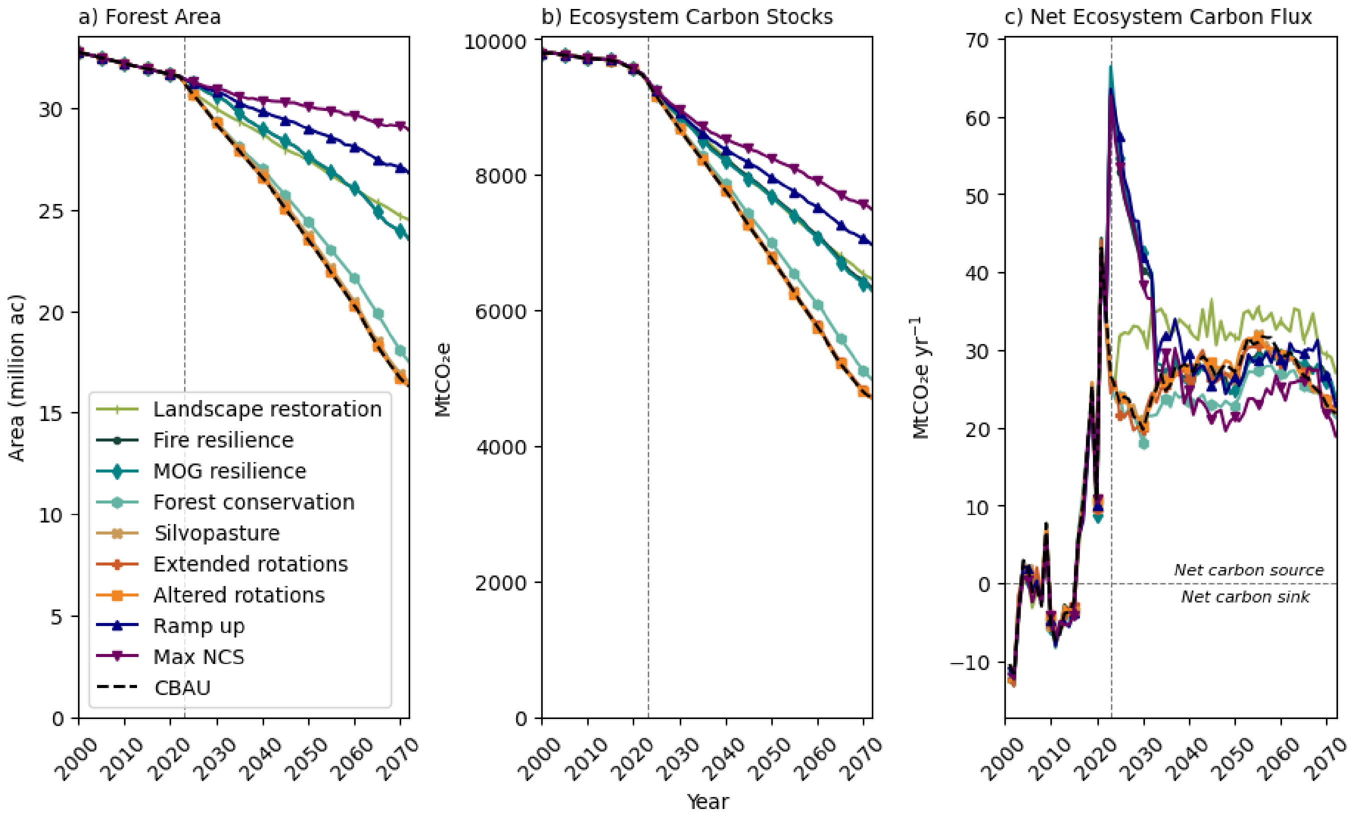


Figure 16. Selected scenario results showing a) total forest area (million acres), b) ecosystem carbon stocks (MtCO$_2$e), and c) annual net ecosystem carbon flux (MtCO$_2$e yr^{-1}) from 2000-2071. Net ecosystem carbon flux refers to the net yearly sequestration of carbon by forests after accounting 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.

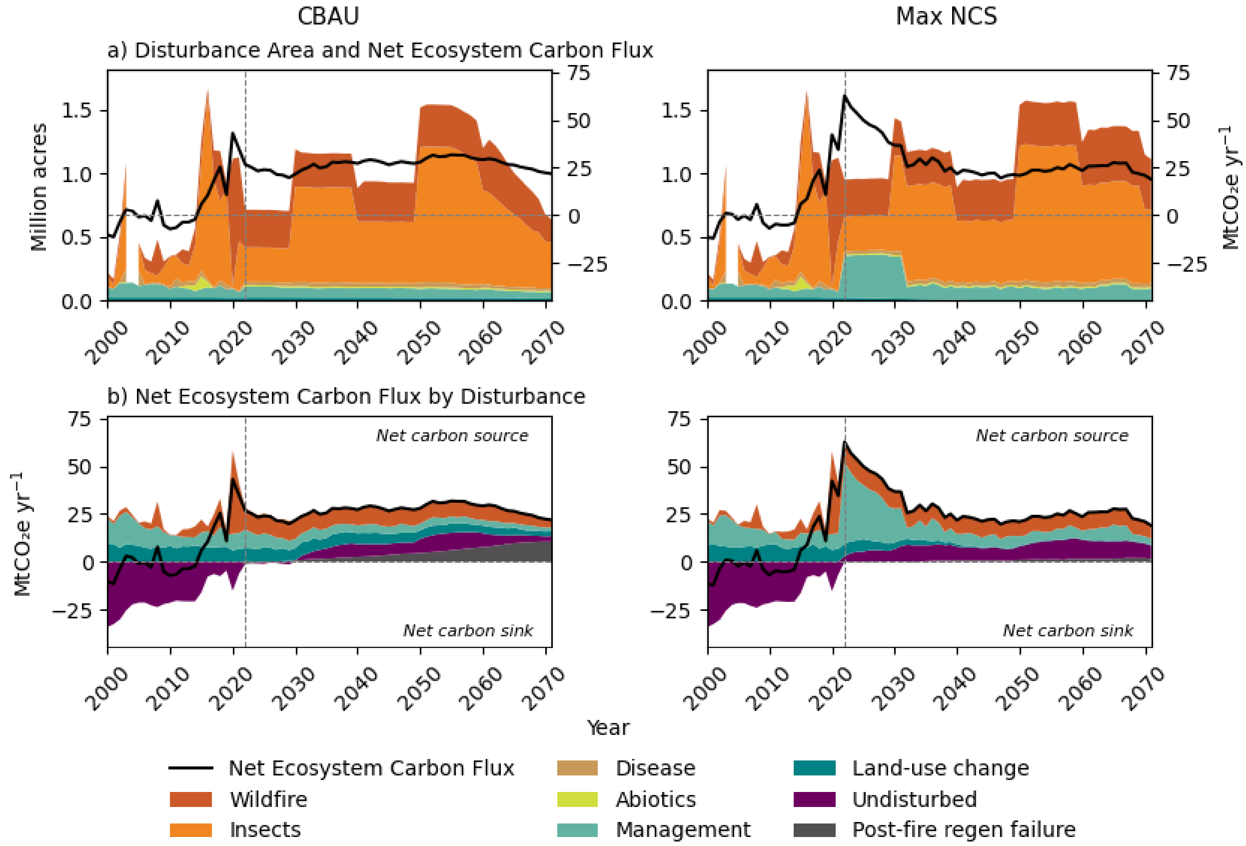


Figure 17. CBAU and Max NCS portfolio results showing a) disturbance area (million acres) by disturbance type and net ecosystem carbon flux (MtCO$_2$e yr^{-1}), and b) annual net ecosystem carbon flux (MtCO$_2$e yr^{-1}) by disturbance type from 2000-2071. Net ecosystem carbon flux refers to the net 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 b), negative numbers for net ecosystem carbon flux represent a net carbon sink and positive numbers represent a net carbon source.

CBAU (discussed in the **Ecosystem Carbon Trends, Forest Area, and Forest Age** section below), these results suggest that allowing hand thinning and prescribed fire treatments in MOG areas does not adversely affect their carbon trajectory and helps to improve the resilience and longevity of these critical forests.

The Landscape Restoration scenario yields better results for forest area (a loss of 22%, or 6.8 million acres, by 2071) and carbon stocks (a loss of 31%, or 2.9 GtCO$_2$e, by 2071) than the Fire Resilience and MOG Resilience scenarios (**Figure 16**), because this scenario includes active reforestation and restoration on millions of acres affected by wildfire. Overall, net ecosystem carbon flux is higher for Landscape Restoration than the resilience scenarios (except for during the initial resilience treatment phase) due to sustained harvest removals from post-fire salvage and reforestation treatments. Compared with CBAU, net carbon flux for this scenario is an average of 35% higher than CBAU during the treatment phase (31.1 vs 23 MtCO$_2$e yr^{-1}), 22% higher than CBAU (33.3 vs 27.4 MtCO$_2$e yr^{-1}) post-treatment, and 17% higher (32.6 vs 27.9 MtCO$_2$e yr^{-1}) during the maintenance phase (**Figure 16**). As with the Max NCS portfolio, a portion of this flux simply represents a lateral transfer of salvaged carbon from the ecosystem to the wood products sector rather than a carbon emission to the atmosphere (**Figure 14**). Post-fire regeneration failure is 65% lower than CBAU for the Landscape Restoration scenario (12.7 vs 4.4 million acres by 2071), though not as low as the scenarios that include wildfire resilience treatments. This indicates that though post-fire restoration is a critical technique for maintaining a forested landscape over time, practices that aim to prevent regeneration failure in the first place have a greater positive impact on forest area. As the Ramp Up portfolio demonstrates, these two approaches are even more powerful when combined.

The remaining modeled scenarios (Forest Conservation, Silvopasture, Extended Rotations, and Altered Rotations) have more limited impacts on ecosystem carbon dynamics, though each of them accumulates more carbon in the forest ecosystem than CBAU by 2071 (**Figure 14**). The Forest Conservation scenario has the most notable impact of these, helping reduce overall forest loss to 44% (a loss of 13.8 million acres) rather than 48% under CBAU and carbon stock loss to 47% (a loss of 4.4 $GtCO_2e$) rather than 50% under CBAU from 2022-2071 (**Figure 16**). By reducing permanent forest conversion from land-use change, the Forest Conservation scenario also reduces net ecosystem carbon flux relative to CBAU, especially from 2022-2045 when the annual rate of forest conservation is actively increasing and removals and emissions from conversion activities decrease. This leads to net ecosystem fluxes averaging 5% lower than CBAU during the treatment phase (22 vs 23 $MtCO_2e\ yr^{-1}$), 14% lower than CBAU (23.3 vs 27.4 $MtCO_2e\ yr^{-1}$) post-treatment, and 10% lower (25.2 vs 27.9 $MtCO_2e\ yr^{-1}$) during the maintenance phase (**Figure 16**). Post-fire regeneration failure is higher for this scenario than for CBAU, accumulating on 13.4 million acres from 2022-2071. The successful conservation of forestland increases the available area for wildfire in our model – and since we modeled this scenario without subsequent fire resilience treatments after the conservation action, wildfire footprints and emissions increase relative to CBAU (19 vs 19.8 million total acres of wildfire by 2071; 4 vs 4.6 $MtCO_2e\ yr^{-1}$ of wildfire emissions in 2071). The increase in wildfire area creates a corresponding growth in post-fire regeneration failure in this scenario, suggesting the importance of pairing forest conservation with resilience practices to obtain the best ecosystem benefits as demonstrated by the Max NCS portfolio.

Impacts from the Silvopasture, Extended Rotations, and Altered Rotations are smaller than for the Forest Conservation scenario. Forest area losses range from 47% for the Silvopasture scenario to 48% for the Extended and Altered Rotations scenarios (losses of 13.8 to 15 million acres by 2071; **Figure 16**). This difference here is accounted for by the 219,000 acres of new silvopasture established in the Silvopasture scenario; otherwise, all three scenarios do little to change forest area losses relative to CBAU since that is not their primary objective. Carbon stock losses also don't change much from CBAU for these scenarios: all three scenarios lose roughly 50% of their carbon stocks (4.7 $GtCO_2e$) from 2022-2071 (**Figure 16**). Net ecosystem carbon fluxes do reflect more variation between these scenarios, ranging from 4% lower than CBAU for Extended Rotations to 1% higher than CBAU for Silvopasture during the treatment phase, 3% lower than CBAU for Extended Rotations to 1% higher than CBAU for Silvopasture post-treatment, and ranging from 2% lower than CBAU for Extended Rotations to no change from CBAU for Altered Rotations during the maintenance phase (**Figure 16**). Post-fire regeneration failure occurs on the same number of acres for all scenarios and CBAU, which is to be expected given the consistency of forest loss trends and non-fire focus of each scenario.

Ecosystem Carbon Trends by Ownership

As in the **Influence of Future Climate** section, results for our scenarios vary by ownership. Here we present ownership results for the Max NCS portfolio to illustrate the largest and most positive impacts of our modeled practices on forests in California. USFS lands again show the largest changes between scenarios, though this time the Max NCS portfolio helps to stabilize forest area and carbon stocks within the National Forest System (**Figure 18**). Under this portfolio, USFS lands only lose 11% (1.7 million acres) of their forest area from 2022-2071, rather than the 69% loss (10.3 million acres) projected under CBAU. Carbon stocks show similar upward trends from the Max NCS portfolio, dropping 30% (1.4 $GtCO_2e$) rather than the 74% drop (3.4 $GtCO_2e$) of the CBAU scenario. Net ecosystem carbon fluxes are again more variable, averaging 119% higher than CBAU (equating to higher net emissions; 36 vs 16.4 $MtCO_2e\ yr^{-1}$) during the treatment period from 2022-2031, 5% lower than CBAU (meaning lower net emissions; 20 vs 21 MtCO$_2$e yr^{-1}) post-treatment from 2032-2045, and 12% lower (36 vs 16.4 MtCO$_2$e yr^{-1}) from 2046-2071 during the maintenance phase (**Figure 18**). Post-fire regeneration failure occurs on 1.3 million acres by 2071 under the Max NCS Portfolio, a big improvement over the 9 million acres projected on USFS lands under CBAU. Together, these results suggest that the restoration and resilience treatments included in the Max NCS portfolio are effective at reducing the impacts of future wildfires and climate change, minimizing carbon losses and creating more stability on USFS lands.

Private and Native American forest lands exhibit similar benefits from the Max NCS portfolio, losing 5% (0.6 million acres) of forest area instead of 29% (3.6 million acres) under CBAU and 10% (0.4 GtCO$_2$e) of carbon stocks rather than 27% (1 GtCO$_2$e) by 2071 (**Figure 18**). Average net ecosystem carbon fluxes are 73% higher than CBAU (8.5 vs 4.9 MtCO$_2$e yr^{-1}) during the treatment period, 29% lower than CBAU (3.2 vs 4.5 MtCO$_2$e yr^{-1}) post-treatment, and 30% lower (4.5 vs 6.4 MtCO$_2$e yr^{-1}) during the maintenance phase (**Figure 18**). Post-fire regeneration failure drops from 2.8 million acres under CBAU to 0.8 million acres under the Max NCS portfolio by 2071.

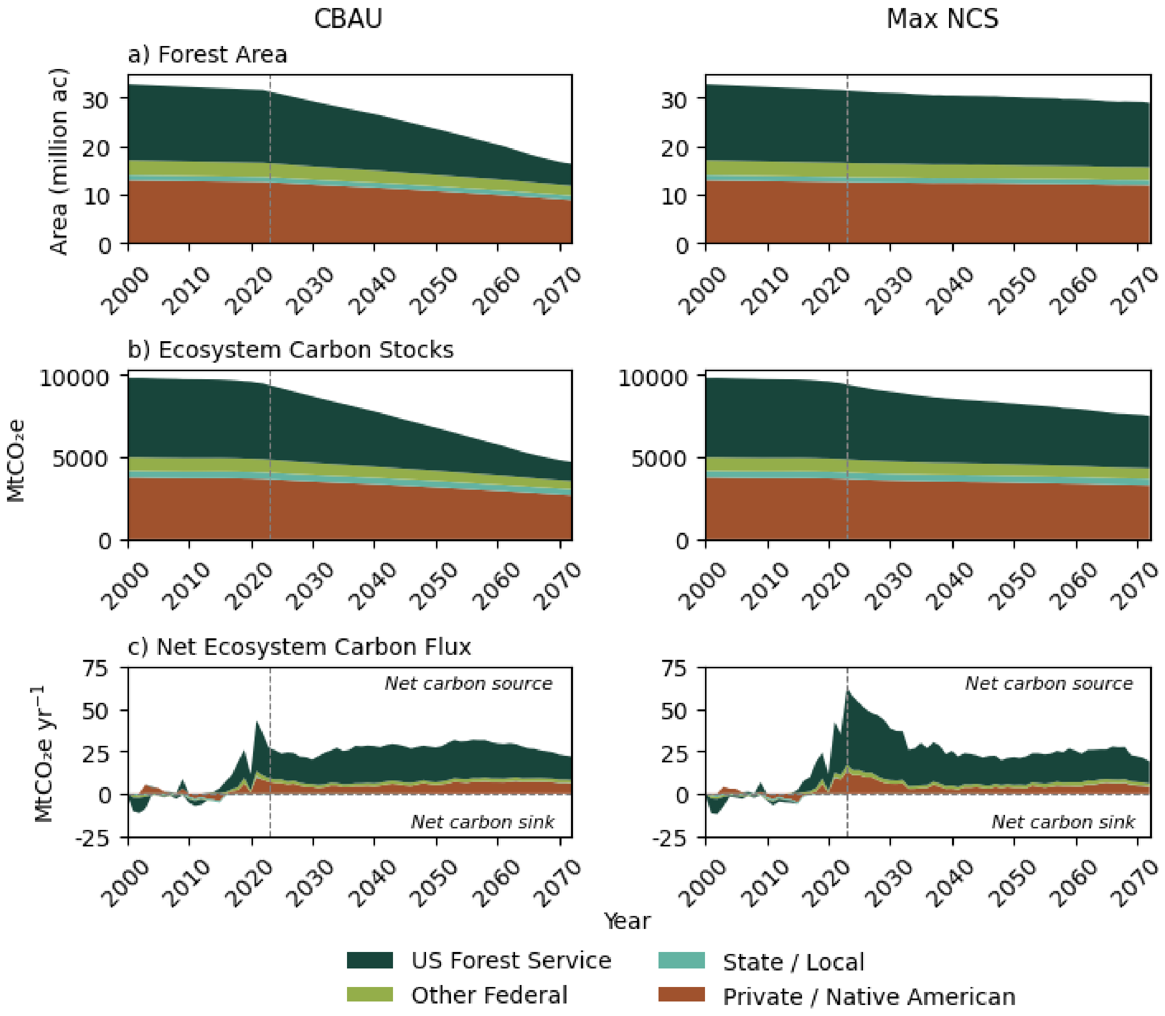


Figure 18. CBAU and Max NCS portfolio results showing a) total forest area (million acres), b) ecosystem carbon stocks (MtCO$_2$e), and c) annual net ecosystem carbon flux (MtCO$_2$e yr^{-1}) by ownership class from 2000-2071. Net ecosystem carbon flux refers to the net yearly sequestration of carbon 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.

Since state/local and other federally managed forests experienced relatively small impacts from climate change in the CBAU scenario, they also experience smaller benefits from the Max NCS portfolio. Forest area losses are minimized under Max NCS for both ownerships, with 2% (0.02 million acres) and 9% (0.3 million acres) decreases for state/local and other federal forests, respectively (**Figure 18**), compared with losses of 13% (0.1 million acres) and 30% (0.9 million acres) under CBAU. Carbon stocks are similarly stabilized, with state/local forests losing just 1% (0.006 $GtCO_2e$) vs 9% (0.04 $GtCO_2e$) under CBAU and other federal forests losing 19% (0.2 $GtCO_2e$) rather than 36% (0.3 $GtCO_2e$) under CBAU from 2022-2071 (**Figure 18**). On state/local lands, net ecosystem fluxes average 85% higher than CBAU (though still a net carbon sink; -0.04 vs -0.27 $MtCO_2e\ yr^{-1}$) during the treatment period, no change from CBAU (-0.14 $MtCO_2e\ yr^{-1}$) post-treatment, and 35% lower than CBAU (0.11 vs 0.17 $MtCO_2e\ yr^{-1}$) during the maintenance phase. Other federal forests follow a similar pattern, though fluxes are always higher than CBAU under Max NCS, averaging 32% higher (2.6 vs 2 $MtCO_2e\ yr^{-1}$) during the treatment phase, <1% higher (1.84 vs 1.83 $MtCO_2e\ yr^{-1}$) post-treatment, and 6% higher (2.1 vs 2 $MtCO_2e\ yr^{-1}$) during the maintenance phase (**Figure 18**). Both ownership categories experience less regeneration failure post-fire under the Max NCS portfolio, accumulating 0.02 million acres on state/local lands and 0.2 million acres on other federal lands rather than 0.12 and 0.7 million acres, respectively, under CBAU.

Ecosystem Carbon Trends by Ecoregion

Ecoregional influences of the Max NCS portfolio follow much the same pattern of improvement observed in the ownership-specific results. The Sierra/Cascades ecoregion, which exhibited the largest declines from future climate conditions in the CBAU scenario, has an improved outlook under the Max NCS portfolio. Forest area losses are limited to 8% (1.2 million acres) rather than 56% (8.3 million acres) under CBAU, and carbon stock losses reach 28% (1.1 $GtCO_2e$) instead of 64% (2.5 $GtCO_2e$) by 2071 (**Figure 19**). Net ecosystem carbon fluxes average 96% higher than CBAU (27.9 vs 14.3 $MtCO_2e\ yr^{-1}$) during the treatment period but become more stable during the treatment and maintenance phases, averaging 2% lower than CBAU (16.5 vs 16.9 $MtCO_2e\ yr^{-1}$) and 9% lower than CBAU (16 vs 17.5 $MtCO_2e\ yr^{-1}$) for those phases, respectively (**Figure 19**). Post-fire regeneration failure occurs on 1.2 million acres rather than 7.5 million acres under CBAU. California mixed conifer forests in the Sierra/Cascades retain 87% more forest area and 54% more carbon stocks under the Max NCS portfolio than under CBAU, though still incurring a loss of 0.5 million acres (vs a loss of 3.8 million acres) and 0.6 $GtCO_2e$ (vs a loss of 1.3 $GtCO_2e$) from 2022-2071. Ponderosa pine forests also benefit from practices in the Max NCS portfolio, retaining 89% more forest area (a loss of 0.1 million acres rather than 0.8 million acres under CBAU) and 58% more forest carbon (a loss of 0.08 $GtCO_2e$ vs 0.2 $GtCO_2e$ under CBAU) in this ecoregion. The redwood forest type group (representing giant sequoia) in the Sierra/Cascades experience no loss of forest area (vs a loss of 128 acres under CBAU) and lose slightly more carbon (a loss of 0.00004 $GtCO_2e$ vs 0.00003 $GtCO_2e$ under CBAU) from resilience treatments designed to reduce wildfire vulnerability in critical MOG forests like these.

In the Klamath/Interior Coast Ranges ecoregion, which also showed strong climate impacts from the CBAU scenario, forest area declines by 16% (1.3 million acres) by 2071 in the Max NCS portfolio, an improvement over the 68% (5.4 million acres) lost under CBAU (**Figure 19**). Rather than losing 66% (1.8 $GtCO_2e$) of carbon stocks under CBAU, this ecoregion loses 26% (0.7 $GtCO_2e$) of its carbon stocks by 2071 (**Figure 19**). Net ecosystem carbon fluxes follow a similar pattern of higher emissions during the treatment period (123% higher than CBAU; 18.3 vs 8.2 $MtCO_2e\ yr^{-1}$) and lower and more stable emissions during the post-treatment (14% lower than CBAU; 7.6 vs 8.8 $MtCO_2e\ yr^{-1}$) and maintenance phases (26% lower than CBAU; 5.9 vs 7.9 $MtCO_2e\ yr^{-1}$; **Figure 19**). Post-fire regeneration failure accumulates up to 1 million acres in 2071 under the Max NCS portfolio rather than 4.2 million acres under CBAU. California mixed conifer and Western oak forests (which represent oak woodlands) in the Klamath/Interior Coast Ranges still exhibit losses of forest area, though Western oak loses 67% less (a

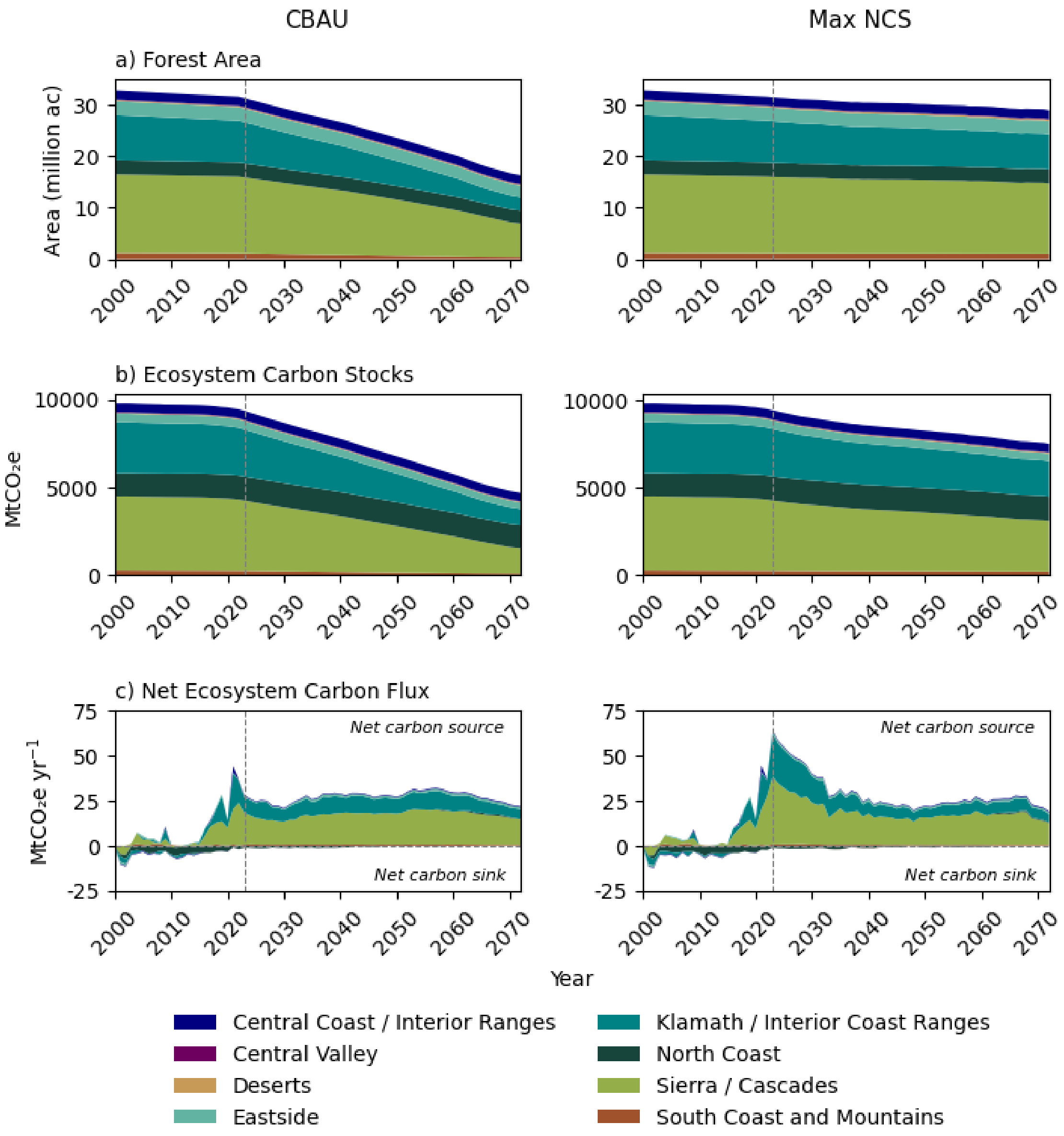


Figure 19. CBAU and Max NCS portfolio results showing a) total forest area (million acres), b) ecosystem carbon stocks ($MtCO_2e$), and c) annual net ecosystem carbon flux ($MtCO_2e\ yr^{-1}$) by ecoregion from 2000-2071. Net ecosystem carbon flux refers to the net yearly sequestration of carbon by forests 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.

loss of 0.7 million acres vs 2.1 million acres under CBAU) and California mixed conifer loses 83% less (a loss of 0.4 vs 2.3 million acres under CBAU) throughout the model period. Both forest types also retain more carbon stocks, with 57% more carbon (a loss 0.2 vs 0.5 $GtCO_2e$ under CBAU) in Western oak and 59% more carbon (a loss 0.4 vs 0.9 $GtCO_2e$ under CBAU) in California mixed conifer forests in this ecoregion under the Max NCS portfolio. Douglas-fir in the Klamath/Interior Coast Ranges retrains 93% more forest area (a loss of 19,233 acres vs 0.3 million acres under CBAU) and 73% more carbon stocks (a loss of 0.1 vs 0.2 $GtCO_2e$ under CBAU) from 2022-2071.

The North Coast ecoregion loses <1% forest area (just 694 acres) and 1% of carbon stocks (0.01 $GtCO_2e$) from 2022-2071 in the Max NCS portfolio, rather than losing 8% of forest area (0.2 million acres) and

5% of carbon stocks (0.07 $GtCO_2e$) under CBAU (**Figure 19**). Though CBAU losses in this ecoregion are not large in the absolute sense, they are significant given that the North Coast contains 77% of California's redwoods (and 79% of MOG redwood forests in the state), which are increasingly vulnerable to and affected by wildfire (Potter 2023; Filmer 2013). Under the Max NCS portfolio, redwood forests on the North Coast gain 15,436 acres and 0.01 $GtCO_2e$ from 2022-2071, nearly three times the area gained (3,535 acres) and enough to reverse the decrease in carbon stocks (a loss of 0.1 $GtCO_2e$) from these forests under CBAU. Hardwood forests, including Western oak and tanoak/laurel, still lose a small amount of forest area and carbon stocks (20,598 acres and 0.02 $GtCO_2e$ collectively) under Max NCS, but they retain 87% more acreage and 72% more carbon than under CBAU (a loss of 0.2 million acres and 0.06 $GtCO_2e$ collectively) during the model period. The result that very little forest area and carbon stocks are lost in this ecoregion under Max NCS suggests that the fire resilience and restoration practices included in this portfolio are especially effective at protecting these important ecosystems. Net ecosystem carbon fluxes also improve from these practices, averaging 20% lower than CBAU (-1.4 vs -1.2 $MtCO_2e\ yr^{-1}$) during the treatment phase, 30% lower (-1.1 vs -0.9 $MtCO_2e\ yr^{-1}$) post-treatment, and 95% lower (0.01 vs 0.2 $MtCO_2e\ yr^{-1}$) during the maintenance phase (**Figure 19**). This is the only ecoregion to show consistently lower carbon fluxes (meaning lower net emissions) from the Max NCS scenario, even during the treatment period when higher emissions are expected. Post-fire regeneration failure occurs on 0.05 million acres by 2071 in the Max NCS portfolio instead of 0.2 million acres under CBAU. This post-fire regeneration failure area is greater than total forest loss because of the overall forest gain and loss dynamics in the portfolio – the North Coast gains forest area through afforestation, reforestation of the current post-fire backlog, and silvopasture, and loses forest via land-use conversion and post-fire regeneration failure. On net, this works out to a loss of 694 acres, including losing 0.05 million acres to regeneration failure.

Consistent with the **Influence of Future Climate** section, the remaining five ecoregions show smaller changes between CBAU and Max NCS. The Eastside and South Coast and Mountains ecoregions show similar magnitudes of forest area and carbon stock losses under the Max NCS portfolio: both ecoregions lose 0.1 million acres of forest area (2% on the Eastside and 7% in the South Coast and Mountains) by 2071 (**Figure 19**). This is a larger improvement over CBAU for the South Coast and Mountains (which lost 0.7 million acres, or 62% of forest area) than the Eastside (which lost 0.4 million acres, or 14%). Under the Max NCS portfolio, carbon stocks decline by 12% and 18% (0.04 and 0.06 $GtCO_2e$) for the Eastside and South Coast and Mountains, respectively, instead of 21% and 66% (0.1 and 0.2 $GtCO_2e$) under the CBAU scenario by 2071 (**Figure 19**). For the Eastside, net ecosystem carbon fluxes are fairly steady throughout the Max NCS portfolio, averaging 1.1 $MtCO_2e\ yr^{-1}$ (79% higher than 0.6 $MtCO_2e\ yr^{-1}$ under CBAU) during the treatment phase, 1.1 $MtCO_2e\ yr^{-1}$ (9% lower than 1.2 $MtCO_2e\ yr^{-1}$ under CBAU) post-treatment, and 1 $MtCO_2e\ yr^{-1}$ (16% lower than 1.2 $MtCO_2e\ yr^{-1}$ under CBAU) during the maintenance phase. The South Coast and Mountains show more improvement in carbon fluxes over CBAU, averaging 19% higher (0.8 vs 0.7 $MtCO_2e\ yr^{-1}$) during the treatment phase and then stabilizing at 21% lower (0.6 vs 0.7 $MtCO_2e\ yr^{-1}$) post-treatment and 23% lower (0.5 vs 0.7 $MtCO_2e\ yr^{-1}$) during the maintenance phase (**Figure 19**). Post-fire regeneration failure occurs on 0.04 million acres on the Eastside and 0.1 million acres in the South Coast and Mountains ecoregion by 2071 in the Max NCS portfolio, reduced from 0.2 and 0.6 million acres, respectively, under CBAU. Eastside pinyon/juniper forests retain 90% more forest area (a loss of 5,572 acres vs 56,196 acres under CBAU) and 50% more carbon stocks (a loss of 0.005 $GtCO_2e$ vs 0.01 $GtCO_2e$ under CBAU) over the model period. In the South Coast and Mountains, Western oak forests lose 84% less forest area (6,370 acres vs 0.4 million acres under CBAU) and 39% less carbon (0.01 $GtCO_2e$ vs 0.1 $GtCO_2e$ under CBAU) from 2022-2071.

The final three ecoregions (Central Coast/Interior Ranges, Central Valley, and Deserts) largely exhibit gains in forest area and carbon stocks in the Max NCS portfolio. Forest area in these ecoregions increases by 1% (0.01 million acres), 20% (0.02 million acres), and 42% (0.1 million acres), respectively, from 2022-2071, rather than decreasing by 2% (0.03 million acres) in the Central Coast/Interior Ranges and exhibiting no change from CBAU in the Central Valley and Deserts (**Figure 19**). Correspondingly, carbon stocks grow by 15% and 38% in the Central Valley and Deserts instead of dropping by 1% (0.0002 $GtCO_2e$) and <1% (0.0001 $GtCO_2e$), respectively, under CBAU, while the Central Coast/Interior Ranges ecoregion still experiences carbon stock losses of 5% (0.025 $GtCO_2e$) rather than 7% (0.03 $GtCO_2e$) in the CBAU scenario (**Figure 19**). These gains in forest area and carbon stocks are largely driven by silvopasture, which adds 0.12 million acres of low-density tree cover to pastureland (without taking the land out of active pasture use, even though they are now tracked as forest in our model) in total for these three ecoregions. Net ecosystem carbon fluxes decrease (meaning lower net emissions) in the Central Valley and Deserts, not exceeding an average of -0.1 $MtCO_2e\ yr^{-1}$ (compared with CBAU fluxes of <-0.01 $MtCO_2e\ yr^{-1}$) from 2022-2071. In the Central Coast/Interior Ranges, carbon fluxes are more variable, fluctuating ±2% (averaging 0.46 vs 0.45 $MtCO_2e\ yr^{-1}$) relative to CBAU (**Figure 19**). Redwood forests in this ecoregion retain 89% more forest area (losing just 665 acres vs 3,880 acres under CBAU) and 17% more carbon stocks (losing 0.008 $GtCO_2e$ vs 0.01 $GtCO_2e$ under CBAU) from 2022-2071. Post-fire regeneration failure accumulation remains at zero acres for all three ecoregions, consistent with CBAU results.

See **Appendix** for tables comparing forest area, ecosystem carbon stocks, and net ecosystem carbon flux by ownership and ecoregion for the CBAU scenario and Max NCS portfolio.

Ecosystem Carbon Trends, Forest Area, and Forest Age

Age class distribution plays an important role in determining the ecosystem carbon trends of each scenario modeled in this analysis. As discussed in the **Influence of Future Climate** section, age class distribution under CBAU shifts significantly over time, with 59% of the landscape over 140 years old and just 4.7% in the 0-19 year age class in 2071 (**Figure 9**). Though these percentages suggest an aging forest landscape, they do not include increasing areas in a state of post-fire regeneration failure, which covers 40% of the landscape in 2071 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 drops from 133 to 104 years from 2022-2071 under CBAU (**Figure 20**).

Per-acre carbon storage and annual sequestration rates – or *carbon stock density* and *carbon flux density* values, respectively – 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 density values account for growth and decomposition in the forest ecosystem prior to harvest removals, therefore including the growth of wood that could later transfer to the HWP pool. In this analysis, we present these metrics for undisturbed forest only, allowing a more direct view into productivity dynamics and forest age by excluding fluxes from disturbances like wildfire or harvest. At a stand or landscape scale, aging forests often exhibit slowing rates of growth and productivity, stemming from interacting competition and resource-use dynamics of individual trees (Binkley et al. 2002), leading to a declining forest carbon sink (Sleeter et al. 2018).

Scenarios that address wildfire impacts have the largest influence on California's forest age class distribution, either by decreasing the occurrence of high-severity wildfire and subsequent post-fire regeneration failure across the landscape (demonstrated by the MOG Resilience scenario) or by reforesting previously burned areas currently in a state of regeneration failure (exhibited in the Landscape Restoration scenario). The Ramp Up and Max NCS portfolios are particularly successful in this realm, as the concurrent pre- and post-fire treatments help more forests survive (and continue to grow) throughout the simulation. Consequently, average stand age increases from 134 to 150 years for the Ramp Up portfolio and from 134 to 149 years for the Max NCS portfolio from 2022-2071 (**Figure**

20). This rise in average forest age points to an increase in the area (though not necessarily the proportion) of older forest under these portfolios: in the Ramp Up portfolio, for example, MOG area grows by 1.3 million acres and makes up 14% of total forest area by 2071, an improvement over the 0.2 million acre gain in the CBAU scenario. Under the Max NCS portfolio, MOG forest area increases by 1.6 million acres while occupying 13% of the landscape (rather than 14% under CBAU) by 2071. This increase in MOG area further indicates that the fire resilience and restoration treatments included in these portfolios—which we model as a light (non-commercial) thinning followed by prescribed fire in old-growth forests—are effective at reducing future losses from wildfire, including in critical MOG forests which are increasingly vulnerable to wildfire and climate change impacts (Anderson et al. 2024; Shive et al. 2021). These practices create a more balanced age class distribution, which, along with a diversity of species and heterogenous forest structure, is a key factor in fostering ecosystem resilience and providing essential forest co-benefits such as wildlife habitat, carbon sequestration and storage, and wood products (Ferrare, Sargis, and Janowiak 2019; Seidl et al. 2016; Vangi et al. 2024; Shifley and Thompson 2011; USDA Forest Service 2023b).

In tandem with a more balanced age class distribution, our modeled portfolios show related decreases in average carbon stock density through the model period, from 289 to 260.1 $tCO_2e\ ac^{-1}$ for the Ramp Up portfolio and from 287.2 to 259.2 $tCO_2e\ ac^{-1}$ for the Max NCS portfolio (compared with smaller decreases from 300 to 288 $tCO_2e\ ac^{-1}$ under CBAU; **Figure 20**). This represents a balancing act between minimizing forest loss and restoring forest acres at more climate-adapted variable and low-density stand structures (Meyer, Long, and Safford 2021; North et al. 2019) – forest area is higher but each acre contains fewer trees and therefore less carbon. These carbon stock densities vary by age class, and the influence of this lower-density restoration activity is visible in the lower carbon stock density in younger forests for the Landscape Restoration scenario and Max NCS portfolio (**Figure 20**). Coupled with higher forest area for the Max NCS and Ramp Up portfolios compared with CBAU, even this lower carbon stock density leads to higher total ecosystem carbon stocks as discussed above (**Figure 16**).

Carbon flux densities vary in similar ways across scenarios and age classes. Under CBAU, net ecosystem carbon flux per acre increases (leading to higher net emissions) over time, rising from -0.03 $tCO_2e\ ac^{-1}\ yr^{-1}$ in 2022 to 0.31 $tCO_2e\ ac^{-1}\ yr^{-1}$ in 2045 as wildfires ramp up in intensity and rising again to 0.46 $tCO_2e\ ac^{-1}\ yr^{-1}$ in 2071 (**Figure 20**) as post-fire regeneration failure increases across the landscape and continues emitting carbon from dead trees and decomposition. Emissions from land in a state of regeneration failure are apparent in the carbon flux density of the youngest age class (forest failing to regenerate has a stand age of zero) in 2071, with a value near 1 $tCO_2e\ ac^{-1}\ yr^{-1}$ for the CBAU, Forest Conservation, Silvopasture, and Extended Rotations scenarios (**Figure 20**). Note that the MOG Resilience and Landscape Restoration scenarios, along with the Max NCS portfolio, do not exhibit these same emissions in 2071 from lands failing to regeneration post-fire, as the total acreage of these lands is much smaller than under CBAU. Max NCS portfolio carbon flux densities are higher than CBAU for early years during the treatment phase (160% higher, or 0.26 vs 0.1 $tCO_2e\ ac^{-1}\ yr^{-1}$, in 2031) but drop below CBAU flux levels during the post-treatment and maintenance phases (41% lower, or 0.27 vs 0.46 $tCO_2e\ ac^{-1}\ yr^{-1}$ in 2071; **Figure 20**). This lower carbon flux density means that each acre of forest under the Max NCS portfolio is growing more or emitting less carbon than under CBAU, and in either case this points to an improved and more consistent rate of carbon uptake from this portfolio.

A general difference in strategies emerges from these per-acre metrics: scenarios that focus on harvest and land use, which often coincide with reducing harvest and other removals, tend to result in higher carbon stock densities, even in younger age classes (**Figure 20**). These increases in carbon stock density are minor for our scenarios relative to CBAU (up to +0.4% for the Extended Rotations scenario in 2071), but the differences are larger when compared to other scenarios that include higher removals from resilience and restoration treatments (i.e., a gain of 0.4% for the Extended Rotations scenario in 2071

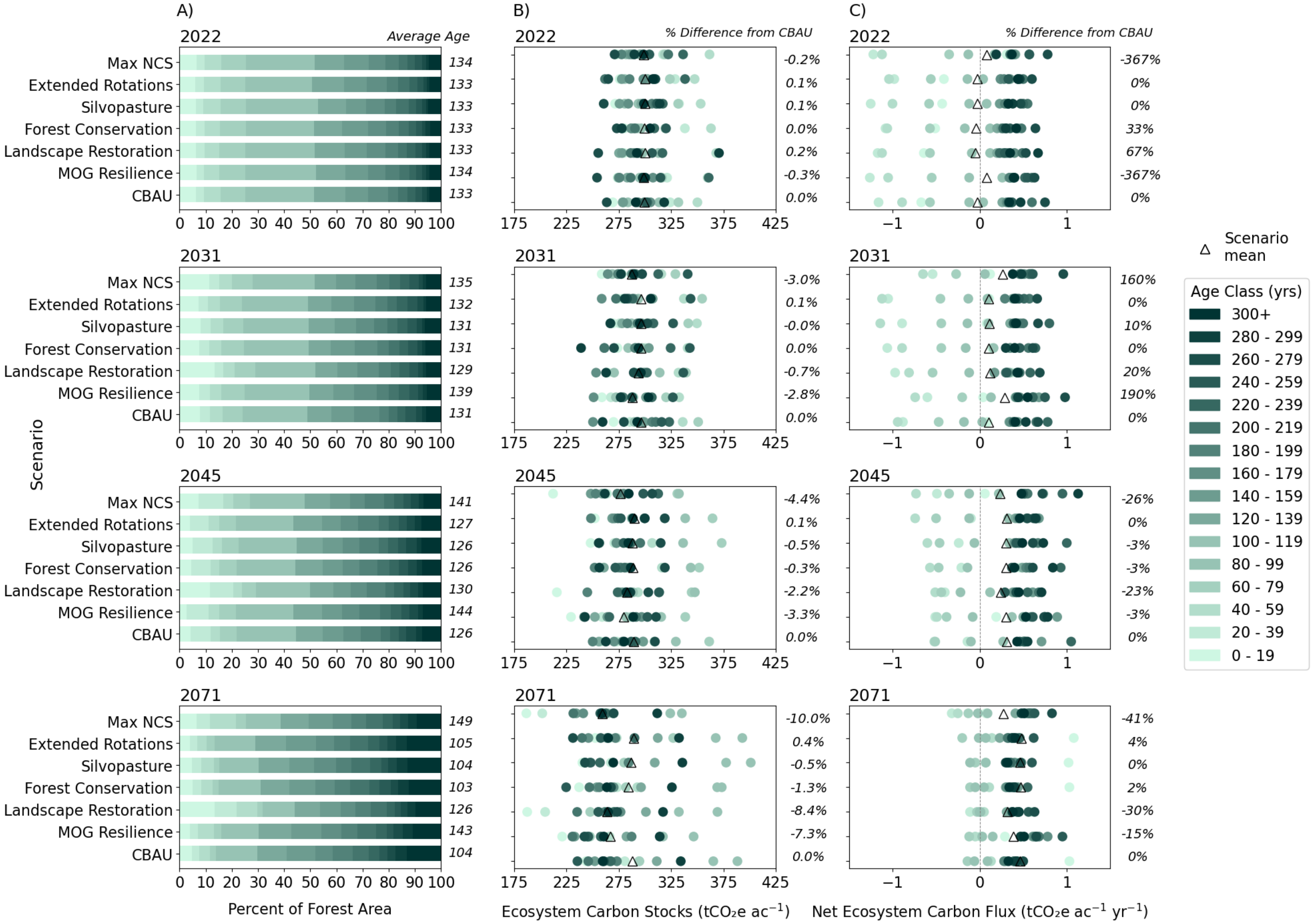


Figure 20. A) Age class distribution, B) ecosystem carbon stock density ($tCO_2e\ ac^{-1}$), and C) net ecosystem carbon flux density ($tCO_2e\ ac^{-1}\ yr^{-1}$) for undisturbed forest in selected scenarios in 2022, 2031, 2045, and 2071. Net ecosystem carbon flux density refers to the net yearly sequestration of carbon per acre of forest across all 14 ecosystem carbon pools, after accounting for decomposition, natural disturbance emissions, and 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.

vs a drop of 7.3% for the MOG Resilience scenario). These scenarios with higher carbon stock densities also have higher carbon flux densities (**Figure 20**), pointing to tradeoffs between carbon storage and carbon sequestration on the same acre of forest. A climate-smart management strategy is one that balances these two dynamics across the forest landscape (Verkerk et al. 2020), much in the way the Max NCS portfolio combines changes in harvest and forest conservation focused activities with resilience and restoration treatments to foster future resilience and stability.

Wood Products Carbon Dynamics

These landscape-scale restoration and resilience treatments remove large amounts of wood material from the forest, and the use of this material plays a significant role in the overall carbon balance of each portfolio or scenario we modeled. California's forest products industry has limited commercial uses for pulpwood and small diameter material aside from bioenergy, so a large portion of tops, limbs, and non-merchantable biomass is usually piled on site after harvest, with the intention of a subsequent pile burn (Eric Huff, personal communication). This piled material does not always get burned in follow-up as intended and is often left to decompose on site instead. Cut hardwood material from permanent forest conversion is often sent directly to landfills where it also decomposes. Hardwood removals during salvage operations are typically used for residential fuelwood and do not contribute to industrial roundwood products. In all these cases, the carbon in this wood is emitted relatively quickly to the atmosphere, contributing to the net carbon source status of the forest. With nearly 3 times the CBAU carbon removals projected to occur in the Max NCS portfolio from resilience and restoration treatments on 7.4 million acres from 2022-2031, current wood utilization strategies will not be enough to reduce additional emissions from this activity.

For this reason, we modeled individual innovative wood utilization strategies (Biochar, Transportation Fuels, or Mass Timber) with the Fire Resilience and MOG Resilience scenarios in addition to "base" Fire Resilience and MOG Resilience scenarios that use business-as-usual HWP assumptions to better understand the influence of the individual wood utilization pathways on carbon dynamics. We modeled the Ramp Up and Max NCS portfolios with Innovative Wood Utilization, which combines all three individual utilization strategies in one trifecta, in addition to base HWP models, recognizing that multiple pathways can be expanded on at the same time. These scenarios include four wood products carbon dynamics: storage, emissions, leakage, and substitution benefits (see the **Harvested Wood Products Model** section for descriptions).

Carbon stored in HWP increases in both current and new products in the Max NCS + Innovative Wood Utilization portfolio, leading to HWP carbon stocks that are 19% higher than CBAU (539.3 vs 454.5 MtCO2e) in 2071 (**Figure 21**). This includes 37.5 MtCO2e stored in mass timber and 9.5 MtCO2e in biochar in 2071. Transportation fuels do not accrue carbon stocks, because we assume they are combusted in the same year they are created. They do, however, provide substitution benefits as discussed below.

Softwood and hardwood removals again vary widely in the Max NCS + Innovative Wood Product portfolio, though both wood types show a spike in removals during the resilience treatment phase from 2022-2031 (**Figure 22**). The average proportion of softwood utilization is consistent between Max NCS and CBAU (65.3% industrial roundwood, 18.8% utilized biomass, 15.9% bark residue), though the total removals under Max NCS are predictably higher (averaging 8.6 vs 5.3 $MtCO_2e\ yr^{-1}$) because of the additional resilience and restoration treatments modeled (**Figure 22**). Hardwood utilization changes for the Max NCS portfolio with the Innovative Wood Utilization product trifecta: on average, more cut biomass is utilized (41.6% vs 4.6% under CBAU), with less biomass used for residential fuelwood (30% vs 51.5%) or sent directly to landfills (19.8% vs 43%; the benefit of reducing permanent forest conversion in this portfolio). Utilization for industrial roundwood increases over CBAU but stays at a

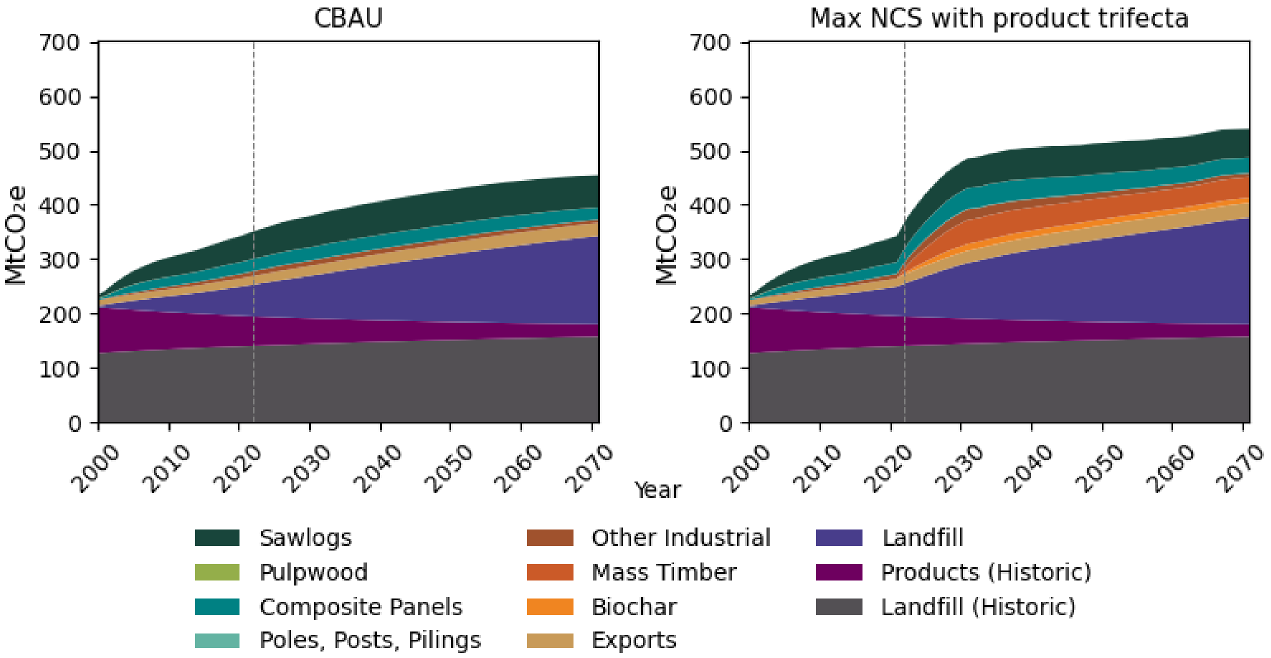


Figure 21. CBAU and Max NCS + Innovative Wood Utilization portfolio HWP carbon stocks (MtCO₂e) by primary product, 2000-2071. Positive numbers denote accruing carbon stocks.

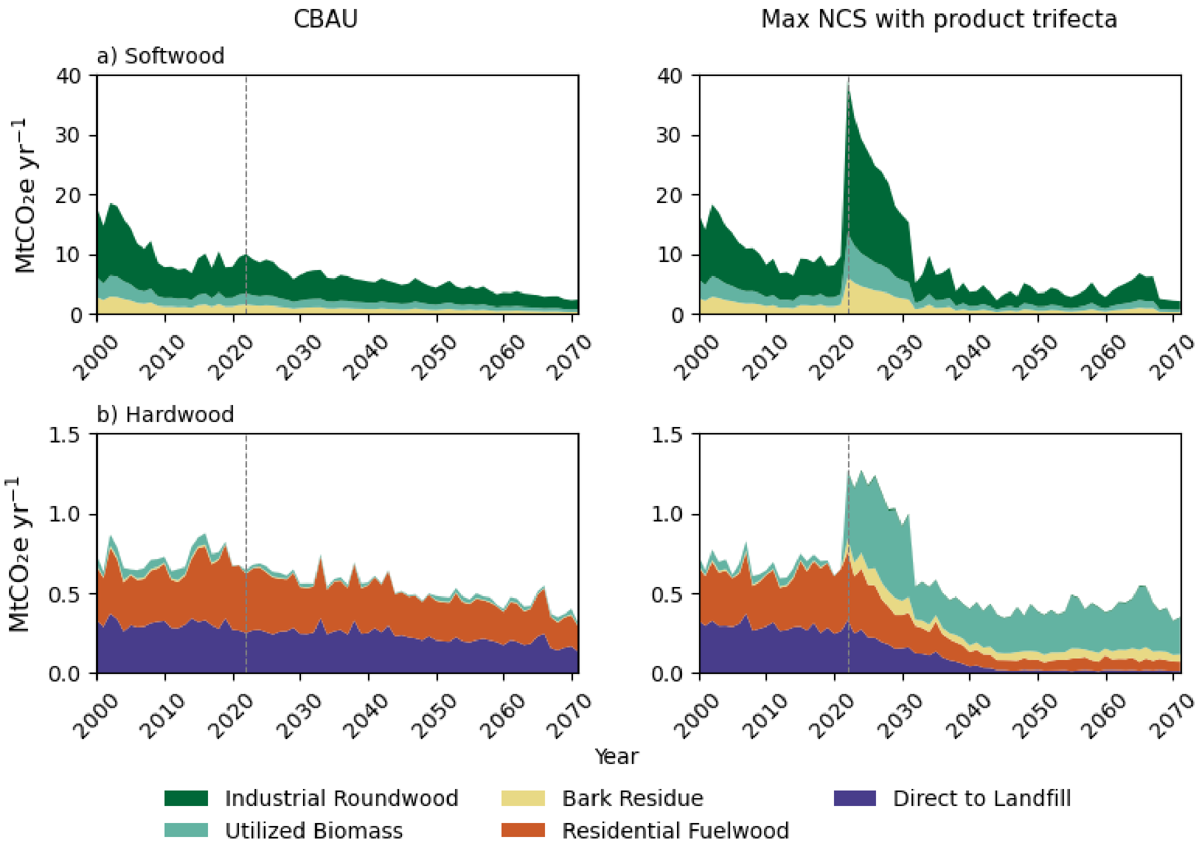


Figure 22. CBAU and Max NCS +Innovative Wood Product portfolio results showing annual HWP removal distribution (MtCO₂e yr⁻¹) for a) softwoods and b) hardwoods from 2000-2071. Removals are comprised of woody material that is cut and removed from the forest and does not include any residues or other materials left on site.

relatively low percentage (0.8% vs 0.1%), driving a similar increase in bark residue (8% vs 0.9%; **Figure 22**). Hardwood removals increase from an average of 0.53 to 0.57 $MtCO_2e\ yr^{-1}$ from the CBAU scenario to the Max NCS + Innovative Wood Product portfolio.

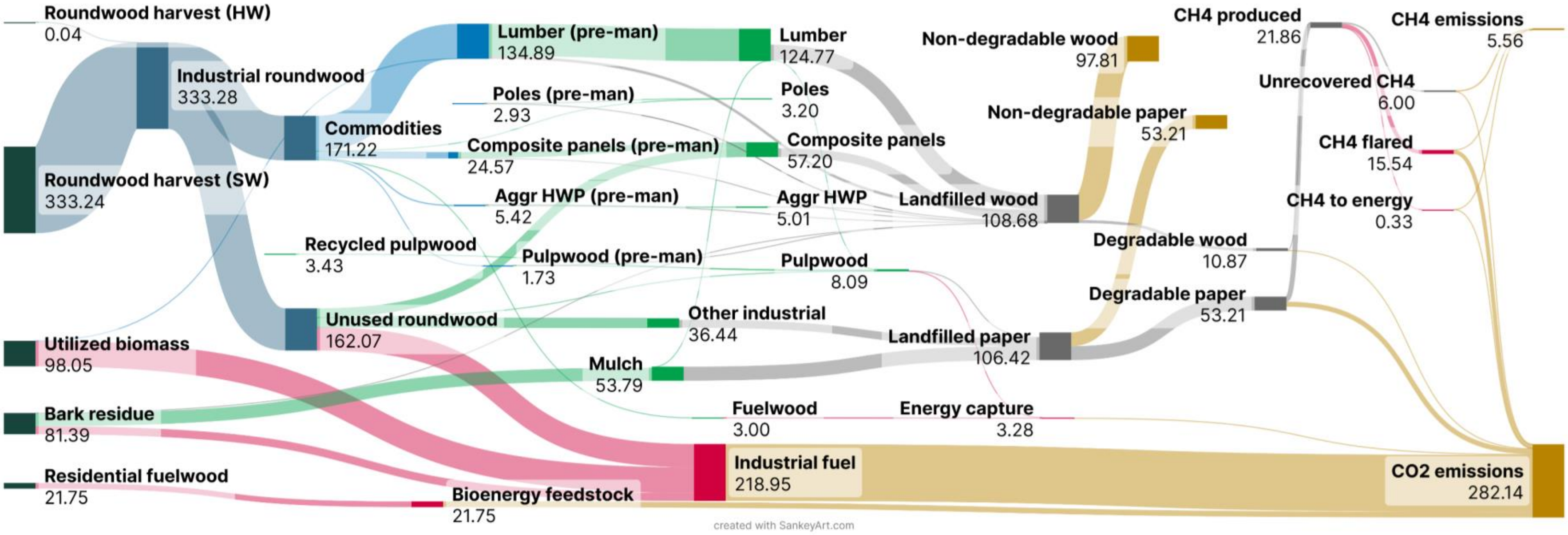
For this portfolio, additional wood removals are distributed among the innovative trifecta products (biochar, transportation fuels, and mass timber), with hardwood and softwood materials modeled in the same way. Additional wood in the utilized biomass category is first allocated to industrial bioenergy, up to the maximum capacity of current bioenergy facilities (further discussed in the **Economic Impacts** section below). Beyond this bioenergy capacity cap, additional removed biomass is split evenly between biochar and transportation fuels in our model. For the Max NCS portfolio with the product trifecta, this amounts to an additional 13.1 MtCO2e each diverted to biochar and transportation fuels from 2022-2031, the only years where utilized biomass removals exceed the state's bioenergy facility capacity (**Figure 23**). Though resilience treatments continue after 2031, treatment footprints are more dispersed and initial treatments have made forests less dense, so these follow-up treatments do not generate additional material beyond current bioenergy facility capacity. Removals from 2022-2031 produce 7.9 million tons of biochar and 7.9 million tons of transportation fuels, a large increase for products not currently made in the state (**Figure 23**).

Additional industrial roundwood removed under the Max NCS + Innovative Wood Product portfolio is diverted from lumber to mass timber. Only removals that exceed CBAU lumber production levels are diverted in our model, in order to preserve the current supply of lumber in the state. This applies for all years of our model period, leading to a total of 52.5 MtCO2e utilized in 29.5 thousand board feet (MBF) of mass timber from 2022-2071 (**Figure 23**).

Each of these innovative products has its own emissions and product substitution dynamics based on source material (roundwood or other biomass) and end use. Building on the MOG Resilience scenario, for example, the MOG Resilience + Biochar scenario has lower HWP emissions (averaging 12.5 vs 15.2 $MtCO_2e\ yr^{-1}$ from 2022-2031) because biochar has a longer half-life than biomass that is burned or left to decompose, which is the typical fate of that source material in our model without innovative wood utilization (**Figure 24**). This benefit accrues during the treatment phase from 2022-2031 because the source material for biochar is produced during that period; in the post-treatment and maintenance phases of the scenario, HWP emissions are the same as the base MOG Resilience scenario. Biochar does not substitute for any products currently in use, so the product substitution benefits are the same as for the MOG Resilience scenario. Driven by the decrease in HWP emissions, the MOG Resilience + Biochar scenario has a lower *net HWP carbon balance* from 2022-2031 than without the innovative wood utilization (averaging -18.7 vs -16 $MtCO_2e\ yr^{-1}$; **Figure 24**). Net HWP carbon balance includes 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 for net HWP carbon balance denote net carbon storage, whereas positive values denote net carbon emissions (a net carbon source).

Though biochar does not confer product substitution benefits when added to the MOG Resilience scenario, both transportation fuels and mass timber do. Transportation fuels made from woody biomass can be used in place of more carbon-intensive traditional diesel and aviation fuel, thereby avoiding carbon emissions from those products (Field et al. 2020; Cabiyo et al. 2021). For the MOG Resilience + Transportation Fuels scenario, product substitution benefits average -5.6 $MtCO_2e\ yr^{-1}$ from 2022-2031, compared with -3.9 $MtCO_2e\ yr^{-1}$ for the base MOG Resilience scenario (**Figure 24**). The immediate combustion of these transportation fuels assumed in our model does not lead to reduced HWP emissions, but the product substitution is enough to provide a lower net HWP carbon balance for the MOG Resilience + Transportation Fuels scenario (an average of -17.7 $MtCO_2e\ yr^{-1}$ vs -16 $MtCO_2e$

A) CBAU



B) Max NCS + Innovative Wood Utilization

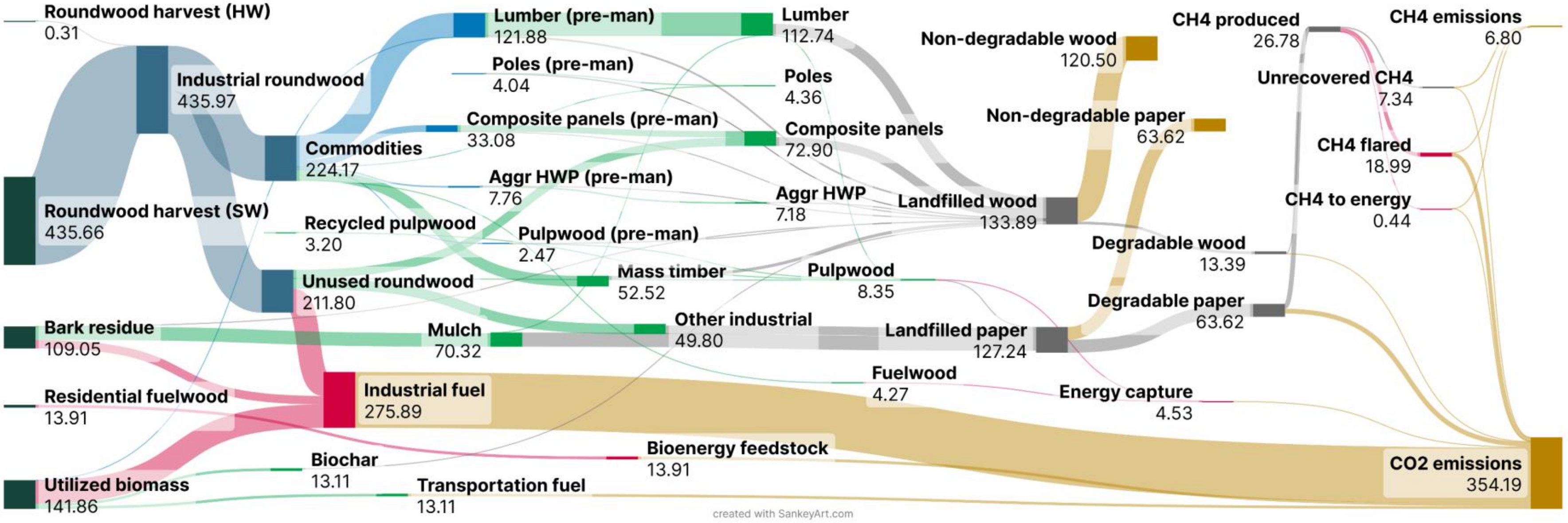


Figure 23. CBAU and Max NCS +Innovative Wood Product portfolio results showing cumulative HWP carbon stocks, emissions, and flows (MtCO₂e) from 2000-2071. Pre-man stands for pre manufacturing; this is included to demonstrate flows of carbon during the manufacturing process of each timber product.

yr^{-1} for the base MOG Resilience scenario) during the treatment phase when these fuels are being produced (**Figure 24**).

Net HWP carbon balance is even lower (meaning fewer emissions and more carbon storage) for the MOG Resilience + Mass Timber scenario, as mass timber has a longer half-life than lumber (its source material) and can substitute for more emissions-intensive materials like concrete and steel. The product substitution benefits for this scenario extend beyond the treatment phase, though they are strongest with the large amount of additional HWP produced during the treatment phase. Since only additional lumber material is diverted to mass timber, emissions from unutilized biomass still exist at the same levels at the base MOG Resilience scenario. Overall, the MOG Resilience + Mass Timber scenario has average substitution benefits of -9.12 $MtCO_2e\ yr^{-1}$ (rather than -3.9 $MtCO_2e\ yr^{-1}$ for the base scenario) and a net HWP carbon balance averaging -21.3 $MtCO_2e\ yr^{-1}$ (instead of -16 $MtCO_2e\ yr^{-1}$ for the base scenario) from 2022-2031 (**Figure 24**).

Relative to stocks, emissions, and substitution, leakage plays a small role in wood products carbon dynamics for California. For the MOG Resilience scenario, for example, leakage is <0.1 $MtCO_2e\ yr^{-1}$ for all wood utilization strategies (**Figure 24**). The Forest Conservation scenario, which reduces the volume of harvest removals through permanent forest conservation, exhibits the highest leakage rates of all the scenarios we modeled, reaching a maximum annual rate of <1.7 MtCO2e yr^{-1} and accumulating 52.4 $MtCO_2e$ by 2071 (**Figure 14**). For most other scenarios, cumulative leakage is <2 $MtCO_2e$ in 2071 (**Figure 14**).

Adding Innovative Wood Utilization to our portfolios amplifies these dynamics by combining all three innovative products into one trifecta. Since this trifecta addresses pathways for both unutilized biomass

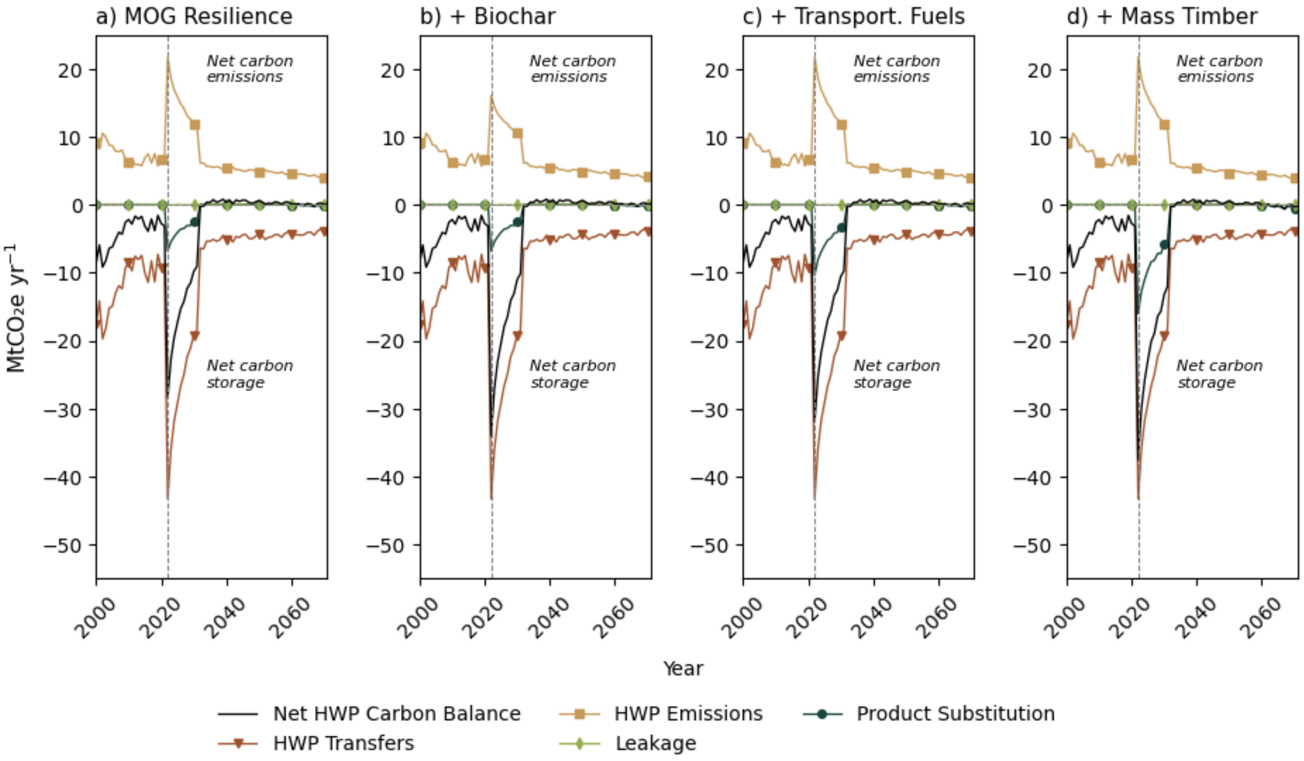


Figure 24. MOG Resilience scenario results showing components of net HWP carbon balance ($MtCO_2e\ yr^{-1}$) with a) business-as-usual HWP utilization, b) biochar, c) transportation fuels, and d) mass timber from 2000-2071. Negative values denote net carbon storage. Positive values denote net carbon emissions (a net carbon source).

and for merchantable material, substitution benefits are higher than for each product individually, especially during the 10-year pulse of fire resilience treatments from 2022-2031 (an average of -9.3 $MtCO_2e\ yr^{-1}$). For the Max NCS + Innovative Wood Utilization portfolio, this leads to a net HWP carbon balance averaging 855% lower than CBAU (-21.9 vs -2.3 $MtCO_2e\ yr^{-1}$) during the treatment phase, 126% higher than CBAU (0.3 vs -1.2 $MtCO_2e\ yr^{-1}$) post-treatment, and 176% higher (0.2 vs -0.3 $MtCO_2e\ yr^{-1}$) during the maintenance phase (**Figure 25**). This portfolio provides less net HWP carbon storage than CBAU in the later years of our model period due to the leakage dynamics of the Forest Conservation scenario component. The Landscape Restoration scenario, which we did not model with innovative wood utilization, also provides steady wood products carbon storage from the removal of additional salvage material during post-fire reforestation activities.

It is important to note that these components of net HWP carbon balance shift with changing assumptions about leakage, particularly for the proportions of substitution benefits realized by each scenario. All results presented here use our 80% leakage assumption for years when harvest is lower than CBAU, discussed in the **Harvested Wood Products Model** section. However, for different leakage assumptions we cannot simply adjust the leakage bar – leakage and substitution benefits interact with each other in a more complicated way. This occurs because a higher leakage rate assumes that a higher proportion of wood product demand in the state will be met by imported products, decreasing the need for other products to be used in place of wood. This dynamic assumes a static demand for wood products even with decreased in-state supply of HWP.

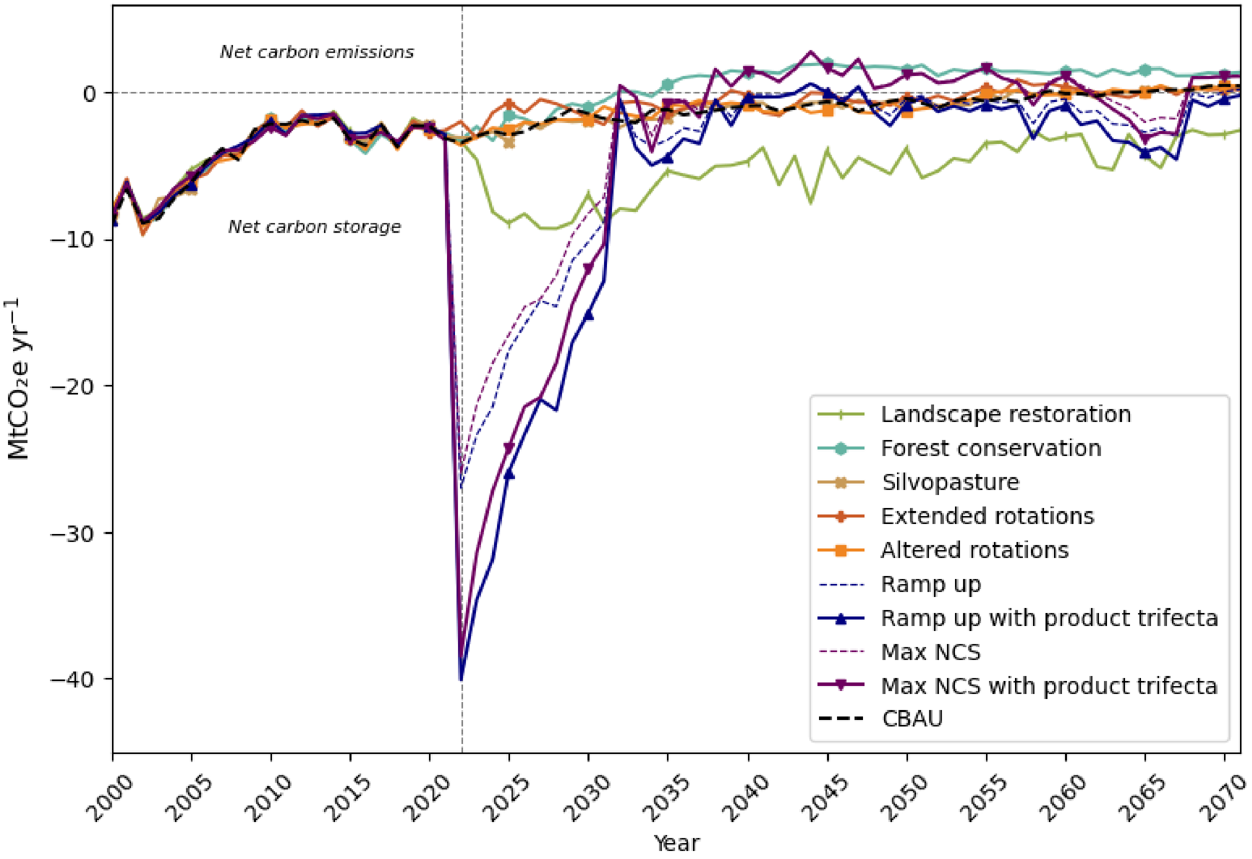


Figure 25. Net HWP carbon balance ($MtCO_2e\ yr^{-1}$) for selected scenarios from 2000-2071. Net HWP carbon balance includes transfers to HWP, emissions from wood products in use and in landfills, substitution benefits in years where harvest is different than CBAU, and leakage in years where harvest is less than CBAU. Negative values denote net carbon storage. Positive values denote net carbon emissions (a net carbon source).

Costs , Revenues, and Wood Processing Capacity

Driven by additional resilience and restoration treatments on millions of acres, the Max NCS and Ramp Up portfolios have substantially higher pre-fire resilience treatment and post-fire restoration costs relative to the CBAU scenario during the treatment phase from 2022-2031. The Max NCS portfolio, which is most effective at mitigating carbon loss in California's forests, is expected to cost $1.7 billion yr^{-1} more than CBAU during the treatment phase, while the Ramp Up portfolio comes in at $1.8 billion yr^{-1} more than CBAU (**Figure 26**). Fire resilience treatments account for 52% of these costs for the Max NCS portfolio, with post-fire reforestation and restoration accounting for the remaining 48%. These proportions shift slightly for the Ramp Up scenario (55% resilience treatments, 45% reforestation and restoration). Following the 10-year pulse of the treatment period, resilience treatment costs effectively return to CBAU levels for both portfolios (**Figure 26**). However, due to the forest loss trend in the CBAU scenario, post-fire reforestation and restoration costs decline under CBAU during the post-treatment and maintenance phases with less forest acres available to treat in our model. Since the portfolio treatments are more successful at keeping forest on the landscape (and therefore allowing the model to execute more acres of treatments), post-fire reforestation and restoration costs for each portfolio remain higher than CBAU in the post-treatment and maintenance phases (for example, $340-409 million needed annually under the Max NCS portfolio; **Figure 26**).

Revenues from the sale of HWP can partially offset the cost of the forest health and fire resilience work needed to avoid large carbon losses in the state. Because HWP prices vary considerably for both industrial roundwood and utilized biomass, we calculate this potential revenue as a range using low and high price scenarios to represent weak and strong timber markets, respectively. HWP revenues from the Max NCS portfolio could potentially offset 31-70% of treatment costs (totaling $385-$884 million), with even higher revenue potential ($412-$946 million, offsetting 41-94% of treatment costs)

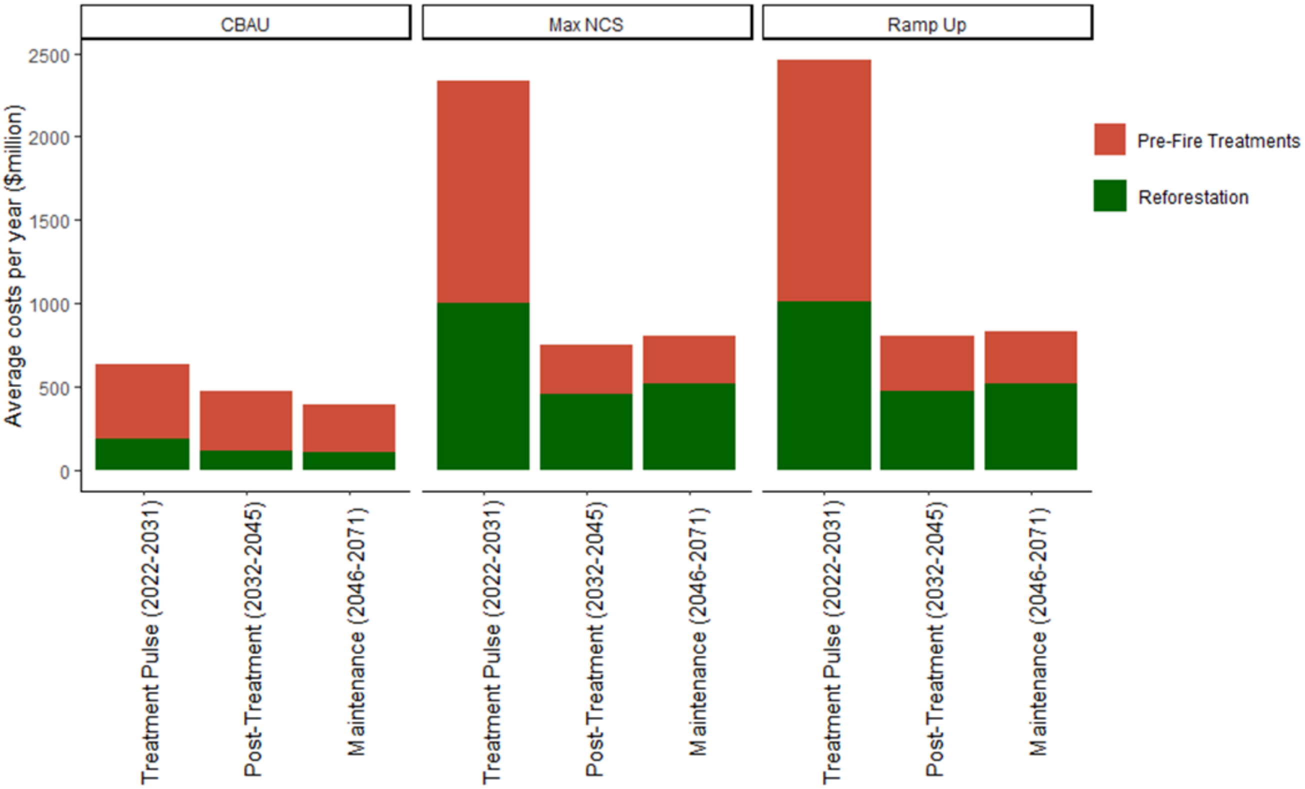


Figure 26. CBAU, Max NCS, and Ramp Up scenario annualized pre-fire treatment and post-fire reforestation and restoration costs ($ million yr^{-1}) by treatment phase.

for the Ramp Up portfolio (**Table 6**). Revenue from the utilized biomass is a relatively insignificant component of total revenue. Assuming a delivered biomass price of $40 per bone dry ton (BDT), which is optimistic under current economic conditions, total revenue from utilized biomass is roughly 4-9% of the total revenue for each portfolio, varying based on assumed delivered log prices. This highlights the importance of high-value wood product markets in financing management on the ground.

These potential revenue figures rely on the assumption that California will have enough processing capacity for the additional industrial roundwood and utilized biomass coming out of the forest from these resilience and restoration treatments. Except for the Great Recession in 2008-2009, California timber harvest has remained relatively constant since 2002 (BBER 2022), and existing processing capacity is generally calibrated to this harvest volume. In this study, we quantify the capacity gap, the difference between modeled wood supply and the existing wood processing infrastructure, to better understand how much additional processing capacity would be needed across the state.

For industrial roundwood, our estimates of processing capacity include both active sawmills and the additional capacity if idled or recently closed mills were brought back online. Currently, California is capable of processing 1,738 million board feet (MMBF) scribner of industrial roundwood, with the potential to increase to 1,922 MMBF scribner if idled or closed mills are included (Forisk Consulting 2024; UCANR Woody Biomass Utilization Group 2024). This capacity varies significantly by forest product region (one of our model classifiers; see **Figure 3** for a map). Based on current active capacity only, log processing capacity would need to increase by 88% (1,537 MMBF scribner) for the Max NCS portfolio and 95% (1,647 MMBF scribner) for the Ramp Up portfolio to accommodate the additional harvested roundwood material during the treatment phase alone (**Table 7**). In 2021, 31 California sawmills processed 1,641 MMBF scribner of wood (Scott 2024) – so assuming the average mill in California is capable of processing 53 MMBF scribner annually, California would need an additional 29-31 sawmills to process and utilize this material.

An even more aggressive scaling of processing capacity would be required to utilize the biomass residues coming from the resilience and restoration treatments in our portfolios (**Table 8**). California biomass electric power facilities consume approximately 1.9 million BDT of biomass each year (California Energy Commission 2024). Approximately 51% of this material is mill residue and the remaining 49% comes from in-forest residue (i.e. non-merchantable material cut during management). Modeled increases in harvested biomass supply under each portfolio would require processing capacity to increase by 112% (Max NCS) and 120% (Ramp Up). This translates to approximately 8-9 additional large-scale bioenergy facilities that only process currently unutilized in-forest biomass. Capacity gaps are large in all six of the modeled forest product regions, highlighting the importance of locating new biomass utilization infrastructure throughout the state.

Note that these results apply to both the base portfolios and their Innovative Wood Utilization counterparts. Under the base portfolio, BAU utilization assumptions apply, but there is still a large influx of additional material being removed from the landscape from the resilience and restoration treatments included in Max NCS that would require new sawmill or biomass utilization facilities for processing. Using this additional material in innovative products would also require new biomass production facilities in California, as capacity for biochar, transportation fuels, and mass timber production is currently extremely limited in the state. Both for new processing facilities and new production capacity, the 10-year timeline of large-scale resilience and restoration treatments modeled in our portfolios may be too short of a procurement window, limiting the potential for utilizing additional harvested material in either current or innovative products.

Table 6. Total costs and revenues from modeled treatments during the treatment phase ($ million). Costs include pre-fire resilience treatments only and do not include post-fire reforestation and restoration costs. Revenue ranges reflect low and high assumptions for delivered log and utilized biomass prices.

Portfolio	Total pre-fire resilience treatment cost ($ million)	HWP revenue ($ million)	Fraction of pre-fire resilience treatment cost covered
Ramp Up	$1,008	$412 - $946	41% - 94%
Max NCS	$896	$385 - $884	31% - 70%

Table 7. Existing sawmill capacity and additional modeled supply (million board feet scribner) for Ramp Up and Max NCS portfolios during the treatment phase (2022-2031). Additional modeled supply represents difference from CBAU.

Forest product region	Sawmill capacity (MMBF scribner)		Additional modeled supply (MMBF scribner)	
	Active	Active + Idled/Closed	Ramp Up	Max NCS
Central Coast	20	20	10	10
North Coast	545	612	183	130
Northern Interior	609	638	613	601
Sacramento	422	422	470	441
San Joaquin	142	231	363	348
Southern California	0	0	8	7
Total	**1,738**	**1,922**	**1,647**	**1,537**

Table 8. Existing biomass utilization capacity and additional modeled supply (thousand bone-dry tons) for Ramp Up and Max NCS portfolios during the treatment phase (2022-2031). Additional modeled supply represents difference from CBAU.

Forest product region	Current production (thousand BDT)		Additional modeled supply (thousand BDT)	
	In-Forest Residue	All Active Facilities	Ramp Up	Max NCS
Central Coast	0	0	8	7
North Coast	0	121	118	80
Northern Interior	482	995	396	390
Sacramento	319	623	322	306
San Joaquin	133	167	243	230
Southern California	0	0	31	31
Total	**935**	**1,905**	**1,118**	**1,044**

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 forest product districts in California), which can be used to filter results to certain areas. These spatial references, along with our landscape resilience needs assessment, can help to prioritize actions in areas with the largest projected climate vulnerabilities or carbon impacts. However, the results in these spatial units are based on historical trends and are not guarantees of future management activities.

2. There are no all-encompassing forest management databases across all landowner categories in California, so we compiled multiple data sources to create one for this analysis. Despite using multiple databases, including timber management plans, our estimates of harvest area may be an undercount, especially for private lands where activity reporting is not comprehensive.

3. The scale of analysis and model functionality does not allow for important stand-level considerations and management targets. Though we simulated uneven aged management, nuances in silvicultural prescriptions and outcomes relevant to land managers such as species composition, stand structure, and diameter distributions are not possible to explore through this effort. Similarly, details on species composition and size classes of harvested material, which are important to more detailed analyses of potential HWP markets, are not available in this study.

4. Using an average of historic trends for our projections removes the possibility of extreme events from our model – for example, since we apply high-severity wildfire to an average of 350,000 acres per year, our model will not capture the probability or impact of a megafire like those from the 2020 fire season. This also does not allow for novel events that have not happened historically, like wildfires in forest types that have not typically burned in large amounts. This limitation is not unique to CBM-CFS3, but it is an important consideration for interpreting our scenario results, especially those related to future climate impacts and wildfire resilience.

5. The 50-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 assumptions about 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) that 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 relatively abbreviated 50-year period to avoid this increasing future uncertainty. We have not conducted a sensitivity analysis for these scenarios, so our results here present one set of possible outcomes influenced by the assumptions made as described in the **Developing Modeling Scenarios** section. 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.

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 California. 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 the innovative wood utilization pathways modeled, where we project a 10-year period of resilience treatments to meet ecological needs and assume additional material can be utilized by industries that do not yet exist in California. We acknowledge that a 10-year procurement timeline may be too short for certain new products and facilities.

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, 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.

8. Our scenarios require assumptions about which classifiers (forest type group, ownership, ecoregion, 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 implemented 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. While this may add uncertainty to the numerical carbon trajectory of each scenario, it does 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 California, 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 California include:

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

- Reducing the impact and severity of future wildfires through *resilience treatments*, including thinning and prescribed fire, at a landscape scale to reduce stand densities and reintroduce beneficial fire in fire-adapted ecosystems.

- Using additional woody material removed from landscape restoration and resilience treatments in *innovative wood products* to reduce decomposition and pile burn emissions from leaving the material on site and gain substitution benefits from using the wood in place of more emissions-intensive materials.

- Reducing the rate of permanent forest loss through *landscape restoration* and *forest conservation* paired with landscape scale *resilience treatments* to reduce disturbance-related carbon losses from these areas.

- Increasing forest extent where ecologically appropriate through *silvopasture*, the low-density integration of trees into active pastureland without removing the land from productive pasture use.

- Increasing carbon stocks while sustaining timber supply by *extending rotations* to optimize tree growth, paired with landscape scale *resilience treatments* to reduce the risk of disturbance-related carbon losses.

- Preparing for increasing negative impacts of climate change and using climate-adapted species and stand structures to promote forest health and resilience and restore key ecological processes.

When implemented concurrently across the landscape, these practices can accomplish up to a **14% decrease in average annual emissions** from California's forests over CBAU and **capture an additional 76 $MtCO_2e$** (leading to 6% lower cumulative emissions) by 2071. Represented by the Max NCS + Innovative Wood Utilization portfolio, climate-smart forestry can help make critical progress towards in the state's forest restoration goals (California Wildfire and Forest Resilience Task Force 2021) and natural climate solutions targets (CNRA 2024), though forests will not be able to act as a carbon sink to offset additional emissions from other sectors. In 2045, the same year as the state's net-zero emissions goal, CSF practices can help reduce annual forest and forest sector emissions by 3% (avoiding emissions of 0.8 $MtCO_2e$ yr^{-1}) while restoring resilience on 10.4 million acres of forest.

California 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. Enabling Indigenous land stewardship, integrating Indigenous Knowledge, and developing a robust research, monitoring and adaptive management process can improve our ability to foster forest resilience under future uncertainty. Focusing on action in the Sierra/Cascades and Klamath/Interior Coast Ranges ecoregions will also be crucial for minimizing future forest carbon losses from those areas.

The difference in impact between our scenarios comes in part from the relative scale of activity. Resilience and restoration treatments on millions of acres have a larger influence on carbon trajectories and stability than practices affecting only thousands of acres. The timing of these treatments in also important, especially in the context of future climate conditions. If wildfires and other natural disturbances ramp up in intensity following our CBAU scenario projections, insect mortality events will increase in the 2030s, followed by greater wildfire acres from the 2040s onwards. 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 aligns well with the timelines of California's restoration and net-zero goals aiming to reach full implementation by 2045 (California Wildfire and Forest Resilience Task Force 2021; CARB 2022a; CNRA 2024).

However, this pace and scale of action requires forest management capacity that is still developing within California. In 2021, for example, resilience treatments (fuel reductions, prescribed fire, and prescribed grazing) were implemented on 402 thousand acres of forest within the state and reforestation (site preparation and tree planting or seeding) occurred on 76 thousand forest acres (Emily Brodie, personal communication). Notably, this rate is higher than we modeled in our CBAU scenario based on historic treatment levels, indicating that capacity is already ramping up. In 2023, this rate increased to 487 thousand acres of resilience treatments and 78 thousand acres of reforestation – an improvement in accomplishments but still shy of the treatment levels included in our scenarios (a peak of 818 thousand ac yr^{-1} for resilience treatments during the treatment phase and up to 172 thousand ac yr^{-1} of reforestation). Building this capacity is critical not only for addressing current treatment needs, but also for having the ability to respond to future needs and especially surge years like the 2020 wildfire season. 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 the gap (Dobrowski et al. 2024).

The resilience and restoration treatments central to California's climate-smart strategies may be costly, requiring up to $1.8 billion annually as these treatments are implemented as determined in this analysis. Depending on timber market conditions, wood product revenues could offset 31% to 94% of these costs; however, a significant portion of these forest resilience activities will likely require alternative funding sources. Additionally, processing capacity for industrial roundwood and utilized biomass would need to expand significantly, with sawmill capacity nearly doubling and biomass utilization capacity more than doubling to manage the increased harvest volume.

The practices listed above are considered climate-smart because they balance both carbon storage and sequestration rates with forest health and resilience. Though the pace and scale of needed restoration and resilience treatments requires large amounts of carbon to be removed from the forest in the near term, overall carbon trajectories are not made worse by this activity so long as biomass cut during these treatments is utilized in some way. Furthermore, landscape conditions and stability will be improved following these treatments, evidenced by more forest area, higher carbon stocks, greater ecosystem carbon sequestration, and higher average stand ages that indicate forests are seeing improved survival and growth because of these efforts. The cost of inaction is significant, leaving forests vulnerable to future climate and wildfire impacts (losses of 48% of forest area and 50% of forest carbon) and destabilizing the future climate mitigation potential of forests in the state – so the question of restoring forest resilience in California is not a matter of if, but how soon.

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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-CA) models, leakage and substitution benefit 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 based on California-specific data rather than keep 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 California-specific data using USDA Forest Service Forest Inventory and Analysis (FIA) data. These data underpin several of the required input tables, as described below.

1. 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), 6 derived from FIA data (USDA Forest Service 2021a). Two classifiers provide spatial references for our data using CAL FIRE's preferred units of spatial analysis (Report Figure 3): Forest Product Regions ("FPRegion") from Standiford et al. (2020) and Ecoregion (created by CAL FIRE based on Bailey's ecosystem section) from the California Forest Carbon Plan (Forest Climate Action Team 2018; CAL FIRE 2016). We added one custom classifier to tag forest undergoing a thinning treatment ("Thinned") and one as a trigger for future climate events and climate-modified yield curves under CBAU ("Climate Mod"). Each unique combination of classifiers (e.g., FPRegion 1 + OWNGRPCD 10 + ... etc.) is used to structure the remaining model input tables, with input values required for each unique combination.

Geospatial Classifier Data

Though the CBM-CFS3 itself is not spatially explicit, a number 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 FPRegion and ecoregion mentioned above. We aggregated land ownership data (CAL FIRE 2020) with forest industry and Tribal lands datasets provided by CAL FIRE to create a map of OWNGRPCD. We recategorized terrain and timberland productivity data from CAL FIRE for our rasters of slope class and productivity class, respectively. To map RESERVCD, we combined 2015 wilderness data from CAL FIRE with 2018 data from the Protected Areas Database of the United States (USGS 2018) to find areas

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

Classifier	Description	Values	
FPRegion	Forest products region (aggregations of counties) used for economic analysis, based on Standiford et al. (2020)	1	Central Coast
		2	San Joaquin
		3	Sacramento
		4	North Coast
		5	Southern California
		6	Northern Interior
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
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
		340	Redwood group
		360	Other western softwoods group
		370	California mixed conifer 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
		970	Woodland hardwoods group
		990	Exotic hardwoods group
		999	Nonstocked
Ecoregion	Ecoregions of California, from the California Forest Carbon Plan (Forest Climate Action Team 2018)	1	Central Coast and Interior Ranges
		2	Central Valley
		3	Deserts
		4	Eastside
		5	Klamath/Interior Coast Ranges
		6	North Coast
		7	Sierra/Cascades
		8	South Coast and Mountains
Slope Class	FIA condition code to denote stand percent slope, binned into 4 classes	1	0-29%
		2	30-49%
		3	50-69%
		4	70+%
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})
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
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%)
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
Climate Mod	Binary code to trigger transition to future climate events and climate-modified yield curves	0	Past climate
		1	Future climate

of designated wilderness or other protection status reserved from management for wood products. We did not have sufficient data to map of 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 created a custom forest type group raster rather than use existing datasets, as we found that each existing dataset showed discrepancies from the FIA inventory data (USDA Forest Service 2021a) that underpin our other model inputs, in some cases creating large over or underestimates in the area of important forest type groups (Table S2). To create a more updated and consistent dataset, we combined data from USFS CALVEG data circa 2015 (USDA Forest Service 2018b), forest type group maps circa 2017 created for our team by LEMMA (2022), and USFS BIGMAP circa 2018 (USDA Forest Service 2018a). CALVEG is commonly used for California (USFS Region 5), but the 2015 data vintage introduced uncertainty about accuracy for more current vegetation conditions, especially after large tree mortality and wildfire events from 2015 onwards. BIGMAP data is a newer USFS product based on FIA data, but it uses NLCD data (Dewitz and USGS 2021) to mask out non-forest areas and therefore employs a higher threshold for defining forestland than FIA (25% minimum canopy cover for BIGMAP vs 10% canopy cover for FIA), leading to acreage estimates from BIGMAP that are smaller than those from FIA (see Table S2; Ty Wilson, personal communication). LEMMA produced a custom forest type group based on FIA plot data with a more permissive forest mask than FIA (Matthew Gregory, personal communication), which allowed us to counterbalance the more restrictive forest mask employed for BIGMAP.

To triangulate a forest type map close to FIA estimates from these three sources, we created an overlay of all three datasets using the Combine tool in ArcGIS Pro and then tested a series of hierarchical decisions for each pixel (for example, prioritizing BIGMAP>LEMMA>CALVEG categorizations or prioritizing BIGMAP for California mixed conifer pixels and LEMMA for Western oak pixels). We fine-tuned these hierarchies by forest type group, testing sensitivities in overall map accuracy to varying pixel-level classifications of forest type group from each existing dataset. We arrived at our final custom dataset by choosing the categorizations from each existing dataset that best fit the FIA acreage estimates and most accurately represented the most common or important forest type groups for our model. The final acreage estimate from our map is within the 95% confidence interval for the FIA acreage estimate (Table S2; USDA Forest Service 2021a), as are the estimates for 14 out of 19 forest type groups. Of the remaining five groups, two are within 6% of the FIA estimate (California mixed conifer and Western oak groups), two are within 17% of FIA (Pinyon/juniper and Lodgepole pine groups), and one is within 23% of the FIA acreage estimate (Other western softwoods group).

2. 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.

3. 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), historic disturbance type (the most common disturbance type over the last 500+ years), and last disturbance type that created the current forest stand.

Table S2. Comparison of California forest area estimates by forest type group from FIA, existing geospatial datasets, and the custom map created for this study.

Forest Type Group		Forest Area (acres)					
TYPGRPCD	Description	FIA	FIA 95% CI	CALVEG	LEMMA	BIGMAP	This study
180	Pinyon / juniper group	**1,518,347**	*1,357,676-1,679,018*	1,723,679	2,104,481	1,006,829	**1,329,709**
200	Douglas-fir group	**1,168,264**	*1,022,200-1,314,328*	3,255,141	1,470,699	1,314,903	**1,308,647**
220	Ponderosa pine group	**2,364,286**	*2,154,643-2,573,929*	3,577,284	2,705,364	2,077,919	**2,186,356**
240	Western white pine group	**145,624**	*87,273-203,976*	78,254	172,691	-	**144,649**
260	Fir / spruce / mountain hemlock group	**1,990,449**	*1,789,794-2,191,104*	2,650,304	2,004,443	1,671,358	**1,870,346**
280	Lodgepole pine group	**943,549**	*805,703-1,081,394*	422,980	779,064	619,455	**779,064**
300	Hemlock / Sitka spruce group	**27,052**	*3,446-50,658*	66,294	33,783	203	**31,261**
340	Redwood group	**793,233**	*668,579-917,888*	1,506,189	619,822	1,000,316	**875,321**
360	Other western softwoods group	**1,961,721**	*1,767,370-2,156,073*	487,519	1,446,015	941,343	**1,504,517**
370	California mixed conifer group	**7,715,167**	*7,393,890-8,036,444*	7,664,268	7,374,930	9,556,277	**8,090,744**
700	Elm / ash / cottonwood group	**38,725**	*13,291-64,158*	66,930	74,828	11,824	**40,165**
900	Aspen / birch group	**63,775**	*28,176-99,373*	51,582	55,862	1,118	**51,169**
910	Alder / maple group	**221,886**	*154,592-289,179*	158,125	276,917	804	**213,855**
920	Western oak group	**9,097,214**	*8,750,667-9,443,761*	6,823,174	13,503,576	7,212,434	**9,677,267**
940	Tanoak / laurel group	**1,789,154**	*1,606,943-1,971,366*	328,400	1,904,658	1,699,356	**1,734,315**
960	Other hardwoods group	**559,099**	*448,701-669,497*	793,951	817,205	43,742	**534,757**
970	Woodland hardwoods group	**104,100**	*60,528-147,671*	19,796	426,327	7,288	**97,309**
990	Exotic hardwoods group	**4,305**	*0-10,275*	32,863	-	-	**9,413**
999	Nonstocked	**1,099,960**	*950,823-1,249,098*	-	1,193,384	44,068	**987,912**
	Total area	31,605,908	*31,230,200-31,981,616*	29,706,733	36,964,048	27,209,237	31,466,776

For this analysis, we used methodologies derived from Bechtold & Patterson (2005) and Pugh et al. (2018) to estimate California'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 California 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 historic 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, but these data are difficult to collect for some California forest types (like oak woodlands). 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 mean 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.

4. 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, Mac Siurtain, and Colbert 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 and alder/maple forest type groups each had insufficient plot density for unique yield curves and were instead assigned values from the other hardwoods 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.

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

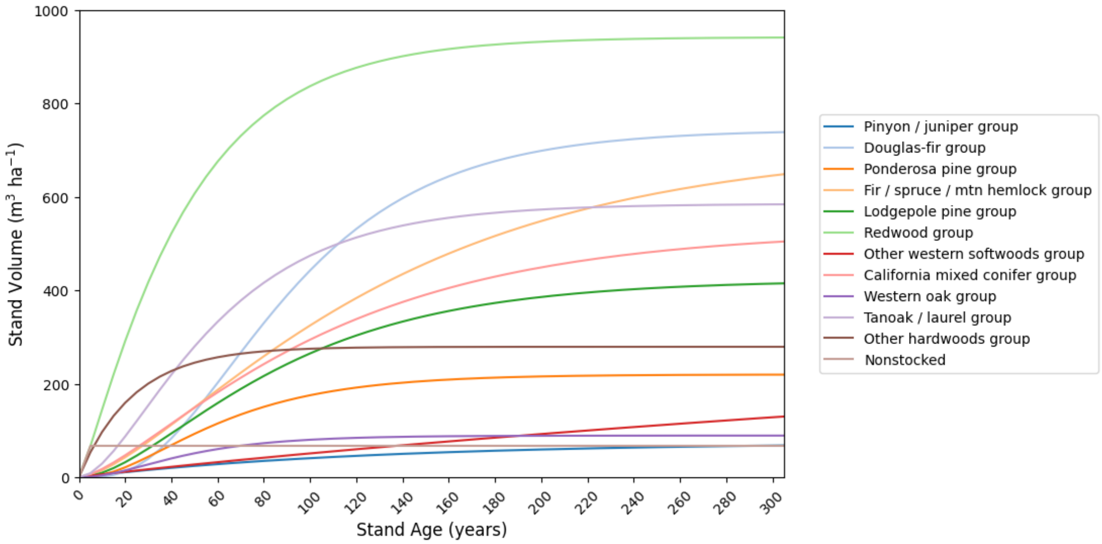

Figure S1. Example of empirically derived yield curves for forest type groups in California under USFS ownership (OWNGRPCD = 10) with a low productivity class (Productivity Class = 2) or average productivity (where all productivity classes have been aggregated due to small sample sizes).

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 S3), applied in the age class corresponding with 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 California. We replaced existing default allometric equations for relevant forest types with recalibrated equations for California conditions, calculated by applying coefficients from Boudewyn et al. (2007) to volume and biomass values from FIA (USDA Forest Service 2021a) following this 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 California. 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 California by 3.4%, though changes vary by tree species ("Overview of the National Scale Volume and Biomass Estimators (NSVB): State Report for California" 2023).

5. *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 California 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 CAL FIRE (CAL FIRE 2024a; 2024b; 2024c; 2024d), 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 California, 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. This is consistent with other efforts within the state, such as those by the Task Force, to compile BAU management practices from multiple sources (Carrie Levine, personal communication).

All datasets listed above are spatially explicit, providing shapefiles for various management practices and ownerships. CAL FIRE datasets include Timber Harvest Plans (THP), Nonindustrial Timber Management Plans (NTMP), Vegetation Treatment Program Treatment Areas (VTP), and Notices of Emergency Timber Operations (EM), all of which are legally required by the state and apply to non-federal lands over variable periods from the 1990s-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 Historic 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. For datasets with data beyond our historic model period (2000-2021), we clipped the data to include just our target years. Datasets that did not cover this full period (VTP and LANDFIRE) were backfilled at the end of our data cleaning process (see Step 6 below).
2. CAL FIRE datasets often included dates for management plan approval, completion, and verification. To avoid overcounting acres where management plans were filed but never completed, we filtered these datasets to completed records only. Some THP records were marked with "admin closeout" dates rather than true completion dates, and these records required manual validation of completion status and year from publicly available harvest plan documentation from the CalTREES "Search Plans" tool (CalTREES 2024). FACTS and LANDFIRE data did not include this information, so we assumed all activities were completed.
3. Some dataset polygons overlapped on the same acres in a given year, either through spatial error or duplicate reporting, especially for the LANDFIRE dataset. To avoid double counting practice acres in the same year, we used a simple dataset hierarchy based on our confidence in each one to choose which data to keep: first FACTS data, then CAL FIRE data, then LANDFIRE 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 meadow restoration), 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 S3). VTP data included broad categories that did not map well to the other datasets (like "Forestland Stewardship" and "Ecological Restoration"), so we used the relative proportions of our more specific practices appropriate for each VTP category to assign VTP acres to each of our model practices.
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 VTP and LANDFIRE datasets (LANDFIRE only provides data from 2007-2016 and VTP data starts in 2005), 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 VTP and LANDFIRE datasets for years where we had data, which we applied to events from the other datasets in those missing years. This approach assumes that VTP and LANDFIRE 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 S3) 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 California, 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 S3). 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

Table S3. Management practice type, data sources, and harvest intensity modeled for California. 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 and data sources		Stand age limits	Softwood harvest intensity	Hardwood harvest intensity
High harvest	Clearcut Patch clearcut Stand clearcut Harvest – high severity	THP, LANDFIRE FACTS FACTS LANDFIRE	50-140	90% cut, 85% removed	90% cut, 0.1% removed
Intermediate harvest	Variable retention Fuelbreak/defensible space Coppice cut Improvement cut Sanitation cut Harvest – medium severity Seed tree seed/removal/ final step Shelterwood prep/ establishment/seed/ removal step Overstory removal cut	THP, NTMP NTMP FACTS FACTS FACTS LANDFIRE THP, FACTS THP, FACTS FACTS	Phase 1: 50-99 Phase 2: 100-140	50% cut, 45% removed	50% cut, 0.1% removed
Group selection	Group selection Selection Uneven aged management Group selection cut	THP, NTMP THP, NTMP NTMP FACTS	100-140	50% cut, 45% removed	50% cut, 0.1% removed
Commercial thin	Commercial thin Thinning – high severity Harvest – low severity	THP, NTMP, FACTS LANDFIRE LANDFIRE	Private lands: 30-50 Public lands: 30-140	30% cut, 25% removed	30% cut, 0.1% removed
Hazardous fuels thin	Thinning for hazardous fuels reduction Thinning – low severity	FACTS LANDFIRE	-	30% cut, no removal	30% cut, no removal
Precommercial thin	Precommercial thin Thinning – medium severity	FACTS LANDFIRE	Private lands: 5-20 Public lands: 10-20	10% cut, no removal	10% cut, no removal
Salvage	Sanitation salvage Salvage cut Emergency timber operation	THP, NTMP FACTS EM	-	90% cut, 90% removed	90% cut, 10% removed, 45% pile burned

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 California management practices.

A key component of these new disturbance matrices was the separate treatment of softwood and hardwood trees after harvest. According to the California timber harvest data used for our CBM-HWP-CA model, only an average of 0.1% of wood arriving at mills is hardwood (Marcille et al. 2020; Dillon and Morgan 2023; BBER 2022). However, volumetric removals from FIA data report that nearly 10% of the trees cut each year are hardwoods (USDA Forest Service 2021a), which may either be removed from the forest or left on site (as is often the case in California). To account for this discrepancy, we updated our harvest disturbance matrices to reflect lower overall removals of hardwood material for products, instead transitioning cut hardwood material into dead organic matter (DOM) pools where it decomposes or is later pile burned (Table S3).

Table S4. Impacts of prescribed fire and pile burns on carbon pools in CBM-CFS3 in California, 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	54% consumed 3% gain from Foliage pool	90% consumed
Aboveground Fast DOM	10-hr fuels, small wood	91% consumed 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
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	-

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 burn) in California 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 S4; 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).

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.

Natural disturbances

Natural disturbance data were collected from various geospatial data sources: wildfire data from CALFIRE (CAL FIRE 2022), the Monitoring Trends in Burn Severity (MTBS 2020), and Rapid Assessment of Vegetation Condition after Wildfire Program (RAVG 2021); and insect/disease/abiotic disturbances from National Insect and Disease Detection Surveys (USDA Forest Service 2019). 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 California 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 Monitoring Trends in Burn Severity (MTBS), Rapid Assessment of Vegetation Condition after Wildfire Program (RAVG), and National Insect and Disease Detection Surveys (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. For pixels within the CAL FIRE fire perimeters dataset that did not have severity data, we gap filled based on the relative proportion of severity for each forest type group from the same year. Based on averages from MTBS and Whittier and Gray (2016), we constructed disturbances 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, this was noted as defoliation event). Disturbance severity averages were the same for both mortality and no mortality categories, with the no mortality events only affected 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 forest vegetation has not recovered then it is deemed a land-use change (Bechtold and Patterson 2005).

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 California 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 -55,137 ac yr^{-1} from 2001-2019 (+5,110 ac yr^{-1} forest gain and -60,247 ac yr^{-1} forest loss), which is a similar trend but greater magnitude than estimates based on FIA data for the same period (+12,191 ac yr^{-1} forest gain and -31,153 ac yr^{-1} forest loss for a net change of -18,962 ac yr^{-1}; Christensen et al. 2021).

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 California hardwood material. Therefore, we modified the deforestation disturbance matrix in consultation with our state partners to include 90% removal of merchantable softwood material and only 50% removal of merchantable hardwood material, both followed by pile burning of remaining material on site. We further assume this hardwood material removed from forest loss will either be kept for residential fuelwood (50% of the time) or sent directly to a landfill (50% of the time) in the CBM-HWP-CA model.

6. *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 California 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 2022-2071 (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.

7. *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.

8. AIDB Adjustments

In addition to collecting data to parameterize these seven input tables, we also updated the AIDB with California-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 California. To find California MAT values, we aggregated mean monthly temperature from PRISM Climate Group (PRISM Climate Group 2024; Daly et al. 2008) into annual values and calculated annual averages for 2000-2021 using the *terra* package in R (Hijmans 2020). 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) and calculated statewide forestland MAT of 11.69 C from 2000-2021. We applied this MAT for our entire simulation period from 2000-2071.

Harvested Wood Products Model Methodology

The harvested wood products model (CBM-HWP-CA), 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).

1. 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-CA tracks carbon going into HWP, including where it goes, its path to get there, and how long it spends in different pools before ultimately being retired (Report Figure 4). It 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 works by tracking proportions of carbon as they move through the HWP stream. For example, a certain proportion of merchantable timber entering the stream will first be exported; a proportion of what 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 *historic carbon* (i.e., carbon entering the HWP stream before the start of our BAU scenario) was calculated using estimates of annual California harvest volumes from USDA Forest Service (Marcille et al. 2020; Dillon and Morgan 2023) 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 California according to Marcille et al. (2020), applied this to BBER (2022) harvest volumes (which do not include bark), and 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 California, 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 S5). Each of these flows has unique rules and utilization pathways within the CBM-HWP-CA model, as discussed below. CBM-CFS3 harvest removals include carbon in bark, so we used the bark expansion factor mentioned above to partition these removals into the bark residue proportion (15.9%) and the wood proportion (84.1%). This wood proportion was further partitioned into the industrial roundwood and utilized biomass flows to represent merchantable and nonmerchantable material, respectively. This step required different calculations for softwood and hardwood material, driven by different wood utilization patterns for hardwoods as described above. For softwoods, we assumed that utilized biomass was represented by the flow of harvested material to bioenergy in Marcille et al. (2020) from 22.4% of roundwood (excluding bark). We therefore calculated the overall proportion of utilized biomass from CBM-CFS3 softwood harvest as 18.8% (22.4% utilized biomass from 84.1% of harvest removals that are wood) and allocated the remaining 65.3% of harvested softwood material (the remainder of the 84.1% of harvest removals that are wood) to the industrial roundwood input flow (Table S5). None of our softwood harvest removals were partitioned to the residential fuelwood or direct-to-landfill flows.

For hardwood removals, these partitions were calculated more dynamically based on the modeled volume of material removed from salvage and permanent forest conversion in each scenario. For any salvage activity in hardwood forest types, we assumed that 100% of the cut material would be allocated to the residential fuelwood flow as firewood. Hardwood material coming from permanent forest conversion form land-use change (deforestation) was split evenly between the residential fuelwood and direct-to-landfill flows, assuming that half the material would be used as firewood and half would be discarded along with other detritus from land clearing activities. We made these assumptions based on conversations with state partners, spurred by the very small hardwood roundwood utilization (1.8% of harvested roundwood, excluding bark) shown in Marcille et al. (2020) that indicated very different utilization patterns between softwood and hardwood material. The remaining partitions of harvested hardwood material to bark residue, utilized biomass, and industrial roundwood were calculated dynamically based on the amount of material entering the fuelwood and landfill flows. For the CBAU scenario, for example, an average of 43% of harvested hardwood material was allocated directly to landfills and 51.5% was used as residential fuelwood. The small remaining portion of hardwood removals was distributed between utilized biomass (4.6%), bark residue (0.9%), and industrial roundwood (0.1%; Table S5).

Table S5. Carbon flow splits for input harvested wood volumes in the CBM-HWP-CA model. Hardwood flow proportions vary based on modeled removals from salvage and deforestation activities in each scenario. Values shown in this table are for the CBAU scenario. 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	0.9%	4.6%	0.1%	51.5%	43%
Softwood	15.9%	18.8%	65.3%	-	-

2. *Exports*

We calculated HWP exports at two stages: raw roundwood exports before commodity production, and commodity exports after production. We used California roundwood export data from the US International Trade Commission trade database (USITC 2024) to determine both proportions of harvested material exported and destination countries and found that California exported 4.1% of softwood roundwood harvested in 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 S2). Destination countries were binned into three categories based on their weighted-average HWP half-life (Table S6; 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 S6. Export destination country bins based on product-weighted average HWP half-life.

Bin	Half-Life Range	Average Half-Life	Major Countries
1	2-5 years	3 years	China
2	5-15 years	9 years	Brazil, Mexico, Vietnam, Italy, India
3	15-30 years	20 years	Canada, Germany, Malaysia

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 again binned by destination country based on average HWP half-life (Table S5).

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-CA. We used mill efficiency data from 1952-2019 (Marcille et al. 2020; Scott 2024) to estimate mill residues as a proportion of total harvest volume after export for domestic HWP. We found that California mills have an average mill efficiency of 44% for softwoods and 48% for hardwoods, meaning that the remaining material – 56% and 52% of total harvest after export for softwoods and hardwoods, 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 Marcille et al. (2020) and Scott (2024) for 1952-2019: pulpwood (only until 1960), composite panels, bioenergy, and other industrial uses (see Report Table 3 and Figure S2 for proportions for softwoods and hardwoods).

4. *Primary Product Ratios*

As noted above, CBM-HWP-CA works by tracking proportions of carbon as they move through HWP streams. These proportions come from *primary product ratios*, which partition harvest volume inputs into various commodities based on their relative historic production. Upon entering the CBM-HWP-CA 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 three domestic commodity pools and four mill residue uses (as noted above) following primary product ratios for California from Marcille et al. (2020) and Scott (2024) from 1952-2019 (Report Table 3, Figure S2). Again, we 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, 92.1% for composite panels, and 98% for poles. We allocated any end-loss carbon that occurs when products are placed into their end-use (7.5% for lumber, 7.9% for composite panels, and 2% for poles) directly to landfills.

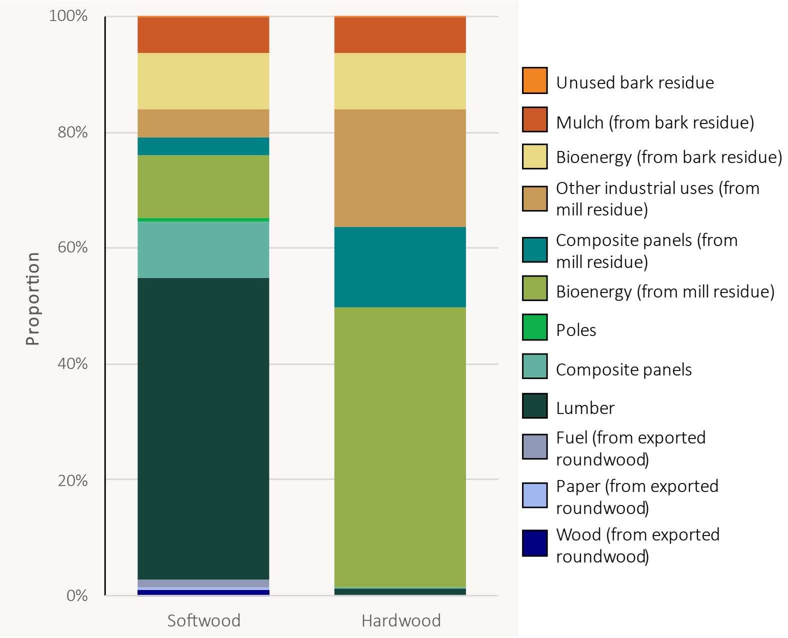

Figure S2. Primary product ratios for commodities produced in California in 2019, differentiated between softwood and hardwood inputs.

5. *Additional Wood Products Streams*

Aside from the model flows related to industrial roundwood, our CBM-HWP-CA model also includes additional wood products streams for residential fuelwood, bark residue, utilized biomass, and direct-to-landfill material, informed by data from Marcille et al. (2020), Scott (2024), and our state partners. Carbon in residential fuelwood 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 substitution benefits for scenarios with additional residential fuelwood relative to CBAU – as described below, substitution benefits were calculated for produced commodities only. 99.99% of utilized biomass also provided immediate carbon emissions via industrial bioenergy uses, though 0.01% was used for log furniture. Bark residues, including bark stripped from exported roundwood, were more evenly split between bioenergy (60.9%) and mulch and landscaping products (38.9%), with 0.2% going unused. We assumed that direct-to-landfill material came mostly from cut hardwoods and residues from permanent forest conversion, in small enough sizes to decompose at a rate similar to landfilled paper (see Product Retirement and Landfills section below).

6. *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 Marcille et al. (2020) to calculate softwood- and hardwood-specific half-lives for all commodities currently produced in California, weighted by wood product market share for each product following the IPCC approach (Pingoud et al. 2006). We also relied on IPCC defaults from Pingoud et al. (2006) for half-lives for international wood, fuel, 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 by assuming all mass timber 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), differentiated by softwood (85.5 years) and hardwood (73.3 years) materials. 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. We assumed a half-life of zero for transportation fuel, as we do for all fuel sources. See Report Table 3 for half-life assumptions for both domestic and international product use.

7. 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 **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 IPCC defaults on biodegradable proportions of landfilled material (Towprayoon et al. 2019) to determine that 10% of landfilled wood and 50% of landfilled paper could eventually be 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 from the California Air Resources Board and IPCC (CARB 2022b; Towprayoon et al. 2019) to these decomposable fractions; half-lives were assumed to be 30.52 years for wood and 17 years for paper. International landfilled product half-lives, also from IPCC, were modeled at 26.5 years for wood and 13.5 years for paper. Finally, we used CARB (2022b) methane generation (k) rates to apply methane emissions of 0.02271 m^3 yr^{-1} from wood and paper. We assumed that 72.8% of generated methane was flared (creating emissions of CO_2 rather than methane) and 27.2% was unrecovered (CARB 2022b). CBM-HWP-CA reports all landfill emissions in mtCO_2e.

Leakage and Substitution Benefit Calculation Methodology

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

1. 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).

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). In this analysis, we applied leakage only to harvest emissions and products derived from industrial roundwood, including lumber, composite panels, and uses of roundwood bark and mill residue. Given that most pulpwood cut in California is pile burned or goes directly into fuelwood and landfills, it is not reasonable to assume that reductions in in-state pulpwood harvest would incur leakage from outside the state.

We calculated that an average of 98.3% of wood products are derived from industrial roundwood sources (including bark and mill residues) in our model, and this figure dropped to 89.8% when we excluded incidental removals from salvage and permanent forest conversion. We therefore assumed that 89.8% of harvested material qualified for the "leakable" industrial roundwood category in our model, and we applied a leakage factor of 80% to this material based on input from our state partners to represent the higher end of potential leakage rates in the literature (Gan and McCarl 2007; Wear and Murray 2004; Pan et al. 2020). This means that 80% of reduced roundwood harvest relative to BAU was assumed to leak out-of-state and the remaining 20% 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.

2. *Substitution Benefits*

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.

We used displacement factors from Cabiyo et al. (2021), which include emissions from harvest, transport, and production but do not factor in building operational emissions. We did not differentiate displacement factors by wood type – all softwood and hardwood products are assumed to displace the same number of emissions from alternative products. These factors were applied only to lumber (0.75 tC/tC), composite panel (0.75 tC/tC), transportation fuels (0.63 tC/tC), and mass timber (1.75 tC/tC) products.

Economic Analysis Methodology

To assess the economic implications of our modeled forest management and wood utilization pathways, we analyzed three economic metrics: 1) estimated treatment costs, 2) potential wood product revenue, and 3) processing capacity constraints. Data inputs and results were processed using Excel and R.

1. *Estimated Treatment Costs*

We used variable cost assumptions for each scenario based on the treatment activities modeled (Table S7). Costs for model activities meant to simulate a harvest-type action (high harvest, intermediate harvest, group selection, commercial thin) were based on the volume removed, not the area treated. Our assumptions were based on data from 81 green timber sales and 14 salvage timber sales from US Forest Service Region 5 from 2017-2021 (USDA Forest Service 2022), which include both stump-to-truck costs as well as erosion control and maintenance. These estimates generally align with recent academic research (Chang et al. 2023). Costs of removing utilized biomass, such as tops and limbs, came from Chang et al. (2023). Mechanical resilience treatment costs (the "resilience mechanical thin" activity used in the fire resilience scenarios) were derived from average per-acre reimbursement rates under the California Forest Improvement Program (CFIP) from 2015-2023 (CAL FIRE 2023). Resilience hand thin costs were taken from Chang et al. (2023) assuming a chainsaw felling system with no extraction, processing, or loading. We derived pile burn costs from Barker et al. (forthcoming) and prescribed fire costs from an analysis of 1,702 US Forest Service fires from 2010-2023 (Figel 2024). There is evidence that these costs may be underestimates given current conditions – however, as prescribed fire use expands in California, we expect economies of scale to reduce future costs per acre

(Hesseln 2000; Hunter and Taylor 2022). Our reforestation costs covered tree planting, site preparation activities, follow-up slash disposal, and herbicide application. To be conservative, we assumed two rounds of site preparation and herbicide applications to ensure successful tree survival. We again used CFIP reimbursement rates to estimate these costs (CAL FIRE 2023).

Table S7. Treatment activity cost estimates based on current rates in California and an additional 35% cost reflecting administrative costs and reasonable profit margins.

Model Activity	Estimated Activity Cost ($ USD)
High harvest Intermediate harvest Group selection Commercial thin Hazardous fuels thin Precommercial thin	Merchantable timber: \$59.43 GT^{-1} Biomass: \$16.99 BDT^{-1}
Salvage	\$53.92 GT^{-1}
Prescribed Fire	\$286 ac^{-1}
Pile Burn	\$735 ac^{-1}
Resilience Mechanical Thin	\$1,742 ac^{-1}
Resilience Hand Thin	\$1,088 ac^{-1}
Reforestation Post-fire Restoration	Tree planting: \$625 ac^{-1} Site prep and slash disposal (2x): \$1,290 ac^{-1} Herbicide (2x): \$835 ac^{-1} Total: \$4,874 ac^{-1}

GT = green metric ton
BDT = bone dry metric ton

Often, costs reported in the literature or through various programs do not reflect administrative costs or reasonable profit margins. To account for this, we assumed that all modeled activities will incur an additional 35% cost reflecting these two factors. We assumed that costs were constant over time in real inflation-adjusted 2024 dollars, and results should be interpreted in real terms as well. It is possible that as a large-scale forest health management program ramps up, tight labor and equipment markets may push up costs at a higher rate than inflation. It is also possible that markets adjust and the sector expands to accommodate this.

Stumpage costs assumptions were derived from bi-annual estimates produced by the California Department of Tax and Fee Administration (CDTFA; 2024). CDFTA conducts regular stumpage value surveys to assess the California Timber Tax on harvesting entities. We used regional averages from 2019—2024 (Table S8), using weights based on harvested species information derived from the California Timber Product Output program (Marcille et al. 2020).

Table S8. Stumpage cost assumptions by forest product region.

Forest Product Region	$/MBF	$/GT
Central Coast	182	44
North Coast	264	64
Northern Interior	186	45
Sacramento	160	39
San Joaquin	99	24
Southern California	52	13

MBF = thousand board feet
GT = green metric ton

Haul costs are a major driver of total treatment cost and vary considerably depending on the distance of the treated area to the nearest sawlog or biomass processing facility. To account for the fact that some regions in California have more processing capacity than others, we calculated average haul costs for each of the six forest product regions in our model. Travel times between each forested FIA plot in California and the nearest processing facility were calculated using the USFS HaulTime model (Gatziolis 2022), with separate haul times estimated for the nearest sawlog processing facility and the nearest facility that processes utilized biomass. We then assumed a haul cost for the region that averaged haul times across all FIA plots.

Haul costs for each region (r) for each biomass type (p) per unit of material removed were then calculated as follows:

$$HaulCost_{r.p} = \left(2 * HaulTime_{r.p} + 1\right) * \frac{MachineRate_p}{LoadedWeight_p}$$

where total haul time is the round trip haul time plus an hour for loading and unloading. Machine rates were assumed to be $163/hour and $154/hour for log trucks and biomass chip vans, respectively (Chang et al. 2023). Loaded weights were assumed to be 22.7 metric tons (t) for log trucks and 13.8 metric bone dry tons (BDT) for biomass chip vans (Chang et al. 2023). We estimated average one-way haul time for each region and facility type (sawmill and bioenergy facility) and then calculated cost per unit of material transported in the model (Table S9).

Table S9. Estimated haul times and haul costs for sawmills and bioenergy facilities by forest product region.

Forest Product Region	Nearest Sawmill (one-way hours)	Haul Cost – Sawlogs ($/t)	Nearest Bioenergy Facility (one-way hours)	Haul Cost – Biomass ($/BDT)
Central Coast	1.85	$33.80	2.30	$62.70
North Coast	1.08	$22.70	1.48	$44.30
Northern Interior	1.39	$27.20	1.68	$48.80
Sacramento	1.10	$23.00	1.24	$39.00
San Joaquin	1.68	$31.40	1.90	$53.70
Southern California	2.20	$38.70	2.83	$74.60

2. Potential Wood Product Revenues

Potential harvested wood product revenues were calculated for a range of pricing assumptions to reflect variation in both log and biomass markets. These markets vary considerably across a number of factors, such as log size, species type, and geography. Prices also vary considerably over time in response to broader log and biomass market conditions. For delivered industrial roundwood logs, we assumed three price levels ($250/MBF, $400/MBF, and $550/MBF) representing the potential spectrum from weak to strong timber markets. While state-wide log pricing is not available in California, our price assumptions generally reflect ranges seen in other western log markets (Figure S3; Rayonier Inc. 2024). For utilized biomass, we assumed prices of $0/BDT, $20/BDT, and $40/BDT.

As noted in the results in the Costs, Revenues, and Wood Processing Capacity section of the report, these log and biomass price levels do not provide full treatment cost recovery under most conditions. However, they are reflective of the current markets, especially for biomass, in California, based on personal communication with market participants. Biomass prices will likely need to be much higher, perhaps up to $100/BDT, to meaningfully contribute to offsetting treatment costs (Cabiyo et al. 2021).

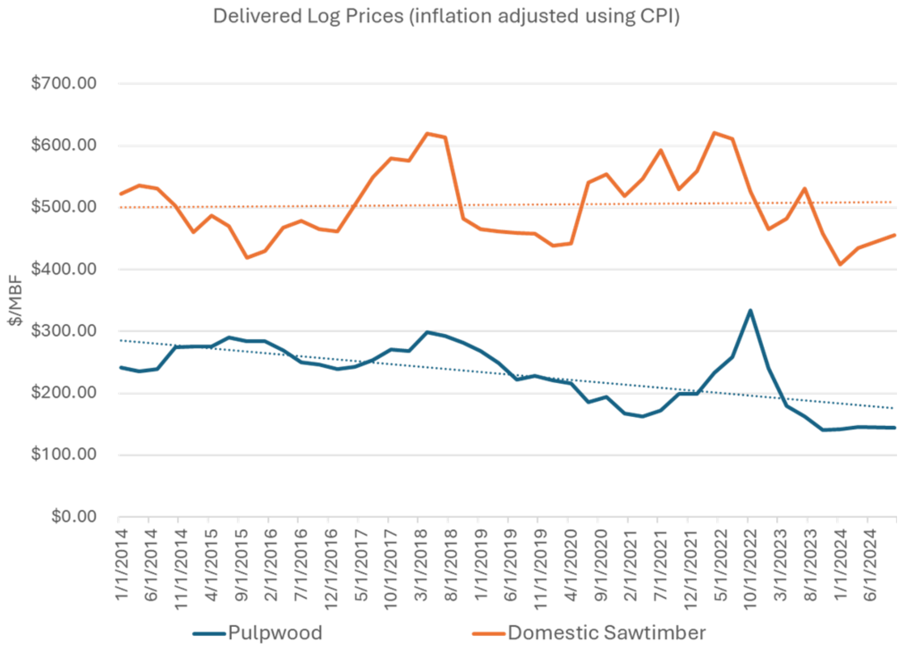

Figure S3. 10 years of inflation-adjusted pulplog and sawlog prices ($ per thousand board feet, MBF) for the Pacific Northwest, as reported in quarterly financial reports by Rayonier Inc. (2024), a timberland real estate investment trust (REIT).

3. *Processing Capacity Constraints*

Mill-level timber utilization was estimated by multiplying installed mill capacity by a state-wide lumber overrun factor of 1.72 from Scott et al. (2024). The lumber overrun estimates the volume of lumber (board feet, lumber tally) per volume of timber input (board feet, scribner). While lumber overruns will vary by mill based on individual mill efficiencies, this methodology allows for a general method of converting mill capacity (in board feet, lumber tally) to timber product demand (in board feet, scribner).

Bioenergy capacity was estimated for 14 facilities that are known to consume primarily forest-based biomass as their primary feedstock. Facilities that utilize mill residues for electricity production were excluded since these are not likely to accept the extra in-forest residues being modeled in our scenarios. 2023 electric power production levels for these facilities were taken from the California Energy Commission Quarterly Fuel and Energy Report (QFER; California Energy Commission 2024). We assumed that 1 BDT would produce 1MWh of electricity. This approach may underestimate biomass demand from the electric power sector for 2 reasons. First, there are facilities that accept biomass that do not currently use in-forest biomass but could potentially do so in the future. Second, our estimate is based on production, not capacity, so production could plausibly increase in the future.

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-CA model.

Climate-Adjusted Business-As-Usual

In recognition of the growing influence of climate change already evident in California'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 2022-2071. This includes modified frequency and severity of natural disturbance events (Westerling 2018; Cal-Adapt 2018; Parks et al. 2016; 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 relative to our BAU projection, we used projections of future acreage or probability of natural disturbance events. For wildfire, we extracted modeled annual area burned by county and decade from 2006-2071 from the Cal-Adapt Wildfire tool (Cal-Adapt 2018), which is based on data from the Fourth California Climate Assessment (Westerling 2018). We chose the high emissions (RCP 8.5) scenario with the central (BAU) population scenario and used an average of the four available GCMs (HadGEM2-ES, CNRM-CM5, CanESM2, MIROC5). We then calculated an annual average of area burned for each decadal period and created a multiplier for increasing fire area by comparing our base period (in this case, 2006-2021) to future decades. We applied this multiplier to the wildfire events in our BAU model by county, filtering only 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). This resulted in an increase in moderate severity fire of +197,432 acres per year and high severity fire of +216,010 acres per year (Report Table 2).

We took a slightly different approach for modifying insect, disease, and abiotic disturbances, based on data from Anderegg et al. (2022). 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. 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 degrees 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 again 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. 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 S10). Though these data are projected only through 2050, we applied these new transition rules for our entire projection period from 2022-2071 for consistency.

Lastly, we incorporated projected declines in productivity due to climate mismatch to modify our yield curves. We extracted data on the average % decline in productivity (%DP) for all modeled species from 2020-2100 from the Climate-Adapted Seed Tool (Stewart and Wright 2023) by seed zone and elevation band. We then overlaid a seed zone map (CAL FIRE 1970) with rasters of our model classifiers to summarize average %DP by forest type group (Table S11) 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) in our model beginning in 2022.

Landscape Restoration

The Landscape Restoration scenario was designed to address post-fire reforestation and restoration needs in California and was constructed with two parts. First, our state partners were interested in the carbon outcomes of addressing the known post-fire reforestation backlog in the state, estimated to be 1.5 million acres from the 2000-2021 wildfires (USDA Forest Service 2024a). 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 10 years from 2022-2031.

Second, we added additional post-fire salvage (plus site prep activities like prescribed fire) and reforestation activities to combat the post-fire regeneration failure added for the CBAU scenario. We

Table S10. 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	Deserts	Eastside	Klamath / Interior Coast Ranges	North Coast	Sierra / Cascades	South Coast and Mountains
180	Pinyon / juniper group	-	90%	84%	-	91%	95%
200	Douglas-fir group	-	82%	78%	80%	73%	-
220	Ponderosa pine group	-	87%	81%	81%	86%	94%
240	Western white pine group	-	73%	71%	74%	68%	-
260	Fir / spruce / mountain hemlock group	-	80%	74%	76%	74%	93%
280	Lodgepole pine group	-	76%	70%	71%	73%	92%
300	Hemlock / Sitka spruce group	-	-	56%	60%	71%	-
340	Redwood group	-	-	74%	79%	-	-
360	Other western softwoods group	-	86%	80%	78%	82%	94%
370	California mixed conifer group	-	84%	80%	81%	84%	95%
700	Elm / ash / cottonwood group	-	81%	-	-	85%	-
900	Aspen / birch group	-	82%	67%	-	82%	-
910	Alder / maple group	-	-	78%	81%	80%	-
920	Western oak group	100%	87%	83%	82%	87%	94%
940	Tanoak / laurel group	-	83%	79%	80%	81%	93%
960	Other hardwoods group	100%	86%	82%	82%	85%	94%
970	Woodland hardwoods group	-	87%	77%	-	87%	96%
990	Exotic hardwoods group	98%	88%	81%	81%	85%	96%
999	Nonstocked	-	90%	84%	-	91%	95%

created a new “Post-fire Restoration” disturbance type to model this, using the disturbance matrix for salvage since it also includes prescribed fire, and used transition rules to restart forest growth in the year following the restoration activities. We targeted this practice at future modeled areas of post-fire regeneration failure, limited to non-reserve areas (RESERVCD=0) and mild and moderate slopes (Slope Class=1 or 2) where salvage and site prep operations would be feasible. We scheduled these events to occur within a relative 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).

Table S11. Estimated average productivity decline (%DP) by forest type group.

Forest Type Group		%DP
TYPGRPCD	Description	
180	Pinyon / juniper group	32%
200	Douglas-fir group	22%
220	Ponderosa pine group	31%
240	Western white pine group	30%
260	Fir / spruce / mountain hemlock group	30%
280	Lodgepole pine group	31%
300	Hemlock / Sitka spruce group	21%
340	Redwood group	21%
360	Other western softwoods group	31%
370	California mixed conifer group	29%
700	Elm / ash / cottonwood group	28%
900	Aspen / birch group	31%
910	Alder / maple group	23%
920	Western oak group	27%
940	Tanoak / laurel group	21%
960	Other hardwoods group	26%
970	Woodland hardwoods group	32%
990	Exotic hardwoods group	25%
999	Nonstocked	30%

For both reforestation and restoration disturbance types, we assumed reforestation occurred at low density based on research from North et al. (2022), represented by the "poorly stocked" stocking class (ALSTKCD=4).

Fire Resilience and Expand Fire Resilience Treatments to Mature and Old-Growth Forest

The Fire Resilience and Expand Fire Resilience Treatments to Mature and Old-Growth Forest (MOG Resilience) scenarios represent one of the biggest priorities for our state partners: increasing resilience treatments across the landscape to reduce the risk and severity of wildfire. State efforts have set goals for increasing treatments to one million acres per year by 2025 (California Wildfire and Forest Resilience Task Force 2021), and modeling for CARB's 2022 Scoping Plan (2022a) identified a need for 2.3 million acres of treatment per year in order to meet statewide emissions goals by 2045.

While these restoration targets encompass all of California's natural and working lands, forests will be a key ecosystem for these fire resilience treatments. Rather than starting with an acreage target for our fire resilience scenarios, we conducted a fire resilience needs assessment for California'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 10-year period.

For our needs assessment, we utilized a map of wildfire hazard potential (WHP; Vogler et al. 2021), an index that quantifies the potential for wildfires to both ignite and be difficult to control, to determine where treatments were most needed. We overlaid this WHP map with rasters of our model classifiers (Ecoregion, OWNGRPCD, slope class, productivity class, and RESERVCD), the forest type group map from LEMMA (2022), and geospatial datasets of wildland-urban interface (CAL FIRE 2019), critical habitat (USFWS 2020), statewide networks of roads (CAL FIRE 2012) and powerlines (California Energy Commission 2020), and fire protection responsibility areas (CAL FIRE 2021) to allow filtering of WHP areas by important ecological conditions or operational considerations. We employed the LEMMA forest type group map, the most expansive of the forest type datasets discussed above, in order to cast the widest net for areas of potential fire resilience treatment need. We classified all pixels within 1,000 feet of a road as having road access and all other pixels as inaccessible from roads, an important logistical constraint determining the kinds of resilience treatments that are feasible to implement. We classified utility corridors as all pixels within 200 feet of a powerline, where we might expect resilience treatments with heavier biomass removal. We included data on wildland-urban interface, ecoregion, and fire protection responsibility areas to enable future prioritization and targeting of treatments, though we did not use these factors in developing our modeling scenarios.

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 scaled down our total acreage estimate (derived from the LEMMA forest type map) to better align with FIA forest area estimates using the relative proportion of needs assessment acres within each FIA forest type group. We filtered our results to focus just on high and very high WHP, where treatments are most urgently needed. We excluded steep slopes (over 70%) from treatment eligibility, given the difficulty of implementing treatments in such steep terrain. Overall, we found 11.2 million acres of forest with high and very high WHP in need of near-term fire resilience treatments (Report Table 1).

This 11.2-million-acre total demonstrates the significant need for fire resilience treatments in California'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 critical habitat acres were deemed ineligible for mechanical and hand thin activities and were therefore limited to prescribed fire treatments. Using these filters, we found that only 7.3 million acres of forest are likely to be eligible for resilience treatments given current techniques, technologies, and policies (Table S12). This total includes 5.2 million acres eligible for mechanical thinning with follow-up prescribed fire, 1.1 million acres eligible for hand thinning and pile burning, and 1 million acres eligible for prescribed fire only.

Table S12. Acres in need of and eligible for fire resilience treatments by treatment approach, ownership, and ecoregion.

Treatment approach: mechanical thin followed by prescribed fire after 15-30 years, maintained with prescribed fire every 15-30 years

Eligibility requirements: slopes from 0-49%, not designated wilderness, not critical habitat, selected forest types (California mixed conifer, Douglas-fir, ponderosa pine, redwood, western oak, fir/spruce/mountain hemlock, lodgepole pine, western white pine)

	Ownership								Total Acres
Ecoregion	USFS	BLM	NPS	Other federal	State/ local	Tribal	Private industrial	Private	
North Coast	3,247	2,320	412	356	1,831	738	21,743	27,527	58,175
Klamath/Interior Coast Ranges	897,953	62,548	-	5,137	12,546	16,482	242,774	171,949	1,409,390
Sierra/Cascades	1,926,750	103,942	-	4,942	38,505	6,527	685,262	357,296	3,123,223
Eastside	218,129	24,783	-	149	1,139	563	60,049	46,064	350,877
Central Coast and Interior Ranges	49,390	22,831	-	20,802	5,653	-	179	2,520	101,375
Central Valley	-	108	-	3	10	7	-	0	128
Deserts, South Coast and Mountains	150,975	7,862	-	1,111	5,435	18,433	-	7,381	191,196
Total Acres	3,246,445	224,394	412	32,500	65,119	42,750	1,010,007	612,737	5,234,363

Table S12, cont. Acres in need of <u>*and*</u> *eligible for fire resilience treatments by treatment approach, ownership, and ecoregion.*

Treatment approach: hand thin followed by pile burn after 5 years, maintained with hand thin/pile burn every 20 years

Eligibility requirements: slopes 50-69%, not designated wilderness, not critical habitat, selected forest types (California mixed conifer, Douglas-fir, ponderosa pine, pinyon/juniper, tanoak/laurel)

	Ownership								Total Acres
Ecoregion	USFS	BLM	NPS	Other federal	State/ local	Tribal	Private industrial	Private	
North Coast	1,408	5,306	874	77	5,527	1,674	47,907	71,718	**134,490**
Klamath/Interior Coast Ranges	329,435	13,285	23	373	3,238	25,631	12,447	55,359	**439,790**
Sierra/Cascades	249,694	34,756	351	226	2,809	1,604	17,252	31,055	**337,747**
Eastside	10,710	3,992	-	28	415	53	88	1,656	**16,942**
Central Coast and Interior Ranges	13,228	5,860	57	1,944	7,294	-	329	25,602	**54,314**
Central Valley	-	1	-	2	-	-	-	41	**45**
Deserts, South Coast and Mountains	84,767	5,354	127	232	5,113	1,520	-	11,078	**108,191**
Total Acres	**689,243**	**68,552**	**1,433**	**2,881**	**24,397**	**30,482**	**78,022**	**196,510**	**1,091,520**

Treatment approach: prescribed fire every 10-30 years

Eligibility requirements: slopes 50-69%, not critical habitat, selected ownerships and forest types (California mixed conifer, Douglas-fir and ponderosa pine on NPS land, western oak on public and Tribal land, redwood)

	Ownership								Total Acres
Ecoregion	USFS	BLM	NPS	Other federal	State/ local	Tribal	Private industrial	Private	
North Coast	338	3,473	2,132	1	8,156	80	7,008	3,423	**24,610**
Klamath/Interior Coast Ranges	466,524	13,628	203	88	6,090	3	908	1,606	**489,050**
Sierra/Cascades	173,240	3,424	158,748	6,335	19,262	1	609	755	**362,374**
Eastside	2,757	-	-	-	5	-	-	4	**2,765**
Central Coast and Interior Ranges	40,940	230	382	100	11,737	-	245	1,901	**55,535**
Central Valley	-	-	-	5	34	-	-	-	**39**
Deserts, South Coast and Mountains	61,976	5,043	176	50	20,804	12	-	82	**88,143**
Total Acres	**745,775**	**25,797**	**161,641**	**6,578**	**66,087**	**96**	**8,769**	**7,770**	**1,022,515**

We modeled this area to receive initial treatments at a steady rate over 10 years from 2022-2031, equating to an average of 735,000 acres per year of additional fire resilience treatments above CBAU during this period. We developed new disturbance matrices for the thinning treatments to represent different cutting intensities and product removal rates for the mechanical thin (40% of biomass cut with 35% product removal for softwoods; 20% biomass cut with 15% product removal for hardwoods) and hand thin (5% biomass cut, all slash piled and no product removals) practices. 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, forest type group, and ownership (Table S13), driving the average activity footprint during the treatment phase (2022-2031) to roughly 790,000 acres per year. We did not include follow-up mechanical thinning activities, emphasizing the return of beneficial fire to the landscape as the key maintenance mechanism for our scenarios.

For the Fire Resilience scenario, we used BAU harvest age limits for the mechanical and hand thin treatments, limiting those activities to inventory records at most 140 years old. For the MOG Resilience scenario, we altered these age restrictions to allow for mechanical thinning in all stands below the old-growth age threshold defined by the US Forest Service (2023c), which varies by forest type and site productivity (Table S13). We also lifted the age restriction entirely for hand thin activities to allow for these treatments in forests of all ages, including old-growth (Table S13). This scenario uses the same acreage targets as the Fire Resilience scenario but has expanded eligibility so more forest can potentially be treated in each year of our model.

Innovative Wood Utilization Scenarios

We ran both the Fire Resilience and MOG Resilience scenarios with BAU wood utilization parameters and with three variations of innovative wood products: biochar, transportation fuels, and mass timber. For the scenarios with BAU wood utilization parameters, additional harvested material was used in the same way as in the base CBM-HWP-CA model (described in the **Harvested Wood Products Model Methodology** section above), just in larger volumes. Notably, additional cut biomass that is not normally utilized was modeled as being left on site to decompose or burn.

For the Biochar and Transportation Fuel scenarios, we diverted this additional cut biomass (non-merchantable) material from fire resilience treatments into biochar or transportation fuels, respectively, after satisfying the current capacity of active bioenergy facilities so as not to model a disruption of the existing bioenergy industry. Note this does not include currently mothballed facilities. This led to variable amounts of material transferred into innovative products each year, depending on how much additional material was cut and removed – but the bioenergy facility capacity was only exceeded during the initial resilience treatment pulse from 2022-2031. In subsequent years, follow-up treatments were more dispersed and forests were less overstocked, so treatments did not generate additional biomass material beyond bioenergy capacity. All additional roundwood (merchantable) material followed BAU wood utilization assumptions. For the Biochar scenario, we created a new biochar product stream in the CBM-HWP-CA 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. For the Transportation Fuels scenario, we created a new transportation fuels product stream in the CBM-HWP-CA model with a half-life of zero (assuming immediate combustion) and calculated substitution benefits (0.63 tC/tC) based on displacing traditional fuel sources (Cabiyo et al. 2021).

For the Mass Timber scenario, we assumed that all additional roundwood (merchantable) material removed during fire resilience treatments would be diverted from lumber into mass timber production, after satisfying the demand from currently active sawmills to preserve the current supply of lumber in

Table S13. Eligibility and treatment intervals for fire resilience treatments in the MOG Resilience scenario. Bolded items indicate important eligibility filters.

Forest Type Group	Ownership	Ecoregion	Slope Class	Stand Age	Productivity Class	Reserve Status	Critical Habitat Status	Thinning	Rx Fire
California mixed conifer, Douglas-fir, Ponderosa pine	USFS, Other Federal, State/ Local	All	All	All	All	**Reserve**	All	-	Every 20 years
			0-49%	**<189 years (CMC) <180 years (DF) <142 years (PP)**	Productive	Not reserve	All	Mechanical thin (40% biomass cut, 35% removed)	Follow up every 15 years
				<256 years (CMC) <260 years (DF) <200 years (PP)	Not productive	Not reserve	All	Mechanical thin (40% biomass cut, 35% removed)	Follow up every 15 years
			50-69%	**<189 years (CMC) <180 years (DF) <142 years (PP)**	Productive	Not reserve	All	Hand thin (5% biomass cut); repeat on 15-year cycle	Follow up pile burn 5 years later; repeat on 15-year cycle
				<256 years (CMC) <260 years (DF) <200 years (PP)	Not productive	Not reserve	All	Hand thin (5% biomass cut); repeat on 15-year cycle	Follow up pile burn 5 years later; repeat on 15-year cycle
	NPS	All	All	All	All	All	All	-	Every 20 years
	Private, Private industrial	All	0-49%	**<189 years (CMC) <180 years (DF) <142 years (PP)**	Productive	All	All	Mechanical thin (40% biomass cut, 35% removed)	Follow up every 15 years
				<256 years (CMC) <260 years (DF) <200 years (PP)	Not productive	All	All	Mechanical thin (40% biomass cut, 35% removed)	Follow up every 15 years
			50-69%	All	All	All	All	-	-
Western oak (Oak woodlands)	All	All	All	All	All	All	**Critical habitat**	-	-
	USFS, Other Federal, State/ Local, Native American	All	0-49%	All	All	**Reserve**	Not critical habitat	-	Every 10 years
			0-49%	All	All	Not reserve	Not critical habitat	Mechanical thin (20% biomass cut, 15% removed)	Follow up every 10 years
			50-69%	All	All	Not reserve	Not critical habitat	-	-
	NPS	All	0-49%	All	All	All	Not critical habitat	-	Every 10 years
			50-69%	All	All	All	Not critical habitat	-	-
	Private, Private industrial	All	All	All	All	All	Not critical habitat	-	-

Table S13, cont. *Eligibility and treatment intervals for fire resilience treatments in the MOG Resilience scenario.*

Forest Type Group	Ownership	Ecoregion	Slope Class	Stand Age	Productivity Class	Reserve Status	Critical Habitat Status	Thinning	Rx Fire
Redwood (Coast Redwood)	All	North Coast, Central Coast & Interior Ranges	All	All	All	All	**Critical habitat**	-	-
			0-49%	**<150 years**	Productive	All	Not critical habitat	Mechanical thin (40% biomass cut, 35% removed)	Follow up every 30 years
				<200 years	Not productive	All	Not critical habitat	Mechanical thin (40% biomass cut, 35% removed)	Follow up every 30 years
			50-69%	**<150 years**	Productive	All	Not critical habitat	-	Every 30 years
				<200 years	Not productive	All	Not critical habitat	-	Every 30 years
Redwood (Giant Sequoia)	All	Sierra/ Cascades, Klamath/ Interior Coast Ranges	All	All	All	All	**Critical habitat**	-	-
							Not critical habitat	-	Every 30 years
Fir/spruce/ mountain hemlock, Lodgepole pine, Western white pine	All	All	All	All	All	All	**Critical habitat**	-	-
	USFS, Other federal, State/ Local, Native American, Private, Private Industrial	All	All	All	All	**Reserve**	Not critical habitat	-	-
			0-49%	**<150 years <151 years (FSM)**	Productive	Not reserve	Not critical habitat	Mechanical thin (40% biomass cut, 35% removed)	-
				<200 years <247 years (FSM)	Not productive	Not reserve	Not critical habitat	Mechanical thin (40% biomass cut, 35% removed)	-
			50-69%	All	All	Not reserve	Not critical habitat	-	-
	NPS	All	All	All	All	All	Not critical habitat	-	Every 20 years
Pinyon/ juniper, Tanoak/ laurel	All	All	All	All	All	All	**Critical habitat**	-	-
							Not critical habitat	Hand thin (5% biomass cut); repeat on 15-year cycle	Follow up pile burn 5 years later; repeat on 15-year cycle
All other groups	All	All	All	All	All	All	All	-	-

the state. Fire resilience treatments continued to generate additional roundwood material above current sawmill capacity even after the initial 10-year treatment pulse, in contrast with the more limited production of additional biomass material in the Bioenergy and Transportations Fuels scenarios. Note that though California is currently a net importer of lumber, we did not assume any additional merchantable material would be used to satisfy this current lumber demand; instead, we diverted all additional material to mass timber to explore the impacts of this innovative wood product on California's net forest carbon balance. All additional cut biomass (non-merchantable) material followed BAU wood utilization assumptions. We created a new mass timber product stream in the CBM-HWP-CA model with a half-life of 85.5 years for softwood inputs and 73.3 years for hardwood inputs (Row and Phelps 1996; Skog and Nicholson 1998; 2000; J. E. Smith et al. 2006) and substitution benefits of 1.75 tC/tC (Cabiyo et al. 2021) based on the assumption that all mass timber would go to construction end uses.

Forest Conservation

The Forest Conservation scenario was constructed to examine the influence of decreasing permanent forest loss to land-use change (largely to development, but also to other non-forest land uses). We parameterized this scenario to include a linear decrease in the amount of CBAU forest loss (which can also be framed as an increase in forest conservation activities) from 2022-2045. The rate of forest loss in this scenario started at 60,248 ac yr^{-1} from 2000-2021, decreasing in a compound way from 2022-2045 by 2,397 ac yr^{-1} until reaching a new equilibrium of 5,109 ac yr^{-1} in 2045, equal to the rate of forest gain to create a state of no net forest loss from land-use change from 2045-2071. The compounding decrease in forest loss leads to the conservation of 716,803 acres of forest from 2022-2045 and 2,150,404 acres from 2022-2071.

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 California.

We used data from the Reforestation Hub (The Nature Conservancy and American Forests 2023; Cook-Patton et al. 2020) that identifies 219,000 acres of pastureland with the potential for reforestation in California. We constructed our Silvopasture scenario to establish silvopastoral systems via tree planting on all 219,000 acres at a linear rate of 9,125 ac yr^{-1} from 2022-2045. 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 modeled all silvopasture acres with the "poorly stocked" stocking class (ALSTKCD=4) and the most common native forest type group for each ecoregion (Table S14) 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

Table S14. Forest type groups used for Silvopasture scenario by ecoregion.

Ecoregion	TYPGRPCD	Description
Central Coast and Interior Ranges	920	Western oak group
Central Valley	920	Western oak group
Deserts	370	California mixed conifer group
Eastside	940	Tanoak / laurel group
Klamath/Interior Coast Ranges	180	Pinyon / juniper group
North Coast	370	California mixed conifer group
Sierra/Cascades	-	-
South Coast and Mountains	-	-

to model this method to prioritize maintaining current forest extent in California and to illustrate the potential for adding trees to pastureland.

Extended Rotations and Altered Rotations

Changing harvest rotations, 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; CARB 2015). However, extended rotations may come at a cost in fire-prone landscapes (Badgley et al. 2022). Through engagement with stakeholders in this project, some private industrial land managers indicated that they are considering shortening their rotations in response to growing wildfire risk to avoid losing their timber revenue.

We constructed two scenarios to examine the relative impacts of these diverging strategies for harvest rotations. We modeled our Extended Rotations scenario as an increase in the modeled minimum harvest age for commercial management, raising it from 50 to 80 years for all forest types and land ownership. Our Altered Rotations scenario utilized this same harvest extension from 50 to 80 years for public lands and included a shortening of rotations from 50 to 40 years on all private and Native American lands. While not all these landowners may be interested in shorter rotations, our model is constrained by the OWNGRPCD classifier and lumps all private and Native American lands together, so we had to apply this shorter rotation to the entire category. Both scenarios applied to our high harvest, intermediate harvest, and group selection management practices. For the multi-entry harvest types (intermediate harvest and group selection), we also adjusted the age limitations for subsequent cuts to reflect the change in age at first entry.

Ramp Up Implementation Portfolio

In addition to the individual scenarios described above, we created two portfolios of multiple concurrent scenarios to illustrate the compounding impacts of pursuing multiple climate-smart strategies simultaneously. We constructed the Ramp Up Implementation (Ramp Up) portfolio by combining the Landscape Restoration and MOG Resilience scenarios.

We ran the Ramp Up portfolio with BAU HWP assumptions from the CBM-HWP-CA model and with Innovative Wood Utilization. This time, instead of diverting additional harvested material into a single innovative product, we modeled a product trifecta where all three products (biochar, transportation fuels, and mass timber) were created at once. For the mass timber portion, we assumed that all additional roundwood (merchantable) material removed during fire resilience and landscape restoration (i.e. salvage) treatments would be diverted from lumber into mass timber production, after satisfying the demand from currently active sawmills. We assumed that all additional cut biomass (non-merchantable) material from fire resilience and salvage treatments was split evenly between biochar and transportation fuel production, after satisfying the current capacity of active bioenergy facilities.

Max Natural Climate Solutions by 2045 Portfolio

We constructed the Max Natural Climate Solutions by 2045 (Max NCS) portfolio to illustrate the full NCS potential of the climate-smart practices included in this analysis. This portfolio includes Landscape Restoration, MOG Resilience, Forest Conservation, Silvopasture, and Extended Rotations scenarios. We ran the Max NCS portfolio with BAU HWP assumptions and with the Innovative Wood Utilization assumptions described for the Ramp Up portfolio above. Though we completed the modeling for this study prior to the release of CNRA's Nature-Based Solutions Climate Targets (2024), there is alignment between the practices included in our Max NCS portfolio and CNRA's forest-related targets (Table S15). Our results can therefore illustrate the climate change mitigation potential of at least partial accomplishment of these targets.

Table S15. Comparison of CNRA nature-based solutions climate targets (2024) with targets used in the Max NCS portfolio for this study. Bolded items indicate CNRA targets that were modeled in this study.

CNRA Forest Category	CNRA target (ac yr^{-1})			Target in this study (ac yr^{-1})		
	2030	2038	2045	2030	2038	2045
Afforestation Oak woodland reestablishment	52,900	52,900	52,900	9,125 (silvopasture)	9,125 (silvopasture)	9,125 (silvopasture)
Conservation **Conserve old-growth,** conserve conifer, riparian, and oak woodland forests	55,100	55,100	55,100	34,268	8,843	7,466
Restoration **Post-high severity fire reforestation and restoration,** restore oak woodlands including enhancing riparian zones	322,100	462,100	322,100	299,321	171,960	171,960
Beneficial Fire **Rx burn, cultural burn, planned managed fire,** planned treatment burned in wildfire	800,000	1,200,000	1,500,000	622,539 (309,030 Rx fire, 313,509 managed fire)	718,747 (413,718 Rx fire, 305,029 managed fire)	784,882 (413,718 Rx fire, 371,164 managed fire)
Other Fuel Reduction Activities **Thinning,** invasive species removal, grazing, **mechanical treatments, uneven-aged harvest**	700,000	800,000	1,000,000	794,265	270,827	270,827
Working Forest Conservation **Extend rotations,** shift intensity of harvest, restore/conserve wildlife habitat	165,200	165,200	165,200	114,864	114,864	114,864
Decrease Conversion **Decrease illegal conversion** and forest degradation by:	-20%	-50%	-90%	-34% *	-65% *	-92% *
Shift to Low/Moderate Severity Fire **Through beneficial fire and other fuel reduction activities, shift the proportion of statewide high severity wildfire to low or moderate severity wildfire** so that:	75% of wildfire is low/mod severity	83% of wildfire is low/mod severity	90% of wildfire is low/mod severity	82% of wildfire is low/mod severity	82% of wildfire is low/mod severity	82% of wildfire is low/mod severity

* Note that the Decrease Conversion targets in this study do not differentiate between legal and illegal forest conversion.

Additional Scenario Results

Table S16a. BAU and CBAU scenario results showing periodic averages of forest area (million acres) by ownership class and ecoregion from 2022-2071. Totals may not sum due to independent rounding.

Forest Area (million acres)

		Ownership Class									
Ecoregion	Period	All		USFS		Other Federal		State / Local		Private / Native American	
		BAU	CBAU	BAU	CBAU	BAU	CBAU	BAU	CBAU	BAU	CBAU
Central Coast and Interior Ranges	2022-2031	1.74	1.74	0.25	0.25	0.12	0.12	0.33	0.33	1.05	1.05
	2032-2045	1.73	1.73	0.25	0.25	0.12	0.12	0.33	0.33	1.04	1.04
	2046-2071	1.72	1.72	0.24	0.24	0.12	0.12	0.33	0.33	1.03	1.03
Central Valley	2022-2031	0.10	0.10	+	+	+	+	0.02	0.02	0.09	0.09
	2032-2045	0.10	0.10	+	+	+	+	0.02	0.02	0.09	0.09
	2046-2071	0.10	0.10	+	+	+	+	0.02	0.02	0.09	0.09
Deserts	2022-2031	0.18	0.18	0.01	0.01	0.12	0.12	0.01	0.01	0.05	0.05
	2032-2045	0.18	0.18	0.01	0.01	0.12	0.12	0.01	0.01	0.05	0.05
	2046-2071	0.18	0.18	0.01	0.01	0.12	0.12	0.01	0.01	0.05	0.05
Eastside	2022-2031	2.64	2.61	1.52	1.51	0.60	0.59	0.01	0.01	0.51	0.50
	2032-2045	2.60	2.53	1.50	1.46	0.59	0.59	0.01	0.01	0.50	0.47
	2046-2071	2.54	2.38	1.47	1.37	0.59	0.58	0.01	0.01	0.47	0.42
Klamath / Interior Coast Ranges	2022-2031	7.91	7.42	4.46	4.10	0.32	0.28	0.07	0.07	3.07	2.97
	2032-2045	7.54	6.08	4.24	3.17	0.27	0.17	0.07	0.06	2.96	2.68
	2046-2071	6.94	3.77	3.89	1.49	0.19	0.11	0.07	0.04	2.79	2.12
North Coast	2022-2031	2.73	2.71	0.04	0.04	0.15	0.14	0.29	0.29	2.25	2.24
	2032-2045	2.72	2.66	0.04	0.04	0.15	0.14	0.29	0.28	2.25	2.20
	2046-2071	2.70	2.58	0.04	0.04	0.15	0.14	0.28	0.27	2.24	2.14
Sierra / Cascades	2022-2031	14.80	14.14	7.81	7.34	1.52	1.48	0.28	0.27	5.19	5.06
	2032-2045	14.61	12.54	7.70	6.21	1.51	1.37	0.27	0.26	5.12	4.69
	2046-2071	14.28	9.04	7.52	3.75	1.49	1.13	0.27	0.25	5.00	3.92
South Coast and Mountains	2022-2031	1.14	1.05	0.79	0.72	0.06	0.05	0.08	0.07	0.21	0.20
	2032-2045	1.10	0.85	0.76	0.57	0.06	0.05	0.08	0.06	0.21	0.17
	2046-2071	1.05	0.56	0.72	0.34	0.05	0.04	0.08	0.05	0.19	0.12
All	2022-2031	**31.25**	**29.96**	14.87	13.95	2.88	2.79	1.08	1.07	12.42	12.15
	2032-2045	**30.59**	**26.67**	14.50	11.69	2.81	2.55	1.07	1.03	12.20	11.39
	2046-2071	**29.51**	**20.33**	13.88	7.24	2.71	2.23	1.06	0.97	11.85	9.88

+ Does not exceed 1,000 acres

Table S16b. *BAU and CBAU scenario results showing periodic averages of ecosystem carbon stocks (MtCO$_2$e) by <u>ownership class and ecoregion</u> from 2022-2071. Totals may not sum due to independent rounding.*

Ecosystem Carbon Stocks (MtCO$_2$e)

Ecoregion	Period	Ownership Class									
		All		USFS		Other Federal		State / Local		Private / Native American	
		BAU	CBAU	BAU	CBAU	BAU	CBAU	BAU	CBAU	BAU	CBAU
Central Coast and Interior Ranges	2022-2031	516.4	514.4	72.2	71.9	24.6	24.6	116.2	115.6	303.4	302.4
	2032-2045	512.6	506.2	71.8	70.4	24.7	24.5	116.8	115.0	299.3	296.2
	2046-2071	508.6	492.5	71.8	68.2	25.0	24.5	117.9	113.5	293.8	286.4
Central Valley	2022-2031	26.3	26.3	+	+	0.1	0.1	4.6	4.6	21.5	21.5
	2032-2045	26.3	26.2	+	+	0.1	0.1	4.6	4.6	21.5	21.4
	2046-2071	26.3	26.2	+	+	0.1	0.1	4.7	4.7	21.5	21.4
Deserts	2022-2031	41.1	41.0	0.8	0.8	28.0	27.9	2.8	2.8	9.4	9.4
	2032-2045	41.1	41.0	0.8	0.8	28.0	28.0	2.8	2.8	9.5	9.4
	2046-2071	41.3	40.9	0.7	0.7	28.2	28.0	2.9	2.8	9.6	9.4
Eastside	2022-2031	476.1	470.4	296.8	293.4	89.4	88.8	2.9	2.8	87.1	85.4
	2032-2045	466.4	446.1	290.1	276.6	90.3	88.6	3.0	2.8	83.0	78.1
	2046-2071	449.6	405.4	277.2	248.2	91.8	88.0	3.1	2.8	77.4	66.4
Klamath / Interior Coast Ranges	2022-2031	2673.6	2495.0	1685.9	1549.1	101.4	92.0	20.1	19.2	866.3	834.6
	2032-2045	2550.9	2031.3	1600.5	1185.8	88.8	67.0	20.2	17.6	841.4	760.9
	2046-2071	2367.5	1281.4	1471.4	585.9	74.4	56.3	20.3	14.3	801.3	624.9
North Coast	2022-2031	1388.2	1372.6	25.9	25.6	87.3	86.2	163.0	161.0	1112.0	1099.8
	2032-2045	1409.4	1366.5	26.7	25.9	90.2	86.6	167.9	162.1	1124.7	1091.9
	2046-2071	1426.8	1335.0	27.4	25.8	93.5	85.6	173.4	161.2	1132.5	1062.4
Sierra / Cascades	2022-2031	3986.2	3779.6	2280.3	2123.1	443.4	427.0	76.6	75.6	1185.9	1153.9
	2032-2045	3845.6	3206.3	2189.6	1703.4	426.4	378.4	76.4	73.1	1153.2	1051.5
	2046-2071	3620.7	2124.7	2044.1	930.3	398.3	282.6	75.7	65.9	1102.6	845.9
South Coast and Mountains	2022-2031	244.5	223.8	164.9	149.7	9.8	9.1	22.0	20.6	47.9	44.3
	2032-2045	234.6	176.3	157.1	113.5	9.5	7.8	22.1	18.9	45.8	36.2
	2046-2071	219.5	111.8	145.4	63.7	9.1	6.3	22.4	16.4	42.6	25.5
All	2022-2031	**9352.4**	**8923.1**	4526.7	4213.7	784.0	755.7	408.2	402.2	3633.4	3551.4
	2032-2045	**9087.0**	**7799.9**	4336.5	3376.3	758.2	681.0	413.8	396.9	3578.5	3345.7
	2046-2071	**8660.1**	**5818.0**	4038.1	1922.7	720.4	571.4	420.5	381.6	3481.2	2942.3

+ Does not exceed 12 metric tons (mt) CO$_2$e

Table S16c. *BAU and CBAU scenario results showing periodic averages of annual net ecosystem carbon flux (MtCO$_2$e yr^{-1}) by ownership class and ecoregion from 2022-2071. 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 represent a net carbon sink and positive numbers represent a net carbon source. Totals may not sum due to independent rounding.*

Net Ecosystem Carbon Flux (MtCO$_2$e yr^{-1})

Ecoregion	Period	Ownership Class									
		All		USFS		Other Federal		State / Local		Private / Native American	
		BAU	CBAU	BAU	CBAU	BAU	CBAU	BAU	CBAU	BAU	CBAU
Central Coast and Interior Ranges	2022-2031	0.2	0.4	+	0.1	--	--	-0.1	--	0.2	0.4
	2032-2045	0.1	0.4	--	0.1	--	--	-0.1	+	0.2	0.3
	2046-2071	--	0.5	--	0.1	--	--	-0.1	0.1	0.1	0.3
Central Valley	2022-2031	--	+	+	+	+	+	--	--	--	+
	2032-2045	--	--	--	+	+	+	--	--	--	--
	2046-2071	--	--	--	+	+	+	--	--	--	--
Deserts	2022-2031	--	--	+	+	--	--	--	--	--	--
	2032-2045	--	--	+	+	--	--	--	--	--	--
	2046-2071	--	--	+	+	--	--	--	--	--	--
Eastside	2022-2031	0.3	0.6	0.3	0.5	-0.1	--	--	--	0.1	0.2
	2032-2045	0.5	1.2	0.4	1.0	-0.1	--	--	--	0.2	0.3
	2046-2071	0.5	1.2	0.5	0.9	-0.1	--	--	--	0.1	0.3
Klamath / Interior Coast Ranges	2022-2031	4.7	8.2	3.6	6.1	0.4	0.5	--	+	0.8	1.6
	2032-2045	4.2	8.8	3.3	7.5	0.3	0.2	--	+	0.7	1.2
	2046-2071	3.7	7.9	3.0	6.3	0.1	--	--	+	0.6	1.6
North Coast	2022-2031	-2.4	-1.2	-0.1	-0.1	-0.3	-0.2	-0.5	-0.3	-1.6	-0.6
	2032-2045	-1.9	-0.9	-0.1	-0.1	-0.2	-0.1	-0.4	-0.3	-1.2	-0.4
	2046-2071	-0.8	0.2	--	--	-0.1	-0.1	-0.3	-0.1	-0.3	0.4
Sierra / Cascades	2022-2031	9.9	14.3	6.2	9.3	1.3	1.7	--	+	2.4	3.3
	2032-2045	8.7	16.9	6.0	12.0	1.2	1.8	--	0.1	1.5	3.0
	2046-2071	8.5	17.5	5.5	11.6	1.2	2.0	+	0.2	1.8	3.6
South Coast and Mountains	2022-2031	0.4	0.7	0.3	0.5	+	+	--	+	0.1	0.2
	2032-2045	0.3	0.7	0.3	0.6	+	+	--	+	0.1	0.1
	2046-2071	0.3	0.7	0.2	0.5	+	+	--	+	0.1	0.1
All	2022-2031	**13.1**	**23.0**	10.3	16.4	1.3	1.9	-0.6	-0.3	2.0	4.9
	2032-2045	**11.9**	**27.2**	9.8	21.0	1.2	1.8	-0.6	-0.1	1.4	4.5
	2046-2071	**12.2**	**27.9**	9.2	19.4	1.1	1.9	-0.4	0.2	2.3	6.4

+ Positive value not greater than 0.005 MtCO$_2$e yr^{-1}
-- Negative value not less than -0.005 MtCO$_2$e yr^{-1}

Table S16d. CBAU and Max NCS scenario results showing periodic averages of forest area (million acres) by ownership class and ecoregion from 2022-2071. Totals may not sum due to independent rounding.

Forest Area (million acres)

Ecoregion	Period	Ownership Class									
		All		USFS		Other Federal		State / Local		Private / Native American	
		CBAU	Max NCS	CBAU	Max NCS	CBAU	Max NCS	CBAU	Max NCS	CBAU	Max NCS
Central Coast and Interior Ranges	2022-2031	1.74	1.74	0.25	0.25	0.12	0.12	0.33	0.33	1.05	1.05
	2032-2045	1.73	1.75	0.25	0.25	0.12	0.12	0.33	0.33	1.04	1.06
	2046-2071	1.72	1.75	0.24	0.25	0.12	0.12	0.33	0.33	1.03	1.06
Central Valley	2022-2031	0.10	0.11	+	+	+	+	0.02	0.02	0.09	0.09
	2032-2045	0.10	0.12	+	+	+	+	0.02	0.02	0.09	0.10
	2046-2071	0.10	0.12	+	+	+	+	0.02	0.02	0.09	0.10
Deserts	2022-2031	0.18	0.20	0.01	0.01	0.12	0.12	0.01	0..1	0.05	0.07
	2032-2045	0.18	0.25	0.01	0.01	0.12	0.12	0.01	0.01	0.05	0.12
	2046-2071	0.18	0.27	0.01	0.01	0.12	0.12	0.01	0.01	0.05	0.14
Eastside	2022-2031	2.61	2.64	1.51	1.52	0.59	0.60	0.01	0.01	0.50	0.51
	2032-2045	2.53	2.61	1.46	1.5	0.59	0.59	0.01	0.01	0.47	0.51
	2046-2071	2.38	2.60	1.37	1.49	0.58	0.59	0.01	0.01	0.42	0.50
Klamath / Interior Coast Ranges	2022-2031	7.42	7.84	4.10	4.42	0.28	0.32	0.07	0.07	2.97	3.04
	2032-2045	6.08	7.47	3.17	4.19	0.17	0.28	0.06	0.07	2.68	2.92
	2046-2071	3.77	7.03	1.49	3.96	0.11	0.24	0.04	0.07	2.12	2.77
North Coast	2022-2031	2.71	2.72	0.04	0.01	0.14	0.15	0.29	0.29	2.24	2.25
	2032-2045	2.66	2.72	0.04	0.04	0.14	0.15	0.28	0.29	2.20	2.25
	2046-2071	2.58	2.72	0.04	0.04	0.14	0.15	0.27	0.29	2.14	2.25
Sierra / Cascades	2022-2031	14.14	14.73	7.34	7.75	1.48	1.51	0.27	0.28	5.06	5.19
	2032-2045	12.54	14.41	6.21	7.55	1.37	1.48	0.26	0.27	4.69	5.10
	2046-2071	9.04	14.02	3.75	7.32	1.13	1.45	0.25	0.27	3.92	4.98
South Coast and Mountains	2022-2031	1.05	1.13	0.72	0.77	0.05	0.06	0.07	0.08	0.20	0.22
	2032-2045	0.85	1.11	0.57	0.75	0.05	0.06	0.06	0.08	0.17	0.23
	2046-2071	0.56	1.09	0.34	0.72	0.04	0.05	0.05	0.07	0.12	0.24
All	2022-2031	**29.96**	**31.12**	13.95	14.76	2.79	2.87	1.07	1.08	12.15	12.41
	2032-2045	**26.67**	**30.44**	11.69	14.28	2.55	2.80	1.03	1.07	11.39	12.28
	2046-2071	**20.33**	**29.61**	7.24	13.78	2.23	2.72	0.97	1.07	9.88	12.04

+ Does not exceed 1,000 acres

Table S16e. CBAU and Max NCS scenario results showing periodic averages of ecosystem carbon stocks (MtCO₂e) by ownership class and ecoregion from 2022-2071. Totals may not sum due to independent rounding.

Ecosystem Carbon Stocks (MtCO₂e)

Ecoregion	Period	Ownership Class									
		All		USFS		Other Federal		State / Local		Private / Native American	
		CBAU	Max NCS	CBAU	Max NCS	CBAU	Max NCS	CBAU	Max NCS	CBAU	Max NCS
Central Coast and Interior Ranges	2022-2031	514.4	515.2	71.9	71.6	24.6	24.5	115.5	115.5	302.4	303.6
	2032-2045	506.2	509.6	70.4	70.1	24.5	24.3	115.0	114.8	296.2	300.4
	2046-2071	492.5	499.6	68.2	67.9	24.5	24.0	113.5	113.1	286.4	294.5
Central Valley	2022-2031	26.3	26.7	+	+	0.1	0.1	4.6	4.6	21.5	21.9
	2032-2045	26.2	28.0	+	+	0.1	0.1	4.6	4.6	21.4	23.2
	2046-2071	26.2	29.5	+	+	0.1	0.1	4.7	4.7	21.4	24.6
Deserts	2022-2031	41.0	43.7	0.8	0.8	27.9	28.0	2.8	2.8	9.4	12.1
	2032-2045	41.0	50.2	0.8	0.8	28.0	28.0	2.8	2.8	9.4	18.5
	2046-2071	40.9	55.6	0.7	0.7	28.0	28.2	2.8	2.8	9.4	24.0
Eastside	2022-2031	470.4	472.6	293.4	294.0	88.8	89.0	2.8	2.9	85.4	86.8
	2032-2045	446.1	456.1	276.6	281.0	88.6	89.2	2.8	2.9	78.1	83.0
	2046-2071	405.4	434.3	248.2	263.0	88.0	89.5	2.8	3.0	66.4	78.7
Klamath / Interior Coast Ranges	2022-2031	2495.0	2579.4	1549.1	1606.6	92.0	98.9	19.2	20.0	834.6	853.9
	2032-2045	2031.3	2359.2	1185.8	1438.3	67.0	89.2	17.6	19.7	760.9	812.0
	2046-2071	1281.4	2145.1	585.9	1287.2	56.3	80.3	14.3	19.6	624.9	757.9
North Coast	2022-2031	1372.6	1383.8	25.6	25.6	86.2	86.6	161.0	162.2	1099.8	1109.4
	2032-2045	1366.5	1396.0	25.9	26.1	86.6	88.2	162.1	165.5	1091.9	1116.3
	2046-2071	1335.0	1399.7	25.8	26.6	85.6	89.7	161.2	169.2	1062.4	1114.2
Sierra / Cascades	2022-2031	3779.6	3850.3	2123.1	2183.0	427.0	436.0	75.6	75.0	1153.9	1156.3
	2032-2045	3206.3	3535.9	1703.4	1955.7	378.4	406.4	73.1	73.2	1051.5	1100.5
	2046-2071	2124.7	3147.1	930.3	1687.0	282.6	359.9	65.9	70.1	845.9	1030.1
South Coast and Mountains	2022-2031	223.8	238.5	149.7	159.3	9.1	9.5	20.6	21.5	44.3	48.2
	2032-2045	176.3	226.0	113.5	147.6	7.8	9.1	18.9	21.1	36.2	48.2
	2046-2071	111.8	211.2	63.7	135.1	6.3	8.5	16.4	20.6	25.5	47.1
All	2022-2031	**8923.1**	**9110.2**	4213.7	4340.9	755.7	772.6	402.2	404.5	3551.4	3592.2
	2032-2045	**7799.9**	**8561.0**	3376.3	3919.6	681.0	734.5	396.9	404.6	3345.7	3502.2
	2046-2071	**5818.0**	**7922.2**	1922.7	3467.6	571.4	680.3	381.6	403.1	2942.3	3371.2

+ Does not exceed 12 metric tons (mt) CO₂e

Table S16f. CBAU and Max NCS scenario results showing periodic averages of annual net ecosystem carbon flux ($MtCO_2e$ yr^{-1}) by ownership class and ecoregion from 2022-2071. 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 represent a net carbon sink and positive numbers represent a net carbon source. Totals may not sum due to independent rounding.

Net Ecosystem Carbon Flux ($MtCO_2e$ yr^{-1})

Ecoregion	Period	Ownership Class									
		All		USFS		Other Federal		State / Local		Private / Native American	
		CBAU	Max NCS	CBAU	Max NCS	CBAU	Max NCS	CBAU	Max NCS	CBAU	Max NCS
Central Coast and Interior Ranges	2022-2031	0.4	0.4	0.1	0.1	--	+	--	+	0.4	0.3
	2032-2045	0.4	0.4	0.1	0.1	--	+	+	+	0.3	0.2
	2046-2071	0.5	0.5	0.1	0.1	--	+	0.1	0.1	0.3	0.3
Central Valley	2022-2031	+	--	+	--	+	+	--	--	+	--
	2032-2045	--	--	+	--	+	+	--	--	--	--
	2046-2071	--	--	+	--	+	--	--	--	--	--
Deserts	2022-2031	--	--	+	+	--	--	--	--	--	--
	2032-2045	--	-0.1	+	+	--	--	--	--	--	-0.1
	2046-2071	--	-0.1	+	+	--	--	--	--	--	-0.1
Eastside	2022-2031	0.6	1.1	0.5	0.8	--	--	--	--	0.2	0.3
	2032-2045	1.2	1.1	1.0	0.9	--	--	--	--	0.3	0.2
	2046-2071	1.2	1.0	0.9	0.8	--	--	--	--	0.3	0.2
Klamath / Interior Coast Ranges	2022-2031	8.2	18.3	6.1	14.7	0.5	0.5	+	+	1.6	3.0
	2032-2045	8.8	7.8	7.5	6.4	0.2	0.2	+	--	1.2	1.0
	2046-2071	7.9	5.9	6.3	4.6	--	0.1	+	+	1.6	1.1
North Coast	2022-2031	-1.2	-1.4	-0.1	--	-0.2	-0.2	-0.3	-0.3	-0.6	-0.9
	2032-2045	-0.9	-1.1	-0.1	--	-0.1	-0.1	-0.3	-0.3	-0.4	-0.6
	2046-2071	0.2	+	--	--	-0.1	-0.1	-0.1	-0.2	0.4	0.3
Sierra / Cascades	2022-2031	14.3	27.9	9.3	19.8	1.7	2.2	+	0.2	3.3	5.7
	2032-2045	16.9	16.5	12.0	12.2	1.8	1.8	0.1	0.1	3.0	2.4
	2046-2071	17.5	16.0	11.6	11.1	2.0	2.0	0.2	0.2	3.6	2.7
South Coast and Mountains	2022-2031	0.7	0.8	0.5	0.6	+	+	+	+	0.2	0.1
	2032-2045	0.7	0.6	0.6	0.5	+	+	+	+	0.1	0.1
	2046-2071	0.7	0.5	0.5	0.4	+	+	+	+	0.1	+
All	2022-2031	**23.0**	**47.1**	16.4	36.0	1.9	2.6	-0.3	--	4.9	8.5
	2032-2045	**27.2**	**24.9**	21.0	20.0	1.8	1.8	-0.1	-0.1	4.5	3.2
	2046-2071	**27.9**	**23.7**	19.4	17.0	1.9	2.1	0.2	0.1	6.4	4.5

\+ Positive value not greater than 0.05 $MtCO_2e$ yr^{-1}
-- Negative value not less than -0.05 $MtCO_2e$ yr^{-1}