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Wildland Fire and Fuels Science Synthesis:
Supporting Landscape and Community Resilience in the Pacific Northwest

# Wildfire and Fuel Treatment Effects on Carbon

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## Why Carbon?

Federal and state forest managers consider the effects of forest management, including no action, on carbon storage because of concerns of increasing atmospheric carbon dioxide ($CO_2$) and other greenhouse gases that contribute to global warming. Most $CO_2$ emissions in the United States result from burning fossil fuels. Forests represent a large store of carbon, but individual stands can absorb or emit substantial amounts of $CO_2$ over durations as short as a decade. Currently, wildland forests (those outside of urban zones) in the United States are a net sink of carbon, offsetting 10 percent of the total greenhouse gas emissions for the country (Domke et al. 2023). As forests under public stewardship mature and climate change increases the incidence of disturbances and droughts, the U.S. forest carbon sink is expected to decline and possibly transform into a carbon source (Coulston et al. 2023). Pacific Northwest forests have the highest carbon densities in the country (Heath et al. 2011), making the potential carbon trajectories in these forests particularly salient for the region and the nation.

There is considerable interest in understanding how management that focuses on restoration, risk reduction, and resilience in the face of increasing wildfire activity is affecting forest carbon. Answers to these questions depend on factors like forest type and condition; style, intensity, and frequency of treatments; and types and amounts of wood product conversions.

## Purpose

This synthesis summarizes the current understanding of forest carbon stocks and their changes in response to fire exclusion, natural disturbances, and fuel reduction treatments.

In this synthesis, we summarize the current understanding of forest carbon stocks, and changes in those stocks, in response to fire exclusion, natural disturbances, and fuel reduction treatments in the West Coast states (California, Oregon, and Washington). Most of the research on carbon and fire has focused on historically frequent-fire forests, but we also consider forest types with historically infrequent or variable fire. We synthesize field and simulation studies of historical and current carbon stocks, effects of management and wildfire on those stocks, and the role and implications of harvested wood products. We focus on Pacific Northwest studies if available but include information from similar forests in California (e.g., mixed conifer) for which more research on fuels, fire, and carbon has been conducted.

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## Carbon Considerations in Forest Management

National forest plan revision assessments must identify and evaluate existing information on the baseline of carbon stocks, including information about disturbance effects on carbon and future trends (CFR 2026). Outside of forest-level planning, interdisciplinary planning teams may also face public expectations to consider the effects of management actions on forest carbon stocks and emissions for National Environmental Policy Act analyses. Information in this chapter can be integrated into these analyses to supplement carbon stock and flux data summarized at the national forest level (USDA Forest Service 2025).

The state governments of California, Oregon, and Washington all have policies that encourage carbon sequestration in the forest sector through strategies that include preventing forest land conversion, promoting forest health and fuel treatments, and increasing storage in wood products (Christensen et al., in press). California's legislature and Oregon's policymakers set statewide sequestration targets for forests of 5 Tg $CO_2$e/year (Christensen et al. 2019a, 2019b). Washington's legislature adopted a policy of sequestering carbon in natural and working lands without specifying a target (Christensen et al. 2020).

The U.S. Department of Agriculture, Forest Service *Climate Adaptation Plan* promotes carbon stability in forests and wood products (USDA Forest Service 2022). The plan states, "Thoughtful carbon stewardship does not seek to maximize carbon at the expense of forest health but rather to optimize carbon within the context of ecosystem integrity and climate adaptation. Some forests, such as those at risk for high severity wildfire, might require hazardous fuels treatments and other forest health interventions that reduce carbon storage in the short term even as they stabilize carbon in the long term" (USDA Forest Service 2022).

### Talking About Forest Carbon

**biomass—**the weight of organic matter, living or dead, expressed as dry weight. (See the "U.S. Standard Equivalents" table for unit conversions relevant to biomass).

**carbon—**an element, and fundamental building block of biomass, that mostly ends up as a greenhouse gas when combusted or decomposed.

**$CO_2$ equivalent ($CO_2$e)—**a metric that describes the 100-year global warming potential of different greenhouse gases (e.g., methane, nitrous oxide, and carbon dioxide) in terms of a common unit: carbon dioxide. If a unit of carbon decomposes to carbon dioxide, the conversion is 1 Mg C = 3.667 Mg $CO_2$e.

**forest sector—**a carbon accounting category that includes forest ecosystems and the wood products extracted from them.

**greenhouse gas (GHG)—**an atmospheric constituent that absorbs infrared radiation from the planet and reradiates it to the surface (i.e., carbon dioxide, methane, nitrous oxide, and other minor compounds).

**sequestration—**the net increase in carbon over a defined period in any location or medium (e.g., ecosystems, landfills, wood products) except the atmosphere.

**stock—**the amount of carbon at one point in time in an entity or carbon "pool", such as plants, portions of plants (e.g., tree boles), dead organic matter, harvested wood products, soils, or an entire ecosystem.

## The Forest Carbon Cycle

When photosynthesis by green plants chemically fixes $CO_2$ from the atmosphere into carbohydrates, carbon is used for maintenance respiration and to create new plant matter, including foliage, wood, roots, fruits, and seeds (fig. 1). Eventually, tree mortality and regular shedding of branches, leaves, and roots transfer carbon from live trees to dead wood, duff, and litter on the forest floor, and to soils. Carbon is emitted from forest ecosystems when both live and dead plant matter are decomposed by animals and microbes or combusted by fire; however, some of the decomposed carbon becomes part of the mineral soil. While $CO_2$ is the primary molecule produced by decomposition and combustion, methane ($CH_4$) and nitrous oxide ($N_2O$) are also produced. The effect of these gases on warming is 28 and 298 times that of $CO_2$, respectively.

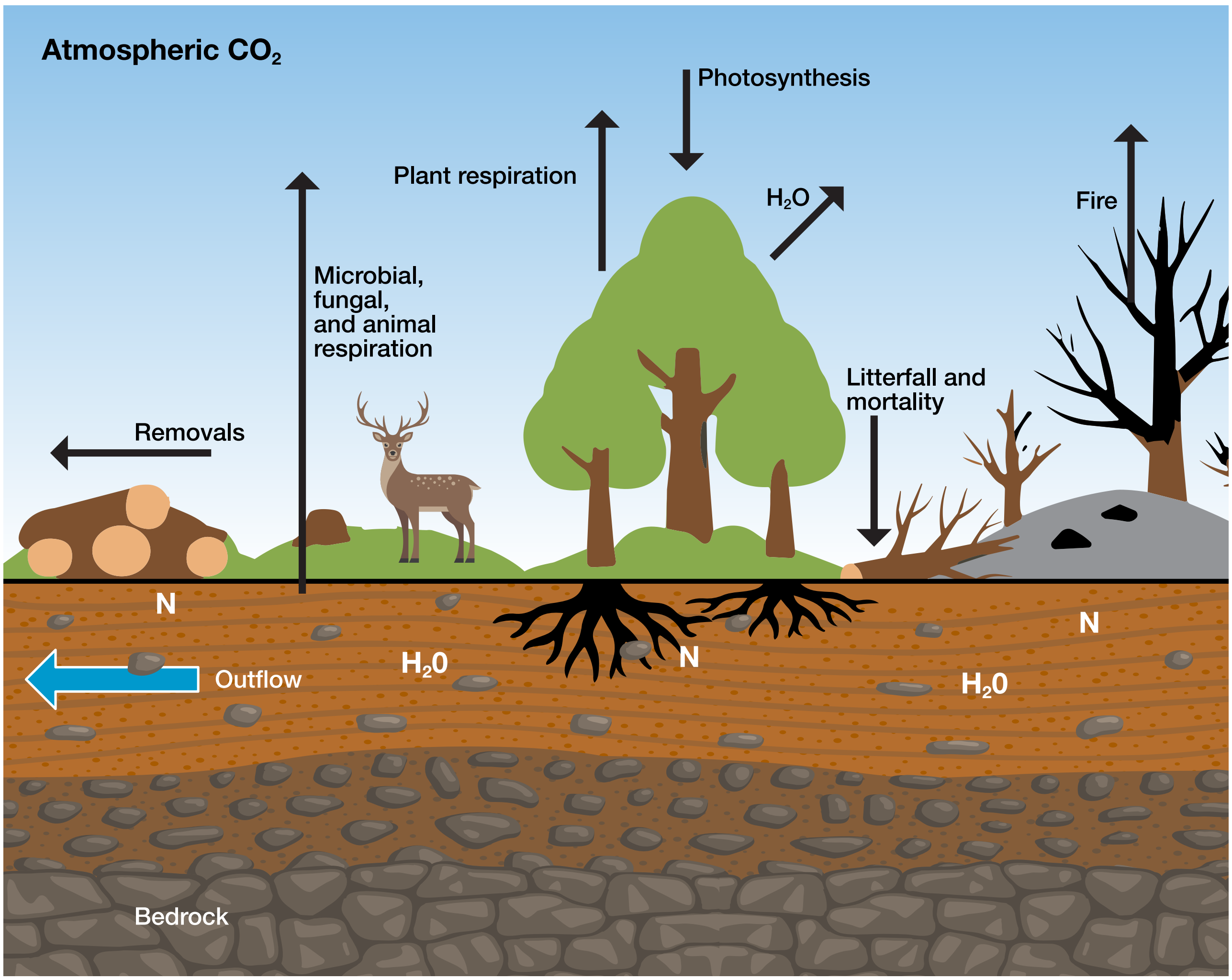


Figure 1—Key components of the forest carbon cycle. Live plants photosynthesize carbon from the atmosphere to create biomass and energy for living cells. Animals and microbes eat and decompose dead plant matter in the soil and on the forest floor. Fire combusts carbon, and logging removals and groundwater transfer carbon from the ecosystem (adapted from Gray et al. 2026).

Tree harvest transfers carbon from forests into the wood products sector, where decomposition and combustion ultimately emit greenhouse gases, although some wood products can store carbon for many decades. Additionally, some carbon is transferred from forests to streams through groundwater.

In the absence of disturbance, most forests follow a predictable trajectory of increasing live-tree carbon with stand age. Young, even-aged stands accumulate carbon quickly as trees grow. Growth of individual trees continues at high rates as trees mature, but stand-level live-tree carbon accumulation is increasingly offset by tree mortality from competition or small-scale disturbances, such as windthrow or root disease. Stands ultimately encounter an upper bound of live-tree carbon stocks that varies substantially with site productivity and the amount of tree stocking a site can support (stockability) (Chisholm and Gray 2024).

A live-tree carbon density (above- and belowground) of 300 Mg C/ha is typical of older, undisturbed western hemlock (*Tsuga heterophylla* (Raf.) Sarg.)/Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) forests that are common in the western hemlock potential vegetation zone in lowlands west of the Cascade Crest. A live-tree carbon density of 150 Mg C/ha is typical of undisturbed white fir (*Abies concolor* (Gord. & Glend.) Lindl. ex Hildebr.)/grand fir (*Abies grandis* (Douglas ex D. Don) Lindl.)/ponderosa pine (*Pinus ponderosa* Lawson & C. Lawson) forests that are common in the white fir/grand fir potential vegetation zone at mid-elevations east of the Cascade Crest and on the west slope of the Sierra Nevada (fig. 2) (Chisholm and Gray 2024). Dead matter on the forest floor also seems to slowly accumulate with age (Giesen et al. 2008). A large proportion of total carbon (30 to 60 percent) is in mineral soil (e.g., Christensen et al. 2019b, 2020), but this carbon pool does not appear to change much except in severe disturbances, as discussed below. While extensive harvest over the past century has resulted in many stands being well below maximum carbon stocks, fire exclusion has promoted high tree density and, potentially, high carbon storage in many historically fire-frequent forests (Davis et al. 2017, Spies et al. 2018).

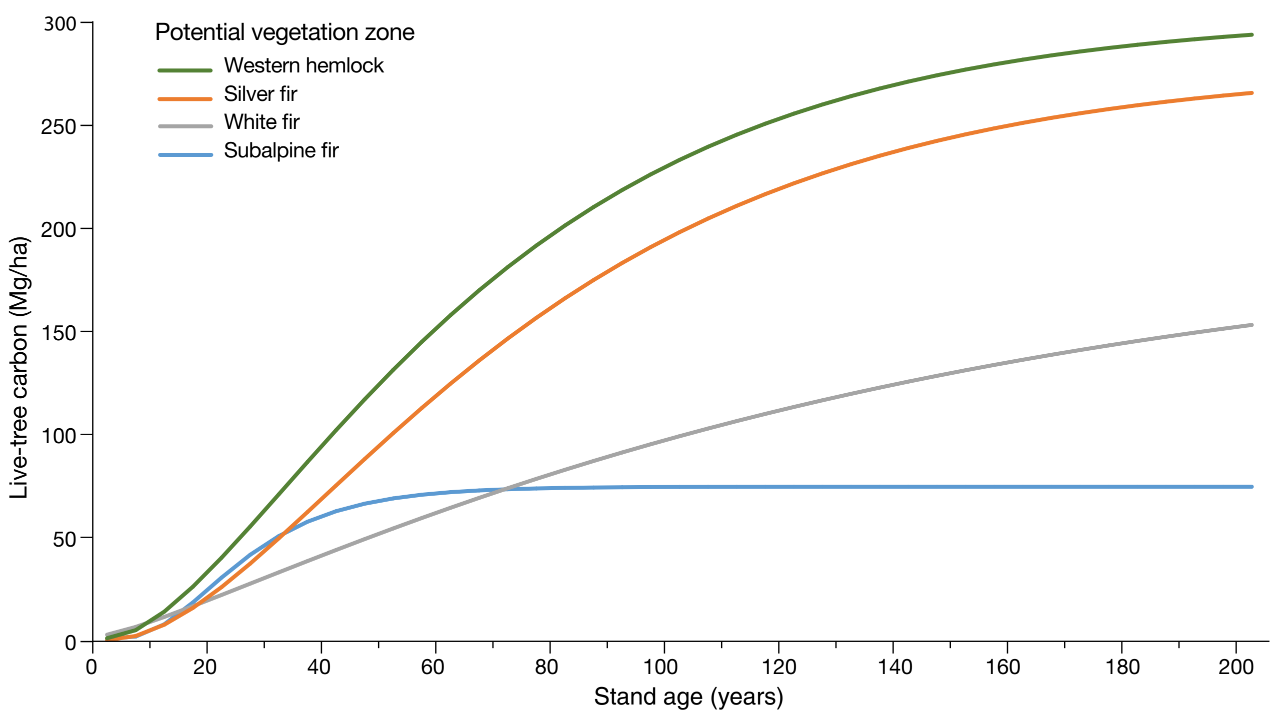


Figure 2—Live-tree carbon accumulation with stand age in undisturbed forest stands of median productivity and stockability for different potential vegetation zones in California, Oregon, and Washington, based on Chisholm and Gray (2024).

## Evidence of Historical Carbon Stores

In designing fuel treatments and forest restoration projects, foresters often use evidence of prefire-exclusion species composition and stand structure to inform desired future conditions for managing forests to be more resilient to wildfire in the future. Forests in the Columbia River Basin that experienced frequent fire occurred at much lower density before 1900 than today, with treeless openings and meadows occupying substantial area (Hessburg et al. 2000). Most of the live-tree carbon was in large, shade-intolerant and fire-tolerant trees, such as western larch (*Larix occidentalis* Nutt.), ponderosa pine, and sugar pine (*Pinus lambertiana* Douglas). Logging, competition by shade-tolerant trees, high-severity fire, and bark beetle outbreaks are thought to have reduced the abundance of large trees in these historically frequent-fire areas (Hagmann et al. 2021). As a result, fire exclusion and forest management have led to a different distribution of carbon across tree sizes and potentially different total carbon stocks compared to historical conditions.

Given the lower percentage of canopy cover, higher frequency of sizeable openings, and regular combustion of dead wood, it seems plausible that before fire-exclusion practices, frequent-fire forests stored less carbon than is found on the current landscape. State-and-transition modeling conducted for a landscape in north-central Washington found that forests with active fire regimes would generally store 25 to 50 percent less aboveground carbon than forests in fire-excluded states (Prichard et al. 2023). The evidence from the few reconstruction studies that have estimated carbon stores explicitly seems to differ depending on forest type and the baseline used for comparison. One study in the Klamath Mountains in California used changes in pollen density to estimate that forest (live-tree) biomass before Euro-American colonization was less than half of modern levels (104 to 128 Mg/ha compared to 250 Mg/ha) (Knight et al. 2022). Studies based on early 1900s inventories of mixed-conifer forest in the Sierra Nevada have found that total tree density was much lower historically, but density of large trees was higher, resulting in similar live-tree basal area to current conditions in the same landscapes (Stephens et al. 2015, 2018). However, remeasurement of unmanaged stands in one of the study areas showed current densities of large trees were similar, and current basal area was greater than historical values (Collins et al. 2017). In contrast, North et al. (2009) found greater stand-level live-tree biomass in reconstructions of stands in 1865 than in modern, never-managed and fire-excluded stands because of the loss of most trees >150 cm in diameter at breast height, possibly from high tree density causing moisture stress resulting in mortality from bark beetles. It is not clear whether historical frequent-fire forests typically stored more carbon than current fire-suppressed forests.

Western forests with longer fire-return intervals (≥50 years) historically had periodic mixed- or high-severity fire events, which resulted in diverse conditions—from large, early-seral patches to underburned forest with a variety of gap sizes (Spies et al. 2018). See Reilly et al. (n.d. [in this series]) for the area and distribution of Pacific Northwest forests by fire regime. Western hemlock/Douglas-fir forests commonly experienced fire at less than stand-replacing severity more frequently than once per 200 years, and in many cases, more frequently than once per 100 years (Merschel et al. 2024, Tepley et al. 2013). Fire exclusion is unlikely to have affected overall carbon stocks in forests with the longest fire-return intervals. However, logging has reduced tree volume density, and therefore carbon density, on forests west of the Cascade Crest since the early 1900s (Davis et al. 2017, Donnegan 2002).

## Fire Effects on Carbon

Wildland fires affect forest carbon stores directly through combustion and indirectly through tree mortality, which transfers carbon from the live-tree to the standing- and down-dead-tree carbon pools. Fire also creates conditions for new plant establishment. Live and dead understory plants, dead wood, and the forest floor are the carbon pools (or "fuels") commonly consumed by low- and moderate-intensity fire, and their characteristics, along with weather, determine fire intensity and behavior (Agee and Skinner 2005). High fuel loads are more likely to result in high-intensity fires that can damage or kill trees. Graminoid- and forb-dominated understories of frequent-fire forests, with thin litter and duff layers and low stocks of down wood, facilitate fast-moving fires that burn at lower intensity. With less crown scorch and cambial heating owing to shorter residence time, these fires lead to greater survival rates for fire-resistant trees (Agee 1993).

Estimates of immediate carbon emissions from wildfire vary substantially but rarely account for a large proportion of the prefire forest carbon. Estimates range from a mean of 19 Mg C/ha on the 2002 Biscuit Fire in southwestern Oregon (Campbell et al. 2007) and a mean of 25.5 Mg C/ha for several 2002–2007 fires in central Oregon (Meigs et al. 2009) to a mean of 72 Mg C/ha in old-growth, mixed-conifer forest on the 2013 Rim Fire in the Sierra Nevada (Harris et al. 2019) (11, 22, and 30 percent of preburn, nonmineral-soil carbon, respectively). Emissions vary with burn severity; the central Oregon study found that combustion in ponderosa pine forests ranged from 23 percent in areas burned at low severity to 35 percent in areas burned at high severity (Meigs et al. 2009). In western Oregon, immediate fire emissions from just the coarse and fine down wood carbon pool ranged from 5.2 Mg C/ha on the 19 percent of burned area where fire severity was very low to 10.3 Mg C/ha on the 27 percent of burned area where severity was high (Chafe and Fried 2025). Combustion of duff and litter accounted for 57 percent of emissions in the Biscuit Fire (Campbell et al. 2007) and, in the 2020 Labor Day Fires in western Oregon and Washington, emitted 9.2 Mg C/ha (Chafe et al., n.d.).

In addition to causing direct emissions from combustion, fire-driven mortality transfers carbon from the live-tree carbon pool to the standing and down dead-tree carbon pool. A followup modeling study of the Biscuit Fire suggested that decay of fire-killed wood may have emitted an additional 7.8 Mg C/ha (5 percent) in the first 10 years after the fire (Campbell et al. 2016). The net change of nonsoil carbon stocks for all forests that burned between 10-year inventory measurements was a loss of 15 Mg C/ha for Oregon and 22 Mg C/ha for Washington (Christensen et al. 2019b, 2020). Remeasurements of wildfire-burned plots have documented reductions of carbon stored in live trees, down wood, and understory vegetation, and increases of carbon stored in standing dead trees, with a net loss of about 11 Mg C/ha over a 7.1-year period at the stand scale, or 1.5 Mg C/ha/year across the national forests of Oregon and Washington (fig. 3) (Gray and Whittier 2014). Net change estimates from inventory plots reflect effects of combustion as well as mortality, decay, and growth between measurements.

Overall, research suggests that in stands where most of the nonsoil carbon is in live trees, wildfire (including high-severity fire) converts most of that live-tree carbon to the dead-tree carbon pool, with the rest emitted primarily via combustion. Nearly all the dead-tree pool carbon is inexorably emitted over decades, transitioning from a strong carbon source to a weak source as the emission rate declines. On the same ground, if natural or artificial regeneration is successful, new carbon will be sequestered from the atmosphere into the live-tree carbon pool, at increasing speed, moving from a weak carbon sink to a strong one. At some point, carbon sequestration from regeneration overcomes the dead-tree carbon pool emissions and switches the stand from a net source to a net sink. The timing of that crossover event depends on many factors and varies considerably.

Soil nitrogen is a key determinant of carbon production in Pacific Northwest forests that are affected by fire. In dense, undisturbed forests, release of nutrients through the decomposition of dead material with high carbon-to-nitrogen ratios is generally slow. In contrast, the combustion of organic matter by fire results in a pulse of unvolatilized nitrogen to the soil that can enhance the growth and palatability of resprouting or regenerating vegetation, including grasses and forbs in frequent-fire environments. Although frequent fire tends to decrease ecosystem nitrogen pools, the nitrogen is more available to plants, at least in the short term (Monleon et al. 1997). A synthesis of fire research in the Pacific Northwest found that fire tends to reduce carbon concentrations in mineral soil B horizons by 10–15 percent (Nave et al. 2022). The synthesis did not find a soil carbon recovery signal over time, but few long-term studies were available. Fires also create charcoal, which is very resistant to decomposition. In summary, the net effect of fire on soil carbon is highly variable but appears to be an overall loss for forests (Bowring et al. 2022).

## Fuel-Reduction Treatments

Fuel management reduces in-forest carbon stocks through the removal of live trees, particularly small trees, for sale as lumber, firewood, biomass, or other products to offset treatment costs, and through the combustion of dead wood, litter, and harvest residues through pile and burn and broadcast burn treatments. Managers can rely on prescribed fire alone, or they can include cutting trees of various sizes, mastication, or mowing. In the short term, these activities result in stands that store less live-tree and dead-tree carbon than unmanaged stands.

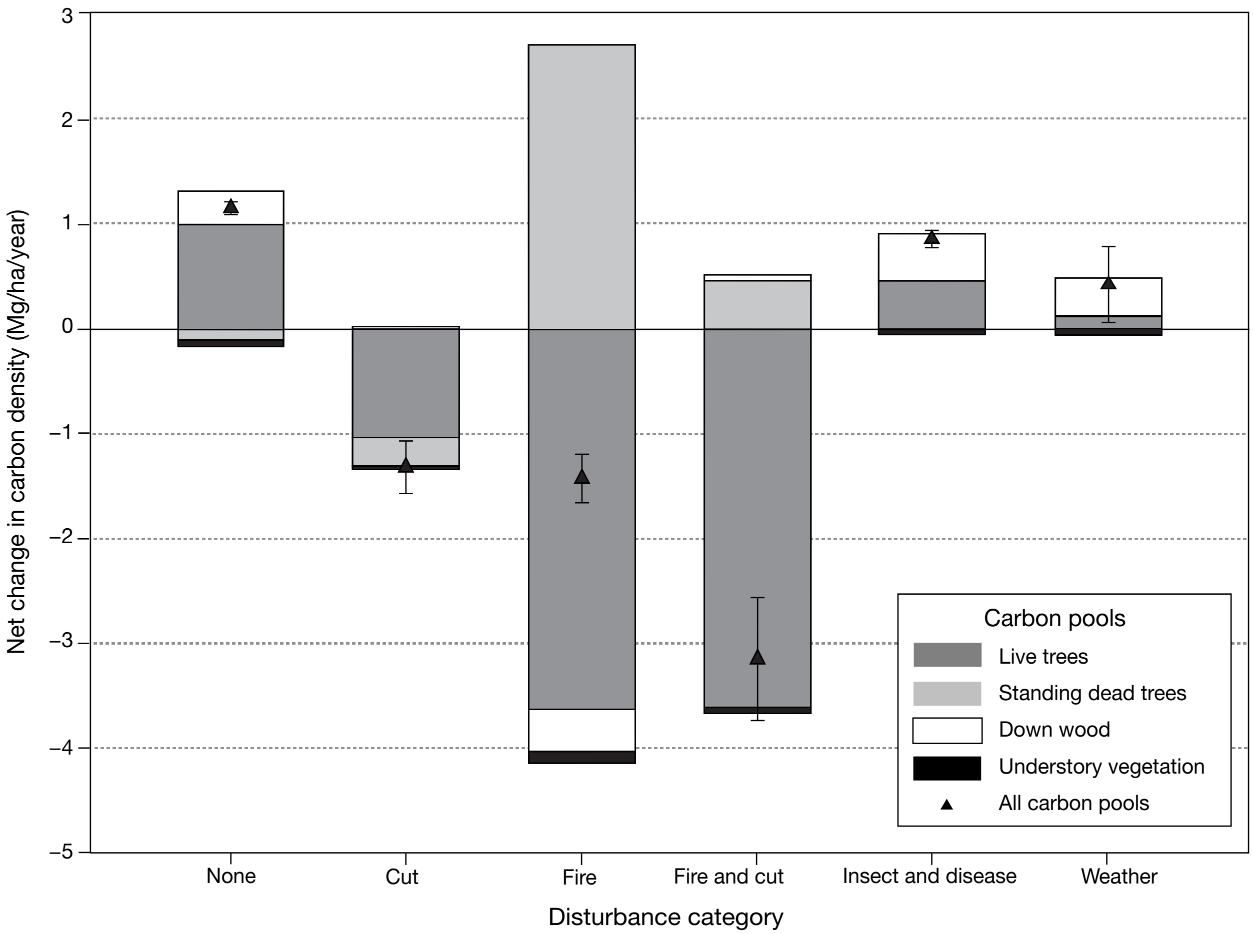


Figure 3—Net annual change in carbon density by disturbance category and carbon pool for all nonsoil carbon pools on national forest lands in Oregon and Washington, 1993–2007. Change is based on pre- and postdisturbance measurements about 7 years apart. Standard error bars are for change in all carbon pools combined. Source: Gray and Whittier (2014).

Treatments may also reduce subsequent tree mortality from bark beetles and drought. Across the network of fire and fire surrogate studies and related studies, fuel treatments that included prescribed burns were more effective at creating snags, killing seedlings, elevating height to live crown, and reducing surface woody fuels than treatments lacking burns (Schwilk et al. 2009, Youngblood et al. 2008). The lowest emissions from modeled wildfire occurred in treatments that were both thinned and burned, with little to no live-tree mortality estimated (Stephens et al. 2012), but with the lowest carbon stocks, even after 20 years (Zhu et al. 2025).

In addition to removing understory trees with no economic value, silviculture aimed at increasing fire resistance in fire-suppressed stands often removes some merchantable midstory and overstory trees to reduce density and susceptibility to damage from future wildfire and enhance resistance to insects and drought (Moreau et al. 2022, Steel et al. 2021). Merchantable trees are processed into salable wood products, which can help pay for the treatments (Stephens et al. 2012). About 50–60 percent of total above- and belowground live-tree carbon of trees >25 cm in diameter at breast height is in the merchantable wood that is removed and utilized, with an additional 10 percent of the carbon in the bark attached to the merchantable wood (calculations based on Pacific Northwest inventory data using Westfall et al. [2024]). Roots and stumps remain in the forest and slowly decay; branches and tops may also remain to decay, be burned after piling or via broadcast burning, or get transported to and utilized by bioenergy facilities depending on economic feasibility (fig. 4).

Figure 4—Slash pile in a thinning unit on the Fremont-Winema National Forest. Forest Service photo by Andrew Gray.

## Making Sense of Wood Products and Carbon

**harvested wood products (HWP)—**products consisting of material removed from the forest (e.g., lumber, paper, mulch, bioenergy, biofuels, biochar).

**leakage—**potential for the reduced harvest of wood products in one area to result in increased harvest in another area to meet demand.

**life cycle analysis (LCA)—**accounting of all material and energy inputs and emissions from producing, using, and discarding a specific product.

**residue—**parts of harvested trees not considered merchantable for traditional wood products, including tops, branches, and all aboveground parts of trees less than 12 to 25 cm in diameter at breast height, depending on local merchantability standards.

**substitution effect—**reduction in net greenhouse gas emissions based on the life cycle analysis of using a product with lower emissions (e.g., lumber instead of steel, energy from wood instead of coal).

## Use of Harvested Wood and Residues

The carbon in harvested trees is not an immediate emission but can be stored in products or emitted when used for energy. Cut sawlogs are hauled to manufacturing facilities for processing into a variety of harvested wood products (HWP), including lumber, plywood, pulp, paper, fuel, energy, or landscaping materials. Most of the wood residue (unsuited for use in a pulp facility, for example, because of distance) generated during HWP processing is now used to power boilers to produce process steam to run the mill, in dry kilns to add value to the finished lumber, or to generate electricity, some of which may be sold on the grid (Lucey et al. 2024). The carbon in logs that will become HWP can follow disparate manufacturing pathways, time in use, and disposal fates depending on the product. It may be stored in use for a century or more (e.g., house framing) or for weeks (e.g., newsprint) before being recycled, discarded into landfills, or combusted in waste incinerators, usually with energy capture to generate electricity. On average, about half the wood sent to mills in the United States ends up in long-term products (Christensen et al. 2019a). Additionally, 88 percent of the HWP carbon in landfill anaerobic environments is permanently stored (Khatri et al. 2023), although $CH_4$ is emitted (with partial capture) from landfills. Nonmerchantable forest residues can be burned to produce energy, either directly or after compacting into briquettes at the harvest site, or used to make oriented strand board, glue-laminated timber, liquid biofuels, or biochar (Lucey et al. 2024, Wilson et al. 2024).

Life cycle analyses (LCAs) are used to estimate all energy and material inputs that go into creating a product (e.g., a wood-frame house). Many carbon assessments include substitution effects by counting the lower emissions from use of HWPs as offsets for emissions associated with alternative products (Lucey et al. 2024). For example, the use of wood in building construction can result in fewer emissions than the use of steel or concrete. Similarly, the use of wood for heating or electricity can be counted as an offset for emissions associated with other energy sources (e.g., fossil fuels). Substitution effects can show that forest harvest and the production of HWPs is beneficial for reducing greenhouse gas emissions beyond the value of carbon stored in the HWPs (Ryan et al. 2010). Another complication with accounting for HWPs is leakage—the potential effect of reduced harvest in one area (e.g., to promote carbon storage or older forests) leading to increased harvest elsewhere (Adams et al. 1996), thus reducing or negating potential carbon benefits of harvest reduction.

### Research Gaps

- Long-term (ideally, multidecade) monitoring studies that follow most or all ecosystem carbon pools over time would enable more accurate estimates of dead wood and forest floor accumulation and decomposition, changes in soil carbon, and the importance of charcoal in carbon pools (e.g., Bormann et al. 2008).
- Field research on fire and fire treatment effects in more lightly studied forest types that are characterized by long fire-return intervals and much greater carbon densities would supplement what we have learned from the primarily frequent-fire forests studied to date. This would better support estimates of changes in carbon stores at a regional scale.
- Comprehensive studies on the uses of wood products derived from forests, their time in use, and their fate once discarded would enable more accurate estimates of carbon sequestration of the combined forest-and-products system, and improve our understanding of how wood utilization changes conclusions derived from considering only in-forest carbon dynamics.

## Management Tradeoffs

Managers pursue fuel treatments to enhance the efficacy and safety of wildfire suppression or to increase the survival of trees selected for retention if or when they experience wildfire. Ontl et al. (2020) identify various management strategies to maintain carbon and climate adaptation on the landscape, including restoring fire in fire-adapted ecosystems, establishing fuel breaks, altering stand structure, promptly revegetating disturbed sites with a diversity of future-adapted species, and protecting high-carbon-density sites. A key question is whether the survival and growth of remaining trees, and storage of wood products, results in greater long-term carbon storage than if most or all the trees were killed by wildfire. The variety of potential treatment and wildfire effects in different forest conditions makes it difficult to determine the long-term effects of fuel treatments on carbon balance (fig. 5). Most fuel treatments and fuel research target forest types that historically experienced frequent fire (Agee and Skinner 2005). In mixed-severity and infrequent-fire forest types, burning slash in harvest units reduces fuels and facilitates planting, and removing small tree ladder fuels may improve resistance. However, rapid growth of fuels may negate the effects of fuel-reduction treatments, including prescribed fire, by the time the stand is affected by wildfire (Morris et al. 2025).

By design, fuel treatments result in a short-term reduction in the carbon stored in the treated stand from removal or combustion of trees. However, understanding the full effect of treatments requires considering longer term carbon retention, including potential emissions from wildfire affecting treated and untreated stands. These considerations are inevitably influenced by assumptions about when the stand will burn following treatment, the conditions affecting fire intensity, and the longevity and end-of-life disposal of any wood products created from mechanical fuel treatment removals.

A synthesis of studies on long-term carbon retention across large landscapes in historically frequent-fire forests found that there were few empirical studies, and the results were not consistent (Restaino and Peterson 2013). Treatment effects ranged from reductions of ecosystem carbon stocks by 12 to 116 Mg C/ha, while associated reductions in wildfire combustion emissions ranged from 1 to 40 Mg C/ha between treated and untreated stands; storage in HWP was not quantified. Conclusions suggested that the direction and magnitude of net effects from fuel treatments that are subsequently affected by wildfire were similarly variable from losses of 33 to gains of 3 Mg C/ha (Restaino and Peterson 2013). Treatments may result in an overall increase in carbon emissions if the treated units do not encounter fire (Restaino and Peterson 2013, Spies et al. 2017). Wildfire effects in treated stands may result in greater

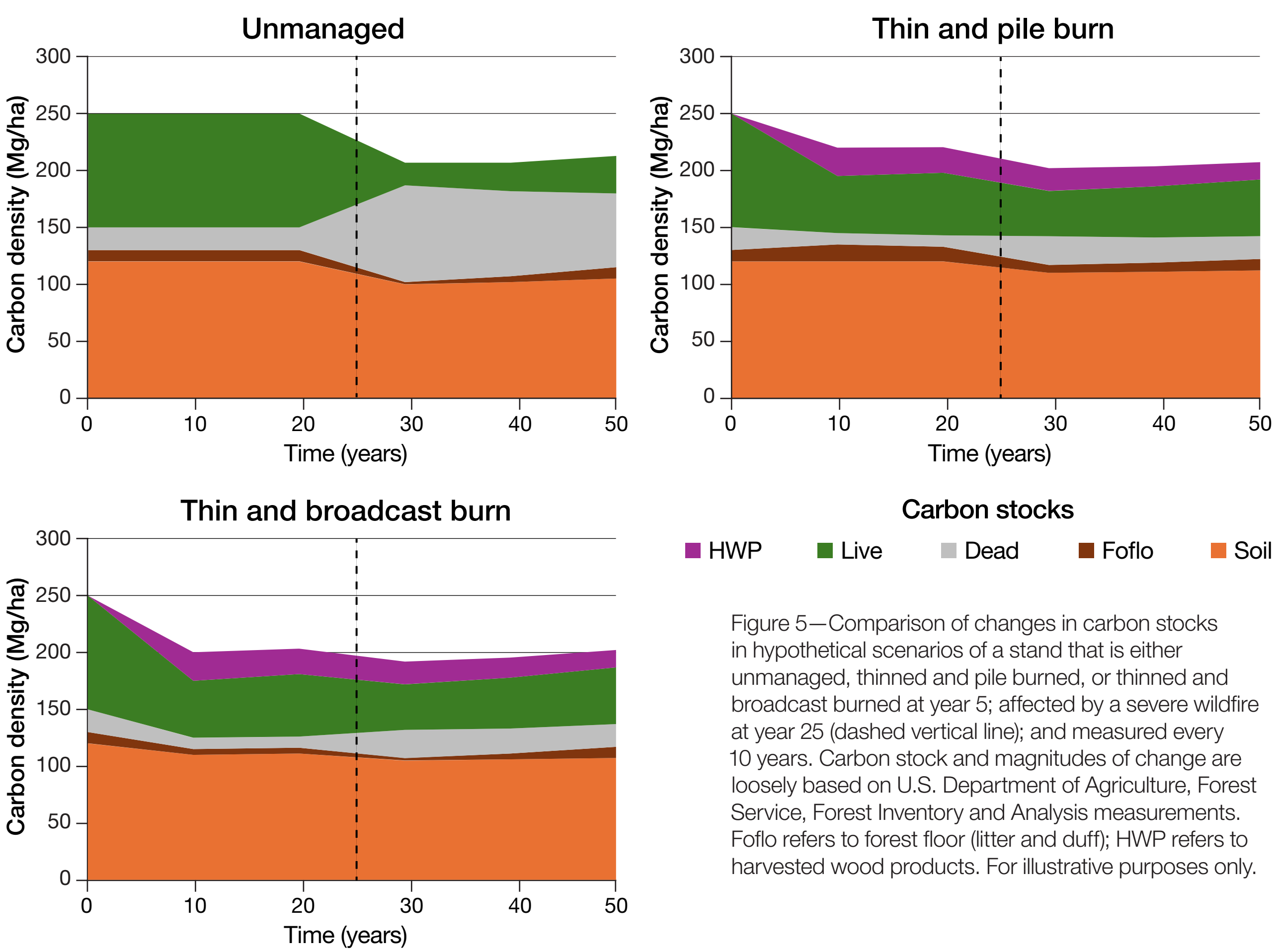


Figure 5—Comparison of changes in carbon stocks in hypothetical scenarios of a stand that is either unmanaged, thinned and pile burned, or thinned and broadcast burned at year 5; affected by a severe wildfire at year 25 (dashed vertical line); and measured every 10 years. Carbon stock and magnitudes of change are loosely based on U.S. Department of Agriculture, Forest Service, Forest Inventory and Analysis measurements. Foflo refers to forest floor (litter and duff); HWP refers to harvested wood products. For illustrative purposes only.

total carbon emissions than in untreated stands for moist, western Oregon forest types with rapid rates of regrowth and fuel accumulation and long fire-return intervals but not for ponderosa pine forest types east of the Cascade Crest with slower growth rates and shorter fire-return intervals (Mitchell et al. 2009). Nevertheless, treatments in moist forest types can reduce the amount of carbon transferred from live-tree to dead-tree carbon pools, therefore reducing its eventual emission (Busby and Fried 2025).

One simulation study found surprising insensitivity of long-term carbon stores to a wide range of possible treatments, treatment effectiveness, wildfire severity, vegetation response, and wood product longevity (Campbell and Ager 2013). They found that forest establishment and growth rates had a greater effect on carbon stores than the nature and efficacy of treatments. Whether and how quickly severely burned stands will regenerate is unclear, especially if areas reburn and global warming continues (Davis et al. 2020, Thompson et al. 2007). Another simulation study for a landscape in eastern Washington found that climate change resulted in more frequent wildfire and reduced carbon stores, but scenarios with prescribed fire and wildland fire use were more resilient to wildfire and stored more carbon than scenarios without either management approach (Furniss et al. 2024). While scenarios with harvest treatments reduced carbon stores relative to other scenarios in the first 40 years, projected increases in wildfire area after 2060 resulted in harvest treatment scenarios having similar carbon stocks to the prescribed fire and wildland fire use treatment scenarios after 100 years.

A simulation study in Sierra Nevada mixed-conifer, old-growth forest predicted that stands treated with thinning and broadcast burning produced lower wildfire emissions than those treated only with thinning; whereas unmanaged stands produced the highest emissions during wildfire. Stands simulated to match the prefire-exclusion forest dominated by large trees and frequent broadcast burning resulted in greater carbon stores than those of fire-suppressed forests when wildfire was simulated (Hurteau and North 2009). In fire-suppressed forests that experienced heightened drought-caused mortality, Hurteau et al. (2024) predicted at least three burns at 5-year intervals might be needed to bring carbon stores in surface fuels down to levels resembling a frequent-fire understory.

In a simulation study of California pine and mixed-conifer forests, Cabiyo et al. (2022) examined the carbon implications of promoting innovative uses for harvested wood while accelerating fuel treatments. They found that increased management and wood use could yield net climate benefits between 6.4 and 16.9 Tg $CO_2$e/year when considering effects from forest management, wildfire, carbon storage in products, and substitution benefits (fig. 6). Products with durable carbon storage (e.g., lumber and manufactured wood multistory buildings) conferred the greatest benefits, but there were also benefits from products that reduced emissions in hard-to-decarbonize sectors, such as industrial heating (Cabiyo et al. 2022).

## Key Takeaways

- The desire to maximize carbon storage may not always be compatible with other management goals for fuel treatments, such as habitat quality, resistance to stand replacing fire, reduction in risk to human communities, and timber production.
- Wildfires result in immediate emissions of 10 to 30 percent of nonsoil forest carbon, depending on forest conditions and fire severity. Stands that grew before the advent of fire suppression and stands that have been treated in recent decades likely store less carbon than untreated stands, even in the initial years after wildfire.
- Managing the transition from dense, fire-suppressed stands to more resilient stands resembling prefire-exclusion forests can yield wood products, with fewer options for wood production once stands attain the desired structure.
- Treatments intended to create fire-resilient stands may also reduce the likelihood of large-scale tree mortality from drought or bark beetles, which would result in stable carbon stores and sequestration rates.
- Model outcomes are sensitive to assumptions and parameter selection. Site-specific, definitive answers are difficult to ascertain considering carbon tradeoffs by treatment type, treatment frequency, products created, wildfire frequency, and wildfire intensity.

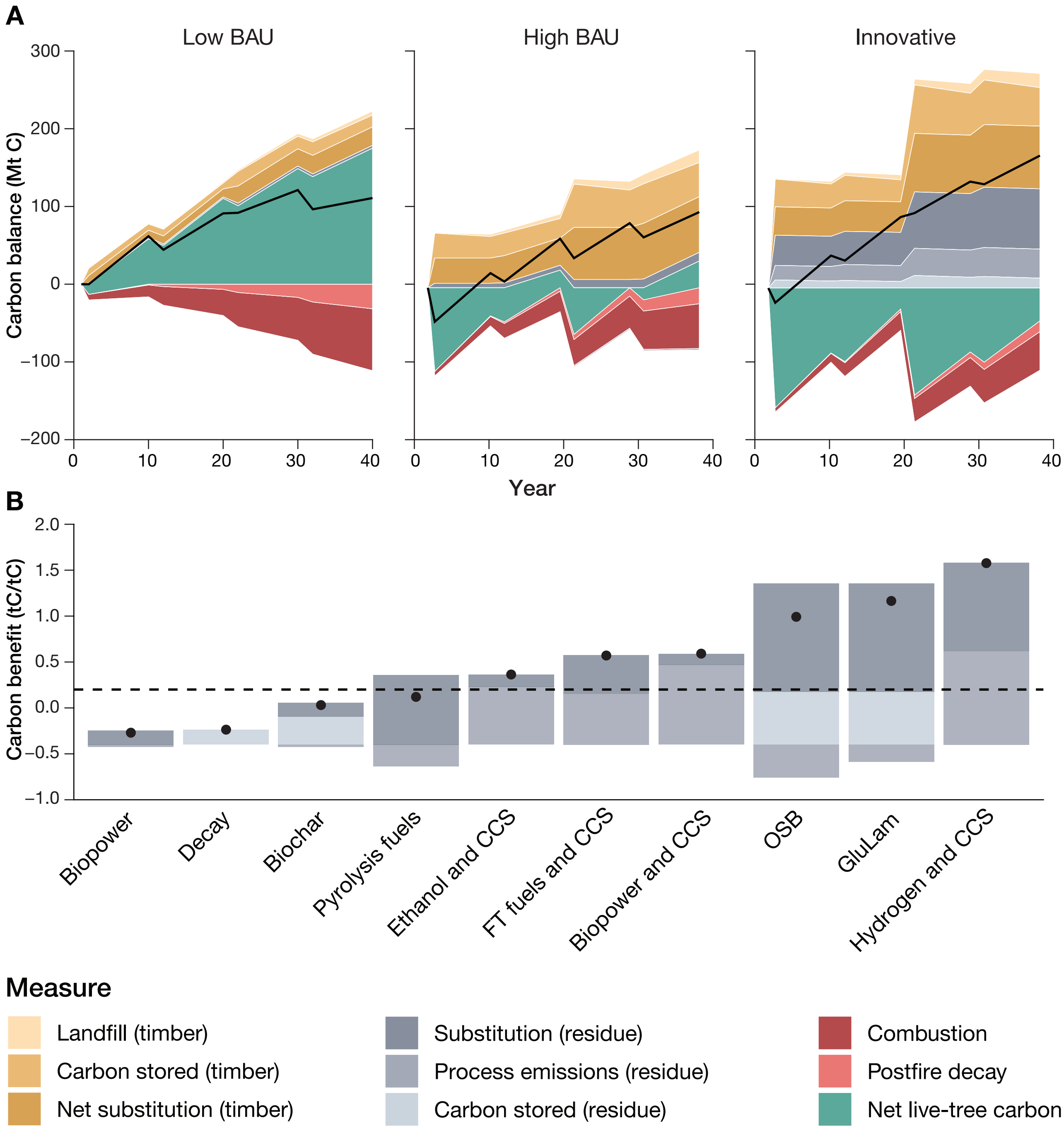


Figure 6—Simulated forest carbon balance across (A) three scenarios and (B) several technology pathways for use of wood and residues from pine and mixed-conifer forests in California. Net carbon values are represented by black lines in A and dots in B. In B, the dashed line represents the threshold used to select the suite of technologies in the innovative scenario. Net live-tree carbon values are relative to carbon stocks in year zero, and large decreases are associated with harvest events. In low business as usual (BAU), management only occurs on corporate land where it is potentially profitable (net revenue >$2,500/ha). In high BAU, management occurs wherever it is net revenue positive with a delivered residue price of $0. In innovative, management occurs wherever it is net revenue positive with a delivered residue price of up to $100 per oven dry ton (Cabiyo et al. 2022). The residue use categories in panel B are biopower (residues burned to generate electricity), decay (residues left to decay), biochar (charred wood), pyrolysis fuels (liquid fuels), ethanol (ethanol fuel), CCS (carbon capture and storage), FT fuels (Fischer-Tropsch liquids), OSB (oriented strand board), GluLam (glue-laminated timber), and hydrogen (hydrogen gas fuel).

## Conclusions

Differences in carbon storage capacity, fire frequency, and species-level resistance traits across Pacific Northwest forests preclude prescriptive generalization. Prescribed fire and mechanical fuel reduction at an intensity that is sufficient to enhance fire resistance almost inevitably reduce in-forest carbon stores and sequestration rates in the short to mid-term. However, reductions in carbon stores and sequestration due to wildfire are potentially greater, especially with reburns and increasing incidence of severe fire behavior and effects. Life cycle analyses suggest that storing extracted wood in long-term products or using it to offset fossil-fuel intensive products or processes can in some cases, and over some time scales, result in reduced carbon emissions overall.

## U.S. Standard Equivalents

| When you know: | Multiply by: | To find: |
|---|---|---|
| Centimeters (cm) | 0.394 | Inches |
| Megagrams (Mg) | 1.102 | Tons |
| Teragrams (Tg) | $1.102 \times 10^6$ | Tons |
| Megagrams per hectare (Mg/ha) | 0.446 | Tons per acre |

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