The western North American forestland carbon sink: will our climate commitments go up in smoke?

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Pathways to achieving net-zero and net-negative greenhouse-gas (GHG) emission targets rely on land-based contributions to carbon (C) sequestration. However, projections of future contributions neglect to consider ecosystems, climate change, legacy impacts of continental-scale fire exclusion, forest accretion and densification, and a century or more of management. These influences predispose western North American forests (wNAFs) to severe drought impacts, large and chronic outbreaks of insect pests, and increasingly large and severe wildfires. To realistically assess contributions of future terrestrial C sinks, we must quantify the amount and configuration of stored C in wNAFs, its vulnerability to severe disturbance and climatic changes, costs and net GHG impacts of feasible transitions to conditions that can tolerate active fire, and opportunities for redirecting thinning-derived biomass to uses that retain harvested C while reducing emissions from alternate products. Failing to adopt this broader mindset, future forest contributions to emission targets will go up in smoke.

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The capacity of forests to provide long-term sinks for atmospheric carbon dioxide (CO_2) depends on forestland carbon (C) carrying capacity and land stewardship that sustains forest C in the context of ongoing wildfires and pest insect outbreaks (Grassi *et al*. 2021). After 100–150 years of fire exclusion, conifer forest encroachment on non-forest and hardwood forest elements and forest densification are widespread below the boreal zone, and the forest C carrying capacity of western North American forests (wNAFs) has been exceeded (Hessburg *et al*. 2019). Nonetheless, current projections of land-sector–based C emissions and removals in the western US and Canada (Fargione *et al*. 2018; Drever *et al*. 2021) do not consider the threat of increasing disturbances on forestland emissions and C carrying capacity (Xie *et al*. 2022). It is well known that wildfires kill trees and immediately release large amounts of stored forest C through the conversion of these stocks into CO_2 and other greenhouse gases (GHGs). However, one type of fire-related emission is currently not reported in GHG inventories—namely, burned areas that continue to release C through decomposition, which effectively convert sinks into sources for years to come. In recent years, as wildfires continue to reduce forested area, increasing burned area deriving from the aforementioned legacy effects has reduced the strength of these land-sector C sinks (eg Liang *et al*. 2017).

In a nutshell:

- Efforts to reduce greenhouse-gas (GHG) emissions from forests depend on stabilized biomass conditions, but climate change is increasing burned area and fire severity
- Current forecasts of future emissions fail to consider legacy impacts of fire exclusion and past management, which, along with climatic changes, are driving increases in burned area, fire severity, and resultant emissions
- Assessing future GHG balances requires quantification of the amounts and configurations of biomass stored in forests, their vulnerability to disturbance, and net impacts of realistic managed transitions to stabilized conditions
- Unless we actively manage the vulnerability of western North American forests to natural disturbances, our GHG emission reduction goals are at great risk

The wNAF domain includes the 12 western US states (including western South Dakota), extending west of the Great Plains, south to the dry and moist mixed conifer forests of northern Mexico, and north to the dry, moist, and cold sub-boreal forests of the Canadian provinces of British Columbia and Alberta. During recent extreme wildfires in wNAFs, GHG emissions have far exceeded gains in C storage resulting from land stewardship (Liu *et al*. 2021). As in historical landscapes, future emissions can be at least partially mitigated by means of evidence-based, targeted stewardship

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interventions (Table 1) that restore vast areas of wet and dry meadows, wetlands, prairies and shrublands, and sparsely treed savannas (ie non-forest elements) while reducing the area, density, and extreme connectivity of vulnerable forests. Realistic pathways to meet net-zero emission goals will require reassessment of the assumed stability of land-sector C sinks (eg Hurteau *et al.* 2024), as well as the release and transfer of some C out of forestlands and transitions to historically common non-forest elements (eg Hessburg *et al.* 2019; Povak *et al.* 2023). These mitigations will provide jurisdictions with a reasonable chance of stabilizing future C sinks and managing transitions that are less chaotic and uncontrollable. Such concepts are well rooted in the scientific community, yet are poorly understood and rarely accepted in political, social, and land preservation communities; these trust barriers markedly limit forward progress at the pace and scale needed to bring about sufficiently influential changes (eg Winter *et al.* 2004).

Forests are fuel, and fuels have increased

Wildfires in forests and their GHG emissions are driven by forest type; by the quantity and spatial connectivity of live and dead organic material stored in woody biomass, necromass, duff, litter, and soil; and by seasonal and longer-term climatic conditions. Fundamentally, forest C stocks are stored potential energy—literally, fuel for fires. After a century of fire suppression and exclusion of Indigenous cultural burning (Kimmerer and Lake 2001), forest densification and widespread tree encroachment into non-forest ecosystems have greatly increased the abundance and connectivity of hazardous fuels. These historical legacies have contributed to increasing trends in wildfire severity and burned area (Table 2; Figures 1 and 2).

Table 1. Targeted, evidence-based interventions from Prichard *et al.* (2021)

Intervention	Effect
Managed wildfires, modified suppression	Allows lightning-ignited wildfires to burn deadwood and understory trees under moderate weather conditions
Management of forest density by forest thinning and prescribed burning	Removes understory and mid-story trees that have accumulated during a long period of fire exclusion (Hagmann *et al.* 2021)
Indigenous cultural burning	Removes accrued understory trees after a long period of fire exclusion; opens the canopy, increases sunlight reaching the forest floor; enhances opportunities for understory plant and animal communities to provide needed foods, medicines, and material resources (Kimmerer and Lake 2001)
Management of species composition	Increases variety in species composition, which benefits more variable fire severity, biodiverse habitats, and multiscale landscape granularity (Hessburg *et al.* 2019)

Table 2. How did we get here?

Indigenous burning and the pre-colonial landscape

Prior to European colonization, Indigenous Peoples proactively managed large areas of western North America with intentional burning[1-7]. Intentional burning and reburning, coupled with fires ignited by lightning, maintained dynamically shifting landscape mosaics of forest and non-forest vegetation. These patchworks supported flashy fuels like grasses, herbs, and shrubs, which delivered fast spreading but low-intensity surface fires to nearby forest patches[8,9]. Such fires were often small and ephemeral, extinguished by diurnal changes in vapor pressure and fuel moisture[10,11]. Intentional burning, practiced for millennia[11], was a transgenerational commitment to secure life-supporting resources, protect lifeways and sacred places, and increase personal safety[1].

European colonization

Displacement and genocide of Indigenous Peoples and curtailment of their burning practices occurred throughout western North America by the 1850s to 1870s[12-14], leading to broad changes in forest conditions. The 1.3-million-ha Big Burn of 1910 cemented in the colonial psyche that wildfires primarily caused great harm[15], and by the mid-1930s, wildfire starts were actively suppressed in many parts of Canada and the US[16]. After World War II, timber harvests accelerated, bolstering concerns about escaped wildfires and their impacts on timber reserves. By the late 1990s, harvesting had removed most of the accessible old-growth forests. In context of that depredation, concern shifted from protecting timber inventories to conserving habitats of old-growth–associated species[17,18]. In the first quarter of the 21st century, the objectives of forest management have again swung to protecting habitats, carbon (C) stocks, and ecosystem services, with a growing awareness that these objectives are unattainable without the return of conditions that can safely support the inevitable return of fire.

Forest management contribution

Along with fire exclusion, 20th-century forest management increased the vulnerability of many forests to wildfires and climate change. Industrial forest harvest and management practices promoted optimal tree stocking; forest growth and yield; and extensive areas of dense, maturing coniferous forest[19]. In many historical forests, broadleaved deciduous or mixed-wood conditions naturally occurred after severe disturbances[20,21]. In forests managed for timber, broadleaf forests were eliminated through cutting and herbicide treatment in favor of even-aged conifer plantations. Broadcast burning treatments were extensively applied to eliminate post-harvest slash residues and fuel hazard[22]. These practices are infrequently applied today.

More recently

In the past several decades, slash pile burning has replaced broadcast burning, due to containment concerns, shrinking burn windows, smoke impacts on human health, and heightening risk of wildfire in plantation forests. Overall, forest management has resulted not only in forest simplification but also in the loss of stabilizing influences (including successional patch heterogeneity, hardwood forests, and non-forest area), with elevated live fuels in dense forests with high logging slash residues[9]. These practices contribute to artificially high C stocks that increase the risk of wildfires and reduce C sequestration potential in landscapes visited by fire.

Notes: [1]Kimmerer and Lake (2001)
[2]Swetnam *et al.* (2016)
[3]Taylor *et al.* (2016)
[4]Roos *et al.* (2021)
[5]Roos *et al.* (2022)
[6]Roos *et al.* (2023)
[7]Copes-Gerbitz *et al.* (2023)
[8]Hessburg *et al.* (2016)
[9]Hessburg *et al.* (2019)
[10]Anderson (1990)
[11]Viney (1991)
[12]Bowman *et al.* (2011)
[13]White (2015)
[14]Lake and Christianson (2020)
[15]Pyne (1984)
[16]Pyne (2017)
[17]Spies *et al.* (2019)
[18]Price *et al.* (2021)
[19]Sedjo (1999)
[20]Johnstone *et al.* (2016)
[21]Mack *et al.* (2021)
[22]Mott *et al.* (2021).

Forest configuration matters

Historically, frequent burning of wNAFs created diverse mosaics of forest and non-forest that reburned through spatially overlapping fires of variable pattern and return interval (eg Povak *et al.* 2023). In the absence of these fires, conifer forests invaded historical non-forest elements, wetlands and wet meadows, and broadleaf forest areas. After more than a century of fire exclusion, landscapes are now dominated by maturing, multilayered, conifer forests through which fire can quickly spread (Table 2). Greater fuel loads and increased connectivity of fuel-laden conditions have elevated the likelihood of severe crown fires in most areas that historically experienced frequent low- and/or moderate-severity fires. Even in moist maritime, boreal, hemi-boreal, and subalpine forests that co-evolved with moderate- and high-severity fire, the burned area and frequency of fires are increasing (Figure 2; Parisien *et al.* 2020). Taken together, these changes, combined with a warming and drying climate, have led to increasingly large, severe, and emissive wildfires (Figure 2; Hagmann *et al.* 2021).

Extreme wildfires and anthropogenic emissions

GHG emissions from extreme wildfires can approach or exceed annual GHG emissions from anthropogenic sources. In 2023, emissions from the area burned in Canada's managed forests, which account for about half of the total forest area burned in the country, exceeded emissions from the entire Canadian economy by a factor of 1.5 (ECCC 2025). In the wNAFs of British Columbia, wildfires in 2017 and 2018 caused direct annual emissions that were three times the combined emissions from all other sectors, and wildfire emissions in the province were even higher in 2023 (Daniels *et al.* 2024). Carbon emissions from the 2020 wildfires in California represented an estimated ninefold increase over emissions from wildfires in 2000 (CARB 2020). Postfire emissions are even higher when decomposition and foregone C sequestration of fire-killed trees are also considered (Kurz *et al.* 2013).

Climate change as a threat multiplier

Fire exclusion, drought, and warmer winter and summer temperatures have increased forest vulnerability to other contagious biotic disturbances with substantial impacts on C fluxes (Kurz *et al.* 2008; Cudmore *et al.* 2010; Hurteau *et al.* 2024). For example, the native mountain pine beetle (*Dendroctonus ponderosae*), which favors dense mature forests, readily spread across 20 million ha of lodgepole pine (*Pinus contorta*) forest in the late-20th and early-21st century—killing 54% of British Columbia's pine forest and spreading to the neighboring province of Alberta. These outbreaks created large deadwood C pools that contribute to increased C loss through decomposition and subsequent burning (Woo *et al.* 2024). Extensive bark beetle outbreaks also occurred throughout the western US.

Forest regeneration (seed production, viability, and establishment) and young tree survival after large and severe fires are also challenged by hotter and drier summers, warmer spring and fall seasons, shorter and warmer winters, and multiyear droughts (Stevens-Rumann *et al.* 2018; Coop *et al.* 2020). In the absence of mitigation, these combined factors and the expanding likelihood of large and severe fires will lead to continued overestimation of potential land sink contributions of wNAFs. These outcomes were predicted and are now worsening (Wear and Coulston 2015; Stevens-Rumann *et al.* 2018).

Where do we go from here?

Forest contributions to jurisdictional GHG inventories are determined by the strength of forest-sector C sinks, which are ideally maintained or enhanced through stewardship (Hagmann *et al.* 2021; Hessburg *et al.* 2021; Prichard *et al.* 2021) that stabilizes C sequestration and reduces forest contributions to GHG emissions. Assessing the net C balance of mitigation options requires careful and geographically appropriate evaluation of emissions from forests, transfers to the forest products sector, and substitution benefits achieved through emission avoidance (eg bioenergy and long-lived wood products that replace fossil-fuel–derived products; Lemprière *et al.* 2013; Smyth *et al.* 2014). In this context, forest stewardship would emphasize the rate at which forests remove C from the atmosphere and reliably store it (ie the strength of the C sink; Kurz *et al.* 2018), rather than protecting the amount of C that wNAFs currently store (ie the current C stock; Sharma *et al.* 2023). In many cases, that will translate into less C stored in forest stocks rather than more (Hurteau *et al.* 2024).

Forest land stewardship reimagined

Modern forestland preservation strategies and the intentional exclusion of fires have worked poorly for forest C sequestration and the survival of myriad wNAF habitats (Calkin *et al.* 2015). The landscape ecology of native forests and their fire regimes, wildlife, and fish habitats (Bisson *et al.* 2003; Gaines *et al.* 2022; Jones *et al.* 2023) tells us that wNAFs evolved with fire and rely on an ongoing, intimate relationship with characteristic fire frequency and severity patterns (North *et al.* 2015). Improving forest landscape resilience to the inevitable wildfires and climatic changes of the 21st century will require proactive, multigenerational, and place-based stewardship approaches to managing forests that are enhanced by cultural and other forms of prescribed burning. Without proactive management, conservation of existing C stocks will be challenged in forested regions where high wildfire danger continues (Sharma *et al.* 2023; Hurteau *et al.* 2024). Without proactive stewardship, insect outbreak and disease incidence and severity will also continue to rise (Kolb *et al.* 2016).

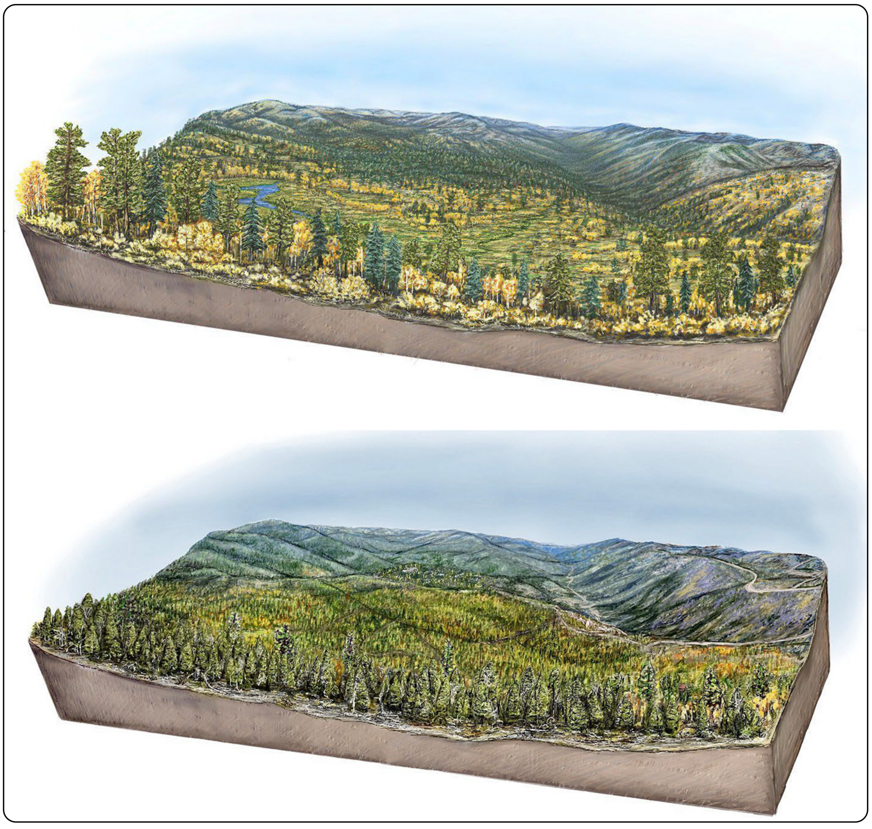

Figure 1. (top) Historical lightning and Indigenous cultural ignitions created dynamically shifting diverse mosaics of conifer and hardwood forest and non-forest (meadow, grassland, wetland, sparse woodland, shrubland patches) conditions. Open-canopy forests were common in drier low montane and mid-montane environments, on south-facing slopes, and on ridgetops, where frequent low- or moderate-severity fires generally maintained these conditions. Closed-canopy forests occurred in cooler and wetter mid-montane and upper montane environments, on north aspects, and in valley bottoms where moderate- and high-severity fires were more prevalent. (bottom) Fire exclusion—beginning with the curtailment of Indigenous cultural burning 150–170 years ago and continuing under aggressive fire suppression—led to dense and layered conifer forests, with conifers encroaching on many non-forest and hardwood patches. Drawings courtesy of Miriam Morrill.

The environmental settings of forests and the suitability of tree species to site-specific climatic and weather conditions will continually change. Species ranges will be widely adjusted by insect outbreaks where high forest density and unsuitable seasonal conditions (solar, temperature, moisture) develop under new climatic forcing. During the 21st century, the spatial distribution of wNAF types will change (Mahony *et al.* 2018). For large landscapes, forest thinning and burning as well as managed wildfire prescriptions—employing fires of all severities—are needed, which will lead to patterns of forest structure, composition, biomass, and necromass that will improve protection of managed and unmanaged forests from uncharacteristically large and severe wildfires and strengthen many fire suppression actions (Table 2 and references therein). Strategies to restore landscape and human community resilience to wildfires will require local landscape and regional modeling to evaluate GHG emissions trade-offs between business-as-usual models of forest stewardship and informed alternatives.

Restoring broadleaf forests

Despite often being characterized as competitors to conifer wood fiber production, broadleaf forest areas are one of several core elements of resilient forest landscapes (Hessburg *et al.* 2019). With high moisture content and seasonally moist understory fuels, broadleaf forests often reduce wildfire spread and intensity. This will be an important contribution where broadleaf forest is expected to increase in area in response to eliminating silviculture treatments aimed at suppressing broadleaf forest regeneration. Moreover, albedo increase is often associated with broadleaf forests, which can offset some of the climate impacts of C losses associated with transitions to non-forest or broadleaf cover (Hasler *et al.* 2024). In some forests, broadleaf trees (when not actively suppressed) will return after stand-replacing disturbance, while in other forests, broadleaf trees will either not return or will occur in mixed-wood compositions after stand-replacing disturbance. Elsewhere, active restoration is needed to counteract previous broadleaf suppression treatments (Kitchen *et al.* 2019). Rebuilding and sustaining broadleaf forests will require transformational thinking and innovation in the forest stewardship, manufacturing, and marketing sectors.

Improved biomass utilization

Diverting woody biomass to long-lived wood products or the bioenergy sector can have a positive impact on jurisdictional GHG inventories while reducing fuel loads and consequently wildfire burned area, severity, and emissions (Jones *et al.* 2010). Active stewardship is sorely needed, when guided by strong evidence-based methods (see review in Prichard *et al.* [2021]) and made more affordable where biomass is utilized, although careful consideration of full life-cycle emissions is crucial for formulating effective policy. To accomplish these outcomes, investments in economically viable wood and bioenergy utilization facilities are needed, as are policy and financial incentives to remove millions of tons of low-value woody biomass derived from thinning operations, fuel reduction treatments, and woody residues after harvests of long-lived wood products (eg see Amiandamhen *et al.* [2020]). The least valuable biomass can be used as bioenergy to offset fossil-fuel emissions and thereby reduce smoke from prescribed burning and future wildfires, all while improving local livelihoods (Jones *et al.* 2010; Amiandamhen *et al.* 2020).

Costs of mitigation

The costs of forest-based mitigation will be high, but the impacts to human health and community infrastructure by failing to mitigate will be higher. In the US, recent research (JEC 2023) shows that human health costs for an average wildfire season range from \$118 billion to \$202 billion per year (here and throughout, all monetary values are expressed in US dollars). The costs accounted for in this analysis included direct deaths and injuries from wildfires (~\$608 million) and long-term mental health impacts (~\$30 million), while short- and long-term exposure to sooty wildfire smoke accounted for much of the remainder. Annualized mortality consequences from sooty emissions (associated with $PM_{2.5}$, or particulate matter with a diameter ≤2.5 μm) in wildfire smoke range from \$39 billion to \$41 billion per year in California alone (Connolly *et al*. 2024), and wildfires in an average year burn more area and produce more total smoke and harmful soot per ton of fuel burned than prescribed fires (Jaffe *et al*. 2020). Moreover, in a recent meta-analysis, Hjerpe *et al*. (2024) demonstrated that for every \$1 invested in fuel reduction treatments in forests of the interior western US that experience frequent fire, \$6 were returned in reduced impacts on health, safety, infrastructure, and ecosystem services. Looking ahead, net cost and cost avoidance assessments would ideally include costs and emissions of prescribed burning and forest thinning treatments, reduced costs and emissions from wildfires, new market creation, and bioeconomic opportunities for woody fuels that would otherwise burn.

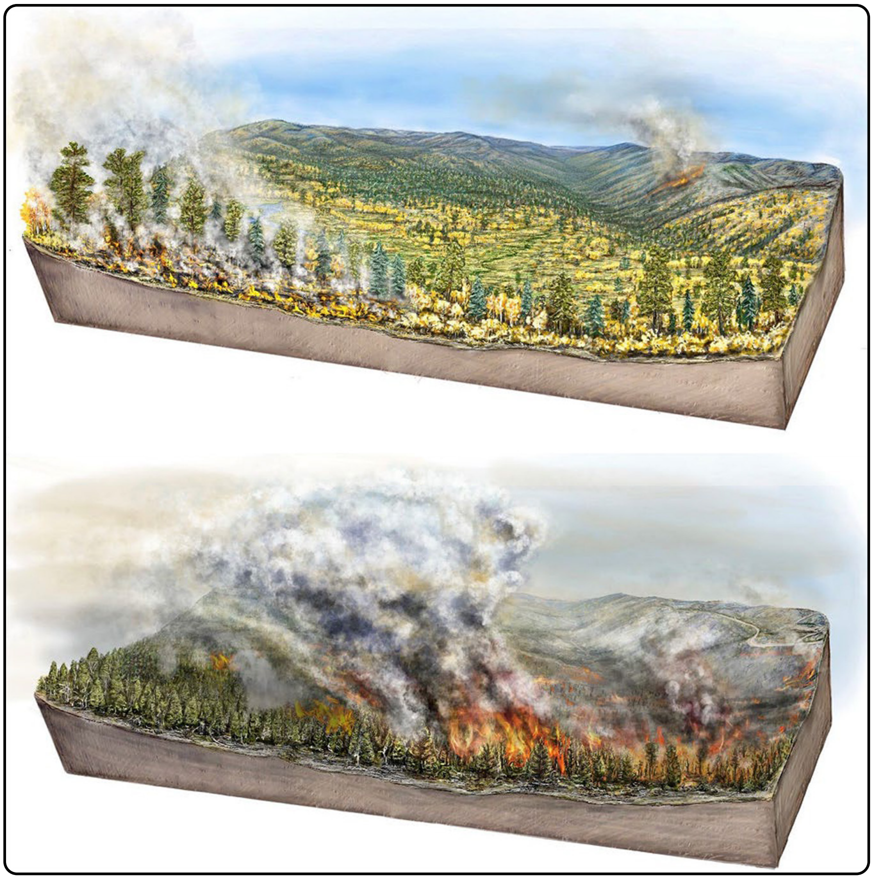

Figure 2. (top) Lightning and Indigenous ignitions burned dry, moist, and cold conifer and hardwood forests, and most burned patches were small- to medium-sized, as in a power law distribution. However, the largest lightning-burned areas typically accounted for the most hectares burned. The effect of the small- and medium-sized burned patches and the heterogeneity of open- and closed-canopy forests and non-forests were to constrain fire behavior by influencing flame length, fireline intensity, rate of spread, and crownfire potential. There was metastability in the patchwork, but these stabilizing feedbacks are mostly absent today. (bottom) Contemporary landscapes, now lacking many non-forest and hardwood forest elements, often burn at high severity. Moreover, today's wildfires derive from the worst 2–5% of fires that escape suppression during hot, dry, and windy days, and create highly simplified forest landscapes and oftentimes poor forest regeneration. Drawings courtesy of Miriam Morrill.

Key knowledge and research gaps

Despite their importance to forest C accounting, wildfire and proactive forest stewardship, along with their ecological and bioeconomic feedbacks, are not well represented in analyses of contemporary climate adaptation solutions (Hessburg *et al*. 2021). This absence limits the collective ability of jurisdictions to evaluate the trade-offs associated with different forest stewardship strategies. Stewardship influences the amount and spatial distribution of C stored in forests, the transfer of C to wood products and their subsequent life cycle, and the effect of wood product uses that displace other emission-intensive products (Smyth *et al*. 2014). However, although analyses of climate adaptation solutions (eg Fargione *et al*. 2018; Drever *et al*. 2021) generally advocate for holding C in forests longer, they fail to account not only for the risks of doing so to total forested area but also for the positive mitigation influences of reducing burned area and fire severity. Methods used in mitigation assessment need considerable updating to include these important influences and to better match the pace and scale required of stewardship actions to stabilize the remaining forest C. Quantifying future wildfire emissions under varied climate-change and landscape stewardship scenarios would reveal the maximum potential reduction of wildfire emissions relative to business-as-usual counterfactuals. Redirecting biomass and its stored potential energy away from wildfire-mediated pathways and toward wood and energy uses can also be a vital component of long-term emission reduction strategies.

Models of fire disturbances, forest succession, and C dynamics generally lack the capacity to sufficiently evaluate the feasibility and trade-offs of transitioning very large landscapes to resilient configurations through a range of stewardship options (Povak *et al.* 2023). Where forest burning and reburning are likely, adequate modeling of the feedbacks between wildfires, vegetation, and fuels is essential to clearly understanding wildfire impacts on forest-sector C sinks and stocks (eg Povak *et al.* 2023; Prichard *et al.* 2023). To identify viable climate-change adaptation options in an uncertain future, scenario analysis of landscape dynamics must include the impacts of climate change on the spatial and temporal dynamics of live and woody fuel loads after increased drought, disease, and insect-induced tree mortality, all of which eventually increase necromass, further promoting wildfire danger and emissions. However, current models of wildfire–climate relationships focus on predicting broad-scale increases in area burned based on modeled relationships calibrated with past climate and projected under future climate scenarios. These models lack the ability to integrate stabilizing feedbacks between vegetation and fuel characteristics and their spatial patterns, climatic drivers, and wildfire dynamics (eg Povak *et al.* 2023; Prichard *et al.* 2023). This knowledge gap severely constrains efforts to understand climate impacts on the C balance of wNAFs.

Similarly, existing landscape-scale fire spread models poorly represent interactions in complex forest and non-forest mosaics. Landscape- to patch-level configurations of forest and non-forest conditions are directly tied to disturbance histories, which influence future fire behavior through cross-scale interactions and feedbacks (Table 2; Hessburg *et al.* 2019; Hurteau *et al.* 2024). Although these multilevel conditions exist in wild and managed landscapes, they are inadequately represented in models of current and projected future wildfires.

As evidenced in recent seasons, wildfires overwhelm the expected contributions of forest-sector C sinks in wNAFs. For reliable C balance projections, models must explicitly integrate expected wildfire and other disturbance dynamics into assessments of future land-sector C sinks and GHG emission reduction pathways. Such models must also allow for assessment of the contributions of alternative mitigation strategies to net-zero goals, mitigation costs, and fire resilient communities. Pathways to more resilient conditions must be designed and implemented with a sound understanding of site-specific climatologies, land-sector C carrying capacity, and the changing landscape ecology of fire.

Active fuel and fire management are essential to emission reduction goals

Climate-change projections for wNAFs consistently indicate an increase in extreme conditions and burned area (Abatzoglou and Williams 2016; McCauley *et al.* 2019; Parks and Abatzoglou 2020; Parisien *et al.* 2023; Hurteau *et al.* 2024). wNAFs that historically experienced low-, moderate-, and high-severity fires are today at rising risk from extreme wildfires, as was witnessed in the 2017, 2018, 2021, 2023, and 2024 seasons. Because all models predict large increases in area burned, and because such increases have been observed globally, there is an urgent need to proactively reduce future area burned through fuel and forest management, including increasing areas of non-forest and hardwood forest conditions. Failing to address this increasing risk at sufficient scales, wildfire emissions from forests will increase more rapidly than sink enhancements from implemented climate-change adaptation solutions and, consequently, emission reduction goals will literally "go up in smoke". Moreover, increasing burned area also fundamentally threatens the contributions of wNAFs to C offsets and C markets (Badgley *et al.* 2022).

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