

Fire-adapted natural climate solutions to reduce wildfire emissions in US forests

Charles M. Truettner^{1,*}, Kendall DeLyser Roney¹, Lisa M. Markovchick², Elizabeth R. Pansing¹, Xanthe J. Walker³, Michelle C. Mack³, Nicholas T. Link³, Mitch Sternberg⁴, Matthew D. Hurteau⁵, T. Ryan McCarley¹, Kenneth J. Davidson¹, Hugh Safford^{6,7}, Katharyn A. Duffy^{6,8}, Nicole Molinari⁹, Derek J. Churchill¹⁰, Patrick Holmes¹, Rose A. Graves¹¹, Danny Norlander¹², Marin E. Chambers¹³, Solomon Z. Dobrowski¹⁴, John S. Gunn¹⁵, Christina M. Restaino¹⁶, Samuel W. Flake¹⁷, Clay Trauernicht¹⁸, Antony S. Cheng¹³, Camille S. Stevens-Rumann¹³, Kerry L. Metlen¹⁹, Christian P. Giardina²⁰, Victoria M. Donovan²¹, Leslie Boby²², Jed Meunier²³, Caitlin Littlefield²⁴, Miranda D. Redmond²⁵, Brian E. Jackson²⁶, Christopher W. Swanston²⁷, Andrew T. Hudak²⁸ and Brian Kittler¹

¹American Forests, Washington, DC 20005, United States

²Fire and Aviation, Grand Canyon National Park, National Park Service, Flagstaff, AZ 86023, United States

³Department of Biological Sciences and the Center for Ecosystem Science and Society, Northern Arizona University, Flagstaff, AZ 86011, United States

⁴Division of Biological Sciences, US Fish and Wildlife Service, Alamo, TX 78516, United States

⁵Department of Biology and the Center for Fire Resilient Ecosystems and Society, University of New Mexico, Albuquerque, NM 87131, United States

⁶Vibrant Planet, Truckee, CA 96161, United States

⁷Department of Environmental Science and Policy, University of California, Davis, CA 95616, United States

⁸School of Informatics, Computing and Cyber Systems, Northern Arizona University, Flagstaff, AZ 86011, United States

⁹Regional Ecology Program, Pacific Southwest Region, USDA Forest Service, Solvang, CA 93463, United States

¹⁰Forest Resilience Division, Washington Department of Natural Resources, Olympia, WA 98504, United States

¹¹The Nature Conservancy, Portland, OR 97214, United States

¹²Resources Planning Program, Oregon Department of Forestry, Salem, OR 97310, United States

¹³Colorado Forest Restoration Institute and Department of Forest and Rangeland Stewardship, Colorado State University, Fort Collins, CO 80523, United States

¹⁴Department of Forest Management, University of Montana, Missoula, MT 59812, United States

¹⁵The Nature Conservancy, Arlington, VA 22203, United States

¹⁶Extension at the University of Nevada, Reno, NV 89557, United States

¹⁷Cary Institute of Ecosystem Studies, Millbrook, NY 12545, United States

¹⁸Department of Natural Resources and Environmental Management, University of Hawai'i at Mānoa, Honolulu, HI 96822, United States

¹⁹The Nature Conservancy, Ashland, OR 97520, United States

²⁰Institute of Pacific Islands Forestry, Pacific Southwest Research Station, USDA Forest Service, Hilo, HI 96720, United States

²¹West Florida Research and Education Center, School of Forest, Fisheries, and Geomatics Sciences, University of Florida, Milton, FL 32583, United States

²²Southern Regional Extension Forestry, University of Georgia, Athens, GA 30602, United States

²³Wisconsin Department of Natural Resources, Division of Forestry, Madison, WI 53707, United States

²⁴Conservation Science Partners, Truckee, CA 96161, United States

²⁵Department of Environmental Science, Policy, and Management, University of California, Berkeley 94720, United States

²⁶Department of Horticultural Science, North Carolina State University, Raleigh, NC 27695, United States

²⁷Save the Redwoods League, McKinleyville, CA 95519, United States

²⁸Rocky Mountain Research Station, USDA Forest Service, Moscow, ID 83843, United States

Received: 13 April 2026. **Revised:** 21 July 2026. **Accepted:** 23 July 2026

© The Author(s) 2026. Published by Oxford University Press on behalf of the American Institute of Biological Sciences. This is an Open Access article distributed under the terms of the Creative Commons Attribution License (<https://creativecommons.org/licenses/by/4.0/>), which permits unrestricted reuse, distribution, and reproduction in any medium, provided the original work is properly cited.

Abstract

Wildfire activity and associated greenhouse gas emissions are increasing across US forests as climate change intensifies fire weather and fuel aridity. These trends challenge forest-based natural climate solutions (NCS) that prioritize carbon accumulation without accounting for wildfire-driven disturbance risk. We synthesize current science and regional expert knowledge to define fire-adapted NCS as forest-based climate mitigation strategies that reduce long-term wildfire emissions while sustaining forest carbon, sequestration capacity, and ecosystem function under changing climate and fire regimes. Across US forests, beneficial fire, forest thinning and biomass utilization, and climate-informed reforestation can stabilize carbon stocks and support post-fire recovery when aligned with regional fire regimes, vegetation, fuels, governance contexts, and workforce capacity. We frame fire-adapted NCS as a carbon stewardship strategy embedded within integrated fire risk management, emphasizing long-term wildfire emissions reduction, forest resilience, and carbon durability over maximizing short-term carbon stocks.

Keywords reforestation, beneficial fire, biomass utilization, climate adaptation, integrated fire risk management

National synthesis

More than three decades ago, climate scientists and fire ecologists warned that climate change and fire suppression would increase wildfire risk across US forests, particularly in frequent fire-adapted systems of the western and southeastern United States (Agee 1993, Covington and Moore 1994, Westerling et al. 2006). National policy responses have tried to innovate and scale proactive management, including fuels reduction and workforce expansion, although management treatments have lagged behind policy initiatives. The resulting impacts include ecosystem degradation, worsening air quality from smoke, growing risk in the wildland–urban interface (WUI), forest loss and regeneration failure, and disruptions to timber and wood supply chains (Stephens et al. 2014, Balch et al. 2017, Davis et al. 2023, Higuera et al. 2023, Bousfield et al. 2025).

Wildfire has accounted for nearly one-third of global forest loss over the past two decades (Jerrett et al. 2022, Tyukavina et al. 2022, Allan et al. 2023, Hessburg et al. 2025). Total greenhouse gas (GHG) emissions from wildfire (hereafter, wildfire emissions) remain difficult to quantify. Carbon dioxide (CO₂) is the primary GHG emitted by wildfires, though wildfires also release other gases and aerosols that can have both warming and cooling effects on the atmosphere while increasing risks to public health (Reid et al. 2016, Jaffe et al. 2020). Wildfire emissions reinforce positive climate–wildfire feedbacks, contributing to the widely recognized US Wildfire Crisis (USFS 2022a). As wildfire emissions increase, they accelerate climate change (Jones et al. 2024, Foster and Rahmstorf 2026), but fire management offers a counter lever.

Euro-American colonization significantly altered the use of beneficial fire across many landscapes in North America, greatly magnified by institutionalized wildfire suppression policies arising in the 1850s (Pyne 1981). But during the 1960s and 1970s, the United States Department of Interior National Park Service (NPS) and the United States Department of Agriculture Forest Service (USFS) increasingly recognized the ecological importance of beneficial fire and fuels management (Kilgore 1973, Van Wagtenonk 2007). However, implementation remained limited for several decades, although the NPS generally advanced beneficial-fire programs earlier and more extensively than the USFS, particularly in the western United States (Turner et al. 2003, North et al. 2015). As wildfire activity and associated wildfire emissions have increased, a policy paradigm has reemerged that emphasizes beneficial fire, forest resilience, and climate-informed forest management alongside suppression as central components of

wildfire hazard reduction and climate adaptation strategies (figure 1; USWFMCMC 2023). Despite this policy shift, implementation has been limited, uneven, and challenged by many structural barriers (Schultz et al. 2019, Smithwick et al. 2024).

As this fire policy paradigm has reemerged, so too has interest in *forest-based natural climate solutions* (NCS): investments in forest management intended to mitigate the effects of climate change by enhancing carbon sequestration (Griscom et al. 2017, Fargione et al. 2018, Shanley et al. 2024). To date, many forest-based NCS assessments and investments have focused primarily on managing human influences on forests, with more limited consideration of climate-driven disturbance and its implications for long-term carbon storage. The complex, interacting controls on wildfire emissions and carbon storage introduce considerable uncertainty regarding the effectiveness of NCS (Buma et al. 2024, Ellis et al. 2024).

A central question is whether forest-based NCS investments should avoid regions of high-wildfire risk, or whether management strategies that reduce wildfire risk can stabilize forest carbon stocks and lower wildfire emissions as a pathway for climate mitigation. Despite growing interest in forest-based NCS, there is limited synthesis of how regionally tailored approaches reduce wildfire risk and emissions, and how co-benefits—such as enhanced drinking water quality, sustainable wood utilization, and safer recreational access—vary across US forests (Prichard et al. 2020a). Addressing this gap requires evaluating forest-based NCS through the lens of wildfire emissions, regional fire regimes, and long-term carbon stewardship.

Fire-adapted NCS pathways

We define *fire-adapted NCS* as forest-based climate mitigation strategies designed to reduce long-term wildfire emissions by managing wildfire hazard, fire behavior, and post-fire recovery while sustaining forest carbon stocks, sequestration capacity, and ecosystem function under changing climate and fire regimes. Like other forest-based NCS, these approaches are evaluated through carbon budgets that account for sequestration, storage, and emissions. However, fire-adapted NCS differ by treating long-term wildfire emissions reduction as a central management outcome rather than wildfire as an external disturbance risk. Their objective is to not simply maximize near-term forest carbon stocks, but to improve the long-term balance among carbon stored in forests, carbon emitted (or retained) during wildfire, and carbon ab-

U.S. Wildfire Policy Timeline



Figure 1 Timeline of US wildfire policy from Euro-American colonization to present .

sorbed through post-fire recovery by increasing forest resilience and sustaining future sequestration.

To evaluate how fire-adapted NCS vary across US forests, we synthesized regional expert knowledge using Geographic Area Coordination Center (GACC) regions as an organizing framework (figure 2). Across GACC regions, burned area from high-severity wildfire has generally increased over the last three decades, whereas trends in fire frequency vary regionally, with increases in some regions and decreases in others (figure 3). Regional teams of research scientists and land managers characterized dominant forest types and fire regimes, identified fire-adapted NCS pathways currently being implemented or emerging in each region, and summarized relevant policies, collaborations, and implementation barriers. Detailed regional syntheses are provided in supplemental materials.

Our synthesis shows that fire-adapted NCS can function as a climate mitigation pathway when matched to local fire regimes, fuel conditions, and management capacity. When appropriately implemented, these strategies can stabilize forest carbon stocks, support post-fire recovery where needed, and provide co-benefits for communities and infrastructure (table 1). Achieving these outcomes will depend on

cross-jurisdictional coordination and shared management resources that support proactive forest management before, during, and after wildfire.

Implementing fire-adapted NCS is increasingly important as climate change increases fuel aridity, lengthens fire seasons, and raises the frequency of extreme fire weather (Jolly et al. 2015, Abatzoglou and Williams 2016, Abatzoglou et al. 2021). Wildfire emissions are shaped by the interacting effects of climate, vegetation, hydrology, land use, governance, forest management, and workforce capacity (Kolden and Henson 2019, Stephens et al. 2020). Under warmer and drier conditions, forest management alone cannot eliminate wildfire risk, but it can influence fire behavior, fuel continuity, post-fire recovery, and the amount of carbon and other GHGs emitted during wildfire. The effectiveness of fire-adapted NCS therefore depends on whether strategies are matched to the dominant controls on wildfire emissions in each region. We evaluate three fire-adapted NCS pathways: (1) beneficial fire, (2) forest thinning and biomass utilization, and (3) climate-informed reforestation. Across these pathways, the goal is not to prescribe a universal solution, but to identify where and how fire-adapted NCS can reduce wildfire emissions while sup-

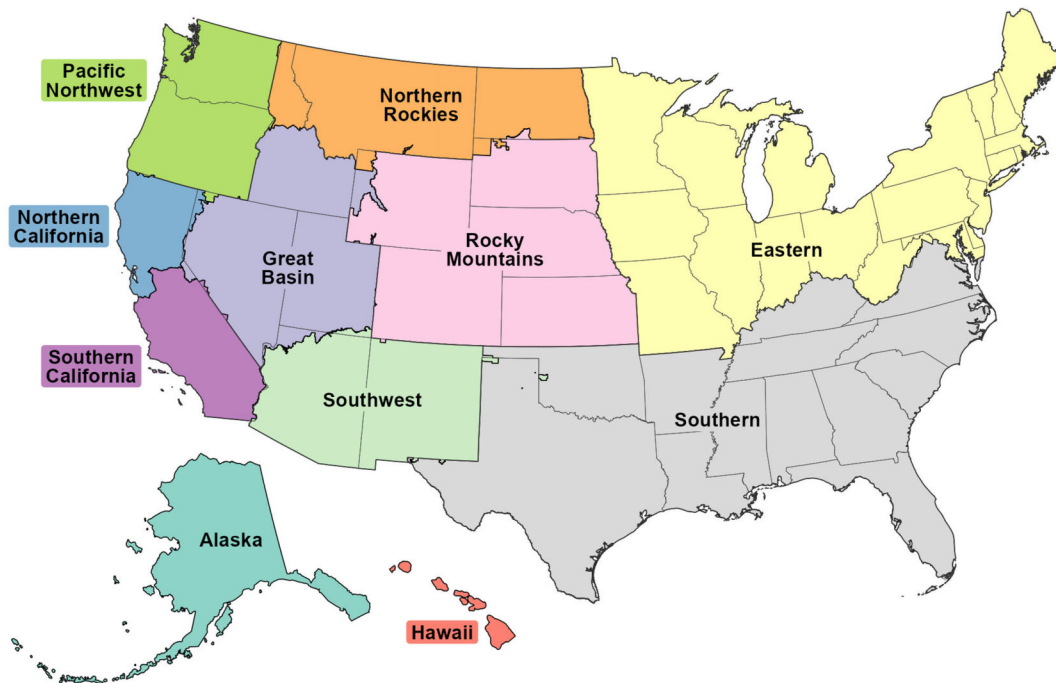


Figure 2 Map of the different GACC regions. Hawaii is classified under the Northern California GACC, but we treated it as a separate region in this study.

porting durable carbon storage, regional adaptation, and associated co-benefits such as drinking water protection, sustainable wood utilization, workforce development, biodiversity conservation, and safer recreation.

Beneficial fire

The contemporary term *beneficial fire* encompasses prescribed fire, Indigenous cultural burning, and managed wildfire. By moderating fuel accumulation and fire behavior, beneficial fire can reduce the likelihood of high-severity wildfire and the large carbon losses associated with combustion of above- and below-ground biomass. In addition to immediate combustion emissions, wildfire-induced tree mortality can produce substantial delayed carbon losses as standing and downed biomass decomposes over subsequent decades. When evaluated across broad spatial and temporal scales, beneficial fire may improve carbon balance by reducing the probability of larger and more severe wildfires, associated combustion emissions, and subsequent mortality-driven carbon losses.

Prescribed fire is most commonly implemented to reduce surface and ladder fuels but also provides co-benefits such as habitat restoration, invasive species control, watershed protection, slower pathogen spread, and supporting cultural norms. When applied to frequent-fire-adapted ecosystems under favorable weather and fuel conditions, prescribed fire can reduce the likelihood of high-intensity fires while reestablishing beneficial fire regimes (Pollet and Omi 2002, Stephens and Moghaddas 2005, Fulé et al. 2012, Hiers et al. 2020, Prichard et al. 2020b). Implementation of prescribed burn practices is constrained by workforce capacity, funding, social resistance, and air quality regulation, with climate change further shifting and, in some cases, narrowing burn windows (Schultz et al. 2019, Yurkonis et al. 2019, Swain et al. 2023). Failure to account for these changes to burn windows can elevate the likelihood of escape during extreme wind events.

These constraints underscore that although prescribed fire remains one of the most effective fire-adapted NCS pathways for reducing high-severity wildfire hazard and associated emissions in many regions, its success depends on adaptive planning, careful monitoring, sustained institutional support, an adequately trained workforce, and community acceptance of some level of risk.

The southern United States demonstrates how prescribed fire can operate as a mature and well-organized fire-adapted NCS pathway where frequent-fire ecosystems, practitioner networks, and supportive liability frameworks align. In longleaf pine (*Pinus palustris*), shortleaf pine (*Pinus echinata*), and oak–pine systems, frequent prescribed fire helps maintain open, fire-adapted structure, limits surface fuel accumulation, and reduces the likelihood of high-emission wildfire events, with more area treated annually than in all other US regions combined (table 1; Waldrop and Goodrick 2012, Cummins et al. 2023).

Indigenous cultural burning is distinct from other fire management activities through its grounding in Tribal and Indigenous laws, objectives, and rights to apply fire for cultural purposes (Clark et al. 2024). Proactive Indigenous fire stewardship reduces fuel loads while supporting biodiversity, reinforces cultural practices, and sustains traditional ecological knowledge (Kimmerer 2011, Lake et al. 2017, Long et al. 2020). Prior to Euro-American colonization, Indigenous cultural burning was extensive, frequent, and multifunctional (Eisenberg et al. 2024). For example, tribes in California and the broader Southwest applied near-annual fire across large landscapes to manage food resources, fiber production, and habitat (Anderson 2006). Indigenous cultural burning was largely prohibited in the United States beginning in the late 19th century, with legal recognition and authorization only reemerging recently (e.g., *California Senate Bill 310*, 2024). Growing recognition of Indigenous cultural burning reflects its cultural, ecological, and management significance, as addressed by the

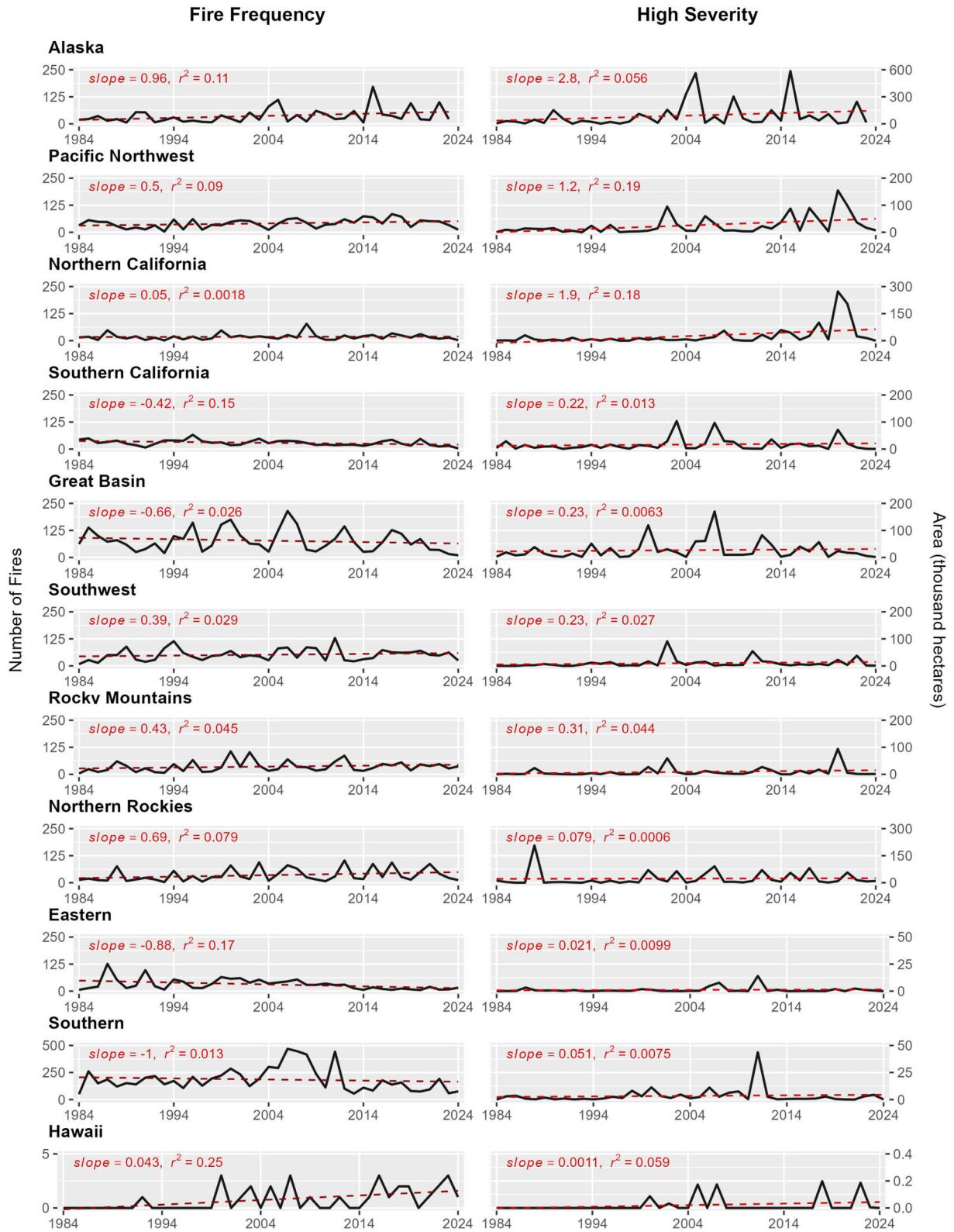


Figure 3 Fire frequency and high-severity fire area for different GACC regions from 1984 to 2024. Methods were replicated from Salguero and colleagues (2020), although extended from the original analysis for 2017–2024.

Table 1 Regions and descriptions of fire-adapted natural climate solutions with key guidance and primary constraints.

Region	Beneficial fire	Forest thinning and biomass utilization	Climate-informed reforestation	Key guidance	Primary constraints
Alaska	Rare and limited to backburning during managed wildfire under constrained conditions	Rare and fuel breaks used selectively to protect communities and cultural resources	Viable in formerly black spruce systems, promote deciduous transition to reduce wildfire emissions and protect soils	Align suppression with protection of belowground carbon; expand Tribal partnerships	Remote access, limited workforce and infrastructure, logistical constraints
Pacific Northwest	Common in dry eastside forests; Limited in moist westside forests	Common in eastside forests; often paired with fire; pile burning remains widespread	Common where high-severity fire and regeneration failure are likely	Expand residue utilization and alternatives to pile burning; sustain resilience programs	Weak biomass markets, limited workforce, loss of institutional capacity
Northern California and Southern Sierra Nevada	Viable and effective but constrained by risk aversion, funding, and workforce capacity	Common but limited by declining mill capacity and underdeveloped biomass markets	Viable but constrained by nursery capacity, permitting, and workforce availability	Expand integrated fire-thinning–reforestation programs; invest in long-lived wood products and residue utilization	Uncertainty in treatment longevity; limited infrastructure and workforce relative to need
Southern California	Rare due to air quality constraints, escape risk, and WUI complexity	Limited to hand thinning, mastication, and pile burning due to minimal biomass markets	Common but often unsuccessful; microsite and mixed shrub–tree approaches show promise	Expand region-specific, prevention-focused strategies and workforce investment	High WUI density, limited infrastructure, harsh post-fire conditions
Great Basin	Limited because low-elevation use can reinforce grass–fire feedbacks; selective use at high elevations	Limited because low-elevation treatments carry tradeoffs; selective high-elevation thinning may reduce crown fire risk	Limited and most applicable for protecting intact high-elevation forests and woodlands	Reduce invasive grass–fire feedbacks; protect intact systems; limit large-fire spread	Extensive federal ownership, remote access, high fire spread potential
Southwest	Common in dry forests; thinning-plus-fire widely applied	Common but constrained by limited markets for small-diameter wood	Viable as climate-informed planting supports recovery in vulnerable systems	Expand biomass utilization and risk-tolerant fire governance	Risk-averse decision-making, limited infrastructure, workforce constraints
Rocky Mountains	Common in dry montane forests; not appropriate in high-elevation lodgepole pine or spruce–fir	Common in dry forests; limited in high-elevation forest types	Viable in favorable microsites (e.g., north-facing, shaded)	Reform liability and insurance frameworks; strengthen cross-boundary coordination	Extensive WUI, air-quality constraints, inequitable resource distribution
Northern Rockies	Common in appropriate forest types; outcomes depend on timing and conditions	Viable as effectiveness depends on persistence, forest type, and remoteness	Viable and increasingly important where regeneration failure occurs	Advance cultural burning and landscape-scale coordination; integrate post-fire recovery	Limited workforce and nursery capacity, constrained funding
Eastern	Viable in oak–pine systems and barrens	Common silvicultural approach to increase resilience and heterogeneity	Viable and applied selectively to stabilize carbon and enhance resilience	Expand co-management, modernize smoke management, incentivize low-value wood use	Fragmented ownership, limited burn windows
Southern	Common due to strong prescribed fire frameworks and initiatives	Limited due to weak markets following pulp and paper declines	Common and effective in longleaf pine and savanna restoration systems	Expand workforce development and fire-adapted ecosystem restoration	Expanding WUI, smoke constraints, shifting disturbance regimes
Hawai'i	Rare due to escape risk and grass–fire feedbacks	Limited to targeted grazing and biomass reduction	Viable and applied selectively through agroforestry and native forest restoration	Reduce grass–fire feedbacks; expand Indigenous leadership and restoration	Invasive fuels, limited workforce, fragmented governance

Note: For forest-type specific discussion, see the appropriate regional section in supplementary information.

congressionally established US Wildland Fire Mitigation and Management Commission (USWFMMC 2023).

Although all wildland fires are “managed” in a broad sense, we define *managed wildfires* here as are naturally ignited fires that are intentionally managed for resource benefits (Stevens-Rumann et al. 2025). These fires are closely monitored and allowed to burn under favorable weather conditions and approved management plans, most often in wilderness or remote landscapes. They rely on robust collaborative partnerships among government and civic sector entities (Davis et al. 2022), and may involve strategic fire operations, including scenario planning, containment lines, or limited back-burning to guide fire behavior toward desired outcomes. The Northern Rockies provide one of the clearest examples of where managed wildfire can be operationally feasible. Large wilderness areas in Montana and Idaho retain some of the most intact fire regimes in the lower 48 states, creating opportunities to manage naturally ignited fires for resource benefits, although tolerance for this approach declines sharply near communities and outside remote landscapes (Parks et al. 2014).

Pre-wildfire fuel treatments in fire-adapted temperate forests can further enhance the effectiveness of managed wildfire by reducing fire spread and allowing fires to burn at lower severity, thereby releasing less carbon, stabilizing forest carbon stocks, and reducing the need for post-fire NCS interventions (Hurteau et al. 2024, Kelp et al. 2025). Long-running fire programs in Yosemite and Sequoia-Kings Canyon National Parks illustrate the potential for repeated beneficial fire to support carbon stewardship in frequent-fire forests. In these landscapes, managed wildfire and repeated fire use have restored forest structure, increased landscape heterogeneity, improved soil moisture and streamflow, reduced drought-related mortality, and produced forests that are more resistant to subsequent high-severity wildfire (van Mantgem et al. 2011, Stephens et al. 2021).

Managed wildfires can also be effective in the absence of prior fuel treatments, as not all forest types are suitable for thinning or frequent fire. In some ecosystems, repeated pre-fire treatments can promote invasive species that increase burn probability and reduce ecosystem resilience (Brooks et al. 2004, Keeley 2006, Brockway et al. 2009). The Great Basin and Southwest illustrate why beneficial fire must be matched carefully to ecosystem context. In low- to mid-elevation pinyon-juniper systems, prescribed fire can accelerate cheatgrass dominance and reinforce grass-fire feedbacks, increasing the likelihood of recurrent fast-moving fires rather than reducing future wildfire emissions risk (table 1; Balch et al. 2013, Bradley et al. 2018). Hawai'i provides an even sharper contrast because many native forest communities are not fire-adapted, and contemporary wildfire risk is driven largely by invasive grasses, shrublands, and human ignitions rather than forest fuel accumulation. In this context, fire-adapted NCS are better expressed through ignition prevention, targeted grazing, green breaks, agroforestry, and native canopy restoration than through expanded prescribed or managed fire (table 1; Ammondt et al. 2013, Trauernicht et al. 2015, Bremer et al. 2021).

Nevertheless, as climate change increases aridity across US forests (Abatzoglou and Williams 2016, Crimmins et al. 2023), beneficial fire that is adapted to local ecological conditions and implemented by skilled field crews can reduce burn severity and wildfire emissions while promoting ecological co-benefits at scale (Prichard et al. 2021, Hurteau et al. 2024).

Forest thinning and biomass utilization

Thinning treatments use manual or mechanical methods to alter forest structure and composition, reducing stand density and, where appropriate, promoting more fire-resilient species composition and spatial patterns (Agee and Skinner 2005). These treatments immediately reduce stand-level biomass and carbon stocks, while creating structural changes across larger areas that can limit fire spread and intensity during subsequent wildfires. The goal is to stabilize remaining forest carbon and shift *in situ* carbon accumulation toward more fire-resistant carbon pools, such as large-diameter, fire-resilient trees (Stephens et al. 2012, Brodie et al. 2024, Hurteau et al. 2024, Yackulic et al. 2025). Thinning with biomass removal and off-site utilization may reduce emissions relative to thinning followed by on-site biomass burning, decomposition, or subsequent wildfires (Janowiak et al. 2017, Cabiyo et al. 2021, Barker et al. 2025).

Importantly, thinning and biomass removal are not one-size-fits-all solutions, and prescriptions must respond to local stand conditions and density, sustainable and consistent timber market demand, and the proximity and capacity of wood-processing infrastructure. These differences mean that thinning may function as a wildfire-emissions reduction strategy in some systems, but as a resilience, restoration, or hydrologic protection strategy in others. Outcomes from thinning treatments also depend on spatial design and vary among forest types (Ott et al. 2023). For instance, restoring the heterogeneous structural patterns characteristic of mature and old-growth forests can enhance biodiversity, whereas homogeneous fuel structures in some frequent-fire forests can contribute to greater high-severity crown-fire spread when not followed by beneficial fire (Larson and Churchill 2012). However, these relationships are not universal; some forest types, such as lodgepole pine (*Pinus contorta*) in the Rocky Mountains, commonly develop as even-aged, structurally homogeneous stands that often reach maturity. In the eastern United States, thinning and related silvicultural treatments are often better framed as forest-health and drought-resilience strategies than as broad wildfire-emissions reduction tools (D'Amato et al. 2013, Birdsey et al. 2023, Magerl et al. 2023). Reducing competition and restoring structural heterogeneity may support oak-pine systems and fire-enabled oak regeneration in the eastern United States, whereas high-carbon peatlands in this region require hydrologic protection rather than fuel reduction to avoid deep smoldering fires and associated carbon losses (table 1; Arthur et al. 2012, Vose and Elliott 2016, Hanson et al. 2020).

Decades of research show that thinning-plus-fire tends to provide the most reliable reductions in wildfire severity, especially in western US dry mixed-conifer forests (Stephens et al. 2012, Prichard et al. 2021, Davis et al. 2024, Shive et al. 2024). We use the term *thinning-plus-fire* to describe integrated fuel treatments in which mechanical or hand thinning is followed by broadcast prescribed fire or subsequent managed wildfire; in some operational contexts, pile burning may also be used to reduce residual activity fuels. This combination has been shown to reduce fire severity and stabilize forest carbon stocks relative to thinning or fire alone (Davis et al. 2024). In dry eastside forests of the Pacific Northwest, recent wildfire events illustrate the value of integrated treatments. During the 2021 Bootleg Fire, stands previously treated with prescribed fire or thinning-plus-fire generally burned at lower severity than thinning-only or untreated stands, supporting broader evidence that integrated treatments can reduce wildfire emissions in dry, frequent-fire forests when treatment timing, forest type, and maintenance intervals align (ta-



Figure 4 Residue left from a successful, large-scale wildfire risk treatment in the Cleveland National Forest (Southern California). The objective of the management project was accomplished, but these large piles of biomass were left behind and could be utilized as peat replacement growing media for container-grown tree seedlings, as well as vegetable, fruit, ornamental, and floriculture crops (Photograph: N. Molinari).

ble 1; Sanna et al. 2025). Similar evidence from the Rocky Mountains suggests that fuel treatments can provide durable benefits in lower montane ponderosa pine and dry mixed-conifer forests. During the 2020 Cameron Peak Fire, prior thinning, prescribed fire, and mixed treatments moderated fire severity across roughly two decades of treatment records, although these benefits are not readily transferable to lodgepole pine or high-elevation spruce–fir forests where stand-replacing fire is more characteristic (table 1; Vorster et al. 2021, Stevens-Rumann et al. 2025).

Beyond direct effects on fuel loads and fire behavior, thinning and the restoration of fire can also influence hydrologic cycles, albedo, snow accumulation, and water availability (Broxton et al. 2015, Boissramé et al. 2017, Campo et al. 2022). When applied judiciously to restore forest complexity, thinning and thinning-plus-fire can reduce wildfire severity and associated wildfire emissions while sustaining habitat restoration potential and water storage.

Biomass utilization is central to the carbon balance of thinning because removed material can follow very different emissions pathways depending on whether it is burned, left to decompose, or converted into longer-lived or substituted products. Utilization pathways such as lumber, mass timber, biochar, and engineered wood fiber products can extend carbon residence time, reduce reliance on pile burning, and in some cases displace more emissions-intensive materials (Hurteau and North 2009, Cabiyo et al. 2021, Bobo and Jackson 2024). Engineered wood fiber substrates for soilless growing media represent one emerging pathway, particularly where thinning residues, small-diameter material, or mill byproducts can substitute for peat-based products or support nursery systems needed for post-fire reforestation (Raviv et al. 2019, Bobo and Jackson 2024). As with other biomass utilization strategies, climate benefits depend on lifecycle emissions, transportation distances, product longevity, and whether utilization displaces higher-emission alternatives.

Northern California and the southern Sierra Nevada show both the promise and bottlenecks of thinning and biomass utilization. Thinning-plus-fire has strong empirical support for reducing high-severity fire effects and stabilizing live forest carbon in current frequent-fire forests. Biomass utilization could further extend carbon residence time and reduce reliance on pile burning, but sawmill closures, limited processing capacity, and underdeveloped markets for small-diameter biomass continue to constrain implementation (Liang et al. 2018, AF 2025). Southern California highlights a different biomass-utilization challenge. In some large fuel-reduction projects, management objectives can be achieved while substantial residues remain piled on-site because sawmill access and biomass markets are limited, while pile-burning may be restricted by air quality concerns and wildfire risk in densely populated landscapes (figure 4). These residues may then be burned, chipped, or left to decompose rather than converted into longer-lived or substituted products (table 1; Stephens et al. 2018, Acuna et al. 2019, Bobo and Jackson 2024). Where residue piles remain untreated, limited soil contact can slow decomposition, allowing material to persist for extended periods and potentially contribute to future fuel hazards.

Climate-informed reforestation

The probability of natural regeneration in frequent-fire-adapted forests following wildfire often declines with increasing fire frequency and patch size of high-severity burn, as these disturbances reduce seed availability, increase distances to viable seed sources, and impair resprouting and seed viability (Davis et al. 2019, Stevens-Rumann and Morgan 2019, Laughlin et al. 2023, McFarland et al. 2025). More frequent and severe wildfires can also diminish post-fire climatic buffering by reducing canopy cover and surface shading, thereby intensifying heat and drought stress on regenerating vegeta-



Figure 5 Field crew planting deciduous tree seedlings following monitoring protocols in large fire breaks in Interior Alaska (Photograph: N. Link).

tion (Marsh et al. 2022, Crockett and Hurteau 2024). Post-fire planting studies in the Rocky Mountains and Southwest show why climate-informed reforestation must account for topography and microsite conditions at finer scales than regional climate projections. Seedling survival can depend strongly on north-facing aspects, shading, and microsites that buffer heat and moisture stress, suggesting that planting design can influence whether post-fire landscapes recover forest cover or shift toward persistent non-forest states (table 1; Marsh et al. 2022, Marshall et al. 2023, 2024, Holden et al. 2025). Indeed, post-planting cultural treatments that promote seedling survival, coupled with multi-year monitoring, are crucial for achieving reforestation objectives.

Climate-informed reforestation in post-fire landscapes represents a fire-adapted NCS pathway to stabilize forest carbon stocks and support long-term carbon sequestration by aligning regeneration strategies with projected climate conditions and wildfire regimes (Fargione et al. 2018, Crockett and Hurteau 2024). Through decisions on seed sources, seedling stock types, and planting design across stand-to-landscape scales, climate-informed reforestation can promote structural and genetic diversity that enhances resilience to wildfire, drought, and disease (Bastin et al. 2019, Smith et al. 2024, Snieszko et al. 2024, Truettner et al. 2025). In Interior Alaska, climate-informed reforestation in and around fuel breaks is emerging as a distinct fire-adapted NCS pathway (figure 5). Because deciduous birch and as-

pen stands are more fire resistant and emit less carbon during subsequent fires than black spruce (*Picea mariana*) stands, planting or encouraging deciduous species where seed sources are limited may help protect communities and cultural resources while reducing future wildfire emissions and belowground carbon losses (table 1; Johnstone et al. 2010, Walker et al. 2023, 2025, Black et al. 2026, Link et al. 2026). In the Southwest, where reforestation has been challenging because of water availability and desertification, climate-informed reforestation is becoming increasingly operational through facilities such as the Northern Arizona University Greenhouse and the New Mexico Reforestation Center. These efforts link seed sourcing, container stock types, mycorrhizal inoculation, and assisted migration with post-fire planting designs, helping translate experimental work into landscape-scale recovery strategies where warming and high-severity fire are limiting natural regeneration (table 1; Dixit and Burney 2024).

Climate change is altering regeneration conditions in ways that increasingly diverge from those experienced by current forest cohorts, raising the risk of regeneration failure and persistent non-forest states in some regions, particularly where contemporary or projected climates exceed historical seedling establishment niches (Falk et al. 2022). Where wildfires are more severe and extensive, post-fire recovery is further constrained by reduced seed rain as distances to viable seed sources increase; this limitation varies among species,

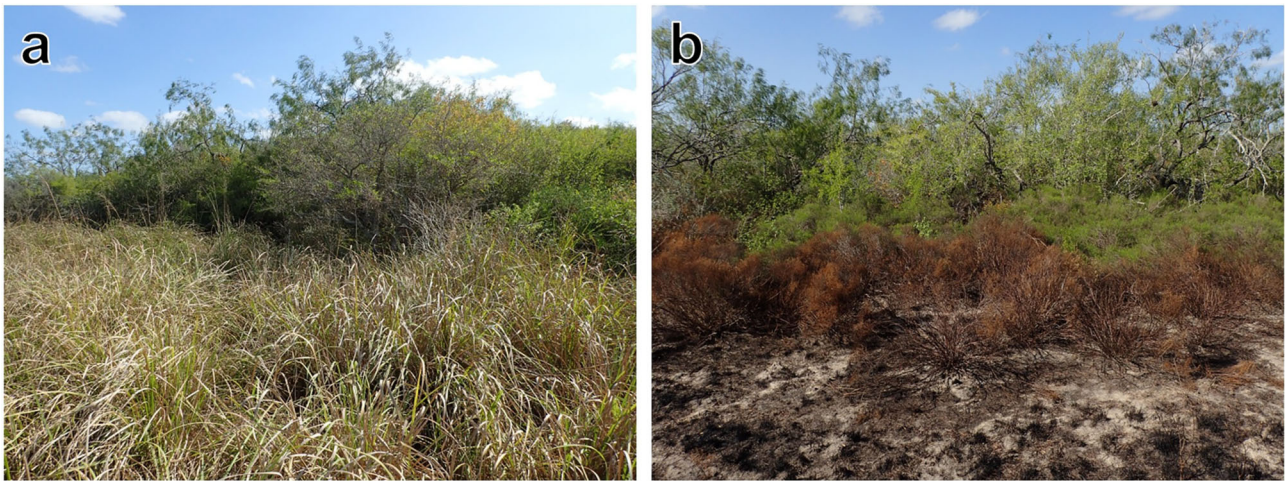


Figure 6 Thornforest-grassland interface (a) pre-prescribed fire and (b) post-prescribed fire. Thorn forests, similar to aspen in the Rocky Mountains, can act as a natural barrier to fire spread in the Rio Grande Valley, Texas (Photograph: M. Sternberg).

burn severity patterns and patch size, and seed dispersal mechanisms (Stevens-Rumann and Morgan 2019, Clark-Wolf et al. 2023, Buonanduci et al. 2024). In the Northern Rockies, hotter droughts, reburns, and increasing fire frequency are pushing some post-fire landscapes beyond regeneration thresholds, making climate-informed reforestation increasingly important but difficult to scale (table 1; Davis et al. 2019, Dobrowski et al. 2024). Experimental efforts such as the Adaptive Silviculture for Climate Change Network emphasize planting and management strategies that increase landscape heterogeneity and resilience rather than attempting uniform reforestation across all burned areas (Larson et al. 2022).

Successful implementation often requires objective-based risk assessment, post-planting management and monitoring, and treatment effectiveness evaluation of resilience outcomes and carbon-related goals (Palik et al. 2022, Bower et al. 2024). Follow-up treatments can include targeted vegetation management to control invasive grasses, native shrubs, and other herbaceous plants that compete with regenerating trees or increase fine-fuel hazards (Keeley 2006). Without continued maintenance, some reforestation efforts may not achieve desired climate mitigation goals or may fail entirely; accordingly, climate-informed reforestation should be viewed as a long-term adaptive management strategy rather than a one-time intervention. In the Southern Plains, climate-informed reforestation can also reduce fire spread by restoring vegetation types that function as natural fuel breaks. Dense thorn forests in South Texas can interrupt grassland fire spread because their structure, higher moisture retention, and limited fine fuels contrast sharply with adjacent invasive grasslands (figure 6), and dominant thornforest species have already been used to reforest ~8000 hectares in the Rio Grande Valley (table 1; Jahrsdoerfer and Leslie 1988, Diamond 1998, Radeloff et al. 2023). Hawai'i similarly demonstrates how climate-informed reforestation can reduce wildfire emissions by interrupting invasive grass-fire feedbacks rather than restoring frequent-fire regimes. Green breaks planted with fire-resistant native species, agroforestry on abandoned agricultural lands, and koa or native hardwood restoration can reduce grass fuels, increase canopy moisture, and support carbon storage while providing food, cultural, and watershed co-benefits (table 1; Ammond et al. 2013, Bremer et al. 2019, 2021, 2025).

Management and policy implications

There is no single national prescription for implementing fire-adapted NCS. Durable outcomes will depend on policy and management frameworks that match strategies to regional fire regimes, vegetation types, ownership patterns, infrastructure, and institutional capacity. In some regions, particularly the southern United States, beneficial fire is well suited because of frequent fire regimes, extensive prescribed-fire experience, and collaborative institutions, including prescribed burn associations (Deak et al. 2025). In drier, fire-adapted forests of the western United States, integrated thinning-plus-fire treatments have been shown to reduce crown-fire potential (Pollet and Omi 2002, Stephens et al. 2009, Davis et al. 2024). In contrast, other ecosystems—including hardwood-dominated forests of the eastern United States, black spruce forests in Alaska, and chaparral systems in southern California—present distinct ecological and operational constraints that limit the applicability of these approaches. Factors such as fire regime, vegetation type, remoteness, infrastructure, and population density shape what is feasible and suggest that management strategies must be adapted accordingly.

Regionally tailored fire-adapted NCS

The Wildfire Commission called for a more balanced US wildfire policy that shifts from an approach dominated by wildfire response toward one that scales proactive land management to reduce wildfire risk and support post-fire recovery (USWFMMC 2023). Many of these recommendations emphasize preparing the nation's diverse regions to better withstand the negative effects of wildfire across both natural and built environments—objectives that can be in part achieved through implementation of regionally tailored fire-adapted NCS.

Together, these examples show that regional tailoring depends less on choosing among fixed fire-adapted NCS than on identifying the dominant controls on wildfire emissions in each system. For instance, the Pacific Northwest shows how sharply fire-adapted NCS can vary within a single GACC region. In dry eastside forests, thinning-plus-fire and beneficial fire are central to reducing high-severity fire and wildfire emissions, whereas moist westside forests often emphasize climate-adaptive silviculture, climate-informed reforestation, and long-term carbon storage because treatment effects may be limited

under moist conditions or extreme east-wind fire weather (table 1; Case et al. 2021, Reilly et al. 2022, Sanna et al. 2025)

Implementation of fire-adapted NCS across pre-fire, active-fire, and post-fire phases can support climate adaptation and ecosystem recovery (Sample et al. 2022, Papa et al. 2023, AF 2025). Integrating these strategies at landscape scales within a framework that prioritizes science-based risk assessments, adaptive management, cross-jurisdictional coordination, and transparent, collaborative governance can help maximize carbon benefits while also supporting ecological and social co-benefits in fire-prone, frequent-fire forests, although outcomes will depend on regional context and uncertainty in system responses.

Carbon stewardship

Fire-adapted NCS exemplify a carbon stewardship approach that prioritizes long-term carbon durability under changing climate and disturbance regimes. The USFS defines carbon stewardship as management that increases or stabilizes biogenic carbon while facilitating ecosystem health, multiple uses, and climate resilience (USFS 2024). In fire-prone forests, this framing shifts attention from maximizing near-term carbon stocks toward sustaining carbon storage, sequestration capacity, and ecosystem function despite increasing aridity, wildfire activity, drought, and insect disturbance (Hoecker et al. 2023, Hurteau et al. 2025).

This shift is important because expectations of carbon stability rooted in the historical range of variability are increasingly misaligned with contemporary and future climates. Changes in species composition, forest structure, and disturbance regimes mean that past conditions may no longer provide reliable benchmarks for future management (McDowell et al. 2020). Fire-adapted NCS are therefore better framed around forward-looking resilience and risk management than restoration to historical conditions alone.

Carbon stewardship reframes fire-adapted NCS as a problem of wildfire-emissions risk management and long-term carbon stabilization, rather than carbon accumulation alone. At the stand scale, some treatments may reduce near-term carbon stocks, but at landscape scales these approaches can reduce the likelihood of unacceptably severe wildfires and associated carbon losses. In some ecosystems, sustaining ecosystem function and reducing the probability of catastrophic carbon loss may require accepting lower live biomass or different forest structure than attempting to maximize short-term carbon storage (Anderegg et al. 2020, North et al. 2022, Yackulic et al. 2025). Fire-adapted NCS therefore prioritize resilience and long-term carbon durability over short-term biomass maximization, recognizing that durable climate mitigation depends on reducing the likelihood of large, high-emission wildfires while sustaining future sequestration.

Cross-cutting constraints on NCS implementation

Across regions, multiple interacting constraints limit the scalability and durability of fire-adapted NCS. Workforce capacity represents an important constraint: proactive fire management, thinning, and climate-informed reforestation require skilled, cross-trained personnel capable of operating across seasons and disturbance phases (ISE 2016, USWFMMC 2023). At the same time, the diversity of employment arrangements (i.e., federal, state, Tribal, private-sector, and contract-based workforces) can provide flexibility in addressing complex, region-specific challenges. Realizing this potential will (Steph

and coordination across institutions to build on-the-ground capacity, strengthen institutional knowledge, and enhance operational continuity. In addition, the patchiness of land ownership and boundaries, especially in the southern and eastern United States, limits cross-jurisdictional projects and coordinated management strategies. Social acceptance and political durability represent additional implementation constraints, particularly where treatment effects, smoke exposure, costs, and benefits are distributed unevenly across rural and urban communities.

Market and infrastructure constraints represent additional limitations to large-scale implementation of forest-based NCS. In many regions, forest biomass removal and reforestation are limited by sawmill capacity, biomass utilization facilities, and nursery infrastructure (Acuna et al. 2019, Dobrowski et al. 2024). Scaling thinning-plus-fire treatments and climate-informed reforestation to levels sufficient to influence wildfire emissions would require sustained, regionally distributed investment in wood processing, nursery capacity, and greater diversity in the tree species grown for reforestation across much of the United States (Clark et al. 2023).

Financing fire-adapted NCS remains challenging, as established mechanisms such as carbon markets often struggle to accommodate the risk, uncertainty, and timing of wildfire-driven carbon dynamics. Forest carbon projects face substantial reversal risk from wildfire and forest health disturbances, and recent analyses suggest that existing buffer pools may be insufficient to absorb these risks (Badgley et al. 2022, Anderegg et al. 2025). At the same time, many forest management methodologies emphasize near-term GHG benefits, limiting incentives for practices that may reduce carbon stocks in the short term but enhance long-term stability (Buchholz et al. 2022).

These constraints extend to emerging strategies, including thinning and biochar crediting, which show promise but remain financially uncertain (Elias et al. 2025, Yackulic et al. 2025). Climate-informed reforestation projects similarly face barriers to private investment due to high upfront costs and delayed carbon returns. Together, these structural limitations constrain the scalability of fire-adapted NCS under current market frameworks, underscoring the need for blended financing approaches that combine sustained public investment, market mechanisms, and reforms to voluntary and compliance carbon markets that better account for wildfire risk and delayed carbon benefits.

State policy and planning innovations

Managing wildfire risks, including wildfire emissions, may benefit from policy frameworks that integrate fire-adapted NCS across prevention, preparedness, response, and recovery while coordinating decisions across governance scales (Bacciu et al. 2022, Kirschner et al. 2023, Oliveras Menor et al. 2025). California, Oregon, and Washington are each experiencing increased fire activity that threatens the long-term carbon storage capacity of their forests. As a result, each state has advanced forest resilience goals as a central component of state climate policies. California's Nature-Based Solutions Climate Targets, reinforced through the Wildfire and Forest Resilience Action Plan and large-scale public investment mechanisms, link beneficial fire, forest thinning and biomass utilization, and climate-informed reforestation with statewide climate mitigation objectives (CNRA 2024). Oregon's Natural and Working Lands Strategy similarly positions fire-adapted forests as a component of climate mitigation (INR 2023). Washington's Forest Health and Climate Resilience Act connects fire-adapted NCS

investments with wildfire risk reduction, forest restoration, and post-disturbance recovery (WSL 2021).

Although developed independently, these policies reflect key elements of *integrated fire risk management* (IFRM). IFRM takes a multi-risk approach within the wildfire–watershed nexus by combining objectives, expertise, and approaches from multiple disciplines and sectors to address interactions among fire and other biotic and abiotic threats (Fernandes et al. 2011, Bacciu et al. 2022). It coordinates mitigation, preparedness, response, and recovery across disciplines, sectors, and jurisdictions to manage fire as a recurring, fuel- and climate-driven disturbance while reducing risks to ecosystems and the services they provide, including long-term carbon stability and reliable delivery of clean, high-quality water (USWFMMC 2023). This framing is increasingly important as aridity dries soils and fuels, increasing area burned and high-severity fire, while post-fire flooding and runoff threaten infrastructure and drinking water supplies (Robinne et al. 2021, Parks et al. 2025). IFRM therefore uses a systems-thinking approach that treats landscape resilience, local livelihoods and knowledge, ecological conservation, risk mitigation, and carbon emissions reduction as connected management objectives rather than separate policy domains (Oliveras Menor et al. 2025).

IFRM is especially relevant to fire-adapted NCS because it links fuel–aridity feedbacks, wildfire emissions, and the wildfire–watershed nexus within a single planning framework. In practice, this means aligning beneficial fire, strategic thinning, post-fire recovery, and watershed protection to improve fuel treatment effectiveness, reduce wildfire severity, support natural fire breaks, and minimize post-fire impacts that can be compounded by extreme precipitation events (Robinne et al. 2021, Kalapodis and Sakkas 2025). Recent work emphasizing that the fuel crisis is also a fuel-plus-aridity crisis further suggests that climate-amplified aridity must be considered alongside prescribed fire and fuel reductions when designing strategies to moderate fire behavior (Abatzoglou et al. 2021, Pascolini-Campbell et al. 2025).

Public and political support for fire-adapted forest management cannot be assumed, especially among urban communities that may experience prescribed fire smoke, temporary closures, or concerns about timber harvesting without directly observing the long-term benefits. Support varies by treatment type and is shaped by perceived outcomes, trust in agencies and practitioners, familiarity with fire, and opportunities for meaningful public involvement (Winter et al. 2002, Rasch and McCaffrey 2019, Paveglio and Edgeley 2023). Building broader support will require sustained engagement, clear communication of treatment goals, risks, tradeoffs, and uncertainties, and stronger connections between forest management and benefits that matter to urban communities, including drinking water protection, reduced exposure to severe wildfire smoke, recreational access, and protection of infrastructure. Collaborative planning and trusted local partnerships will be important for turning broad policy goals into durable public and political support (Hamilton et al. 2023).

At the federal level, there are parallel opportunities to integrate IFRM into large-scale planning by aligning wildfire governance with climate mitigation objectives (USFS 2022b). This approach requires commitment to systems thinking and emphasizes coordinated decision-making across agencies and jurisdictions, continuity across pre-fire, active-fire, and post-fire phases, and explicit consideration of risk, tradeoffs, and long-term outcomes rather than event-based response alone. If implemented through this framework, fire-adapted NCS could strengthen national capacity for proactive fire manage-

ment, science integration, and workforce development while preserving regional flexibility. The recent establishment of the US Wildland Fire Service within the DOI represents a step toward consolidating federal wildfire management capacity, creating both risks and opportunities. If the new service remains narrowly focused on suppression, it could marginalize IFRM and undercut opportunities to scale fire-adapted NCS. However, if it helps institutionalize and coordinate an interdisciplinary, multi-risk, life-cycle approach to connected wildfire, water, and climate risks, it could provide a critical pathway for scaling fire-adapted NCS and explicitly incorporating wildfire emissions risk into forest carbon policy.

Conclusion

Fire-adapted NCS offer a pathway for achieving durable climate mitigation in forests where wildfire increasingly shapes long-term carbon outcomes. Fire-prone forests should not be excluded from climate mitigation strategies, but NCS deployed in these systems must be explicitly aligned with regional fire regimes, vegetation, fuels, markets, and changing climate conditions. Beneficial fire, thinning-plus-fire with biomass utilization, and climate-informed reforestation can reduce wildfire emissions, stabilize forest carbon, slow wildfire–climate feedbacks, and strengthen ecosystem and community resilience when implemented in regionally appropriate ways.

Achieving these outcomes will require carbon stewardship rather than short-term biomass maximization, along with integration of fire-adapted NCS within an IFRM framework. Scaling these approaches will require policy and climate finance mechanisms that incentivize and derisk long-term investment while continuing to support NCS in less fire-prone systems. Durable implementation must be built on local partnerships capable of sustaining work over decadal timeframes, rather than relying on short-term, centralized funding cycles. Ultimately, effective wildfire mitigation through fire-adapted NCS will depend on treating forest carbon policy, climate adaptation, and wildfire risk reduction as connected goals, rather than separate management problems.

Data Availability Statement

Please contact the corresponding author about any notes from regional discussions or for the updated fire frequency and high severity data analysis using methods from Salguero et al. (2020).

Acknowledgments

We thank Jeremy Littell, Chad Hoffman, M. Gwyn Myer, Jon Dale, Rachael Foe, Wes Swaffer, Nicholas Biemiller, Leanna Weisberg, Nicholas Wilhoite, Aaron Russell, Michael Battaglia, Cassandra Rivas, and Natasha Stavros for insightful discussions and valuable feedback during manuscript preparation. We also thank the three anonymous reviewers for their help during the review process. There are no conflicts of interest from any coauthors that need to be disclosed for this study.

Author contribution

C.M.T., K.D.R., E.R.P., and B.K. conceptualized and organized the structure of the study; C.M.T., K.D.R., K.J.D., T.R.M., B.K., and C.W.S. wrote the original draft and reviewed it multiple times throughout the pro-

cess; T.R.M. conducted the spatial analysis; L.M., E.R.P., X.J.W., M.C.M., N.T.L., M.S., M.D.H., H.S., K.A.D., N.M., D.J.C., P.H., R.A.G., D.N., M.E.C., S.Z.D., J.S.G., C.M.R., S.W.F., C.T., A.S.C., C.S.S.R., K.L.M., C.P.G., V.M.D., L.B., J.M., C.L., M.D.R., B.E.J., and A.T.H. participated in regional discussions and multiple rounds of edits. C.M.T., K.D.R., B.K., K.J.D., and C.W.S. wrote the [Management and policy implications](#) section.

Supplemental material

Supplemental data are available at [BIOSCI](#) online.

Funding

Without support from the Resources Legacy Fund, this project would not have been possible, and we are deeply grateful for their partnership and support. In addition, M.D.H. acknowledges support from the National Science Foundation under Award No. 2521103.

References cited

- [Abatzoglou JT](#), Battisti DS, Williams AP, Hansen WD, Harvey BJ, Kolden CA. 2021. Projected increases in western US forest fire despite growing fuel constraints. *Communications Earth & Environment* 2: 227.
- [Abatzoglou JT](#), Williams AP. 2016. Impact of anthropogenic climate change on wildfire across western US forests. *Proceedings of the National Academy of Sciences* 113: 11770–11775.
- [Acuna M](#), Sessions J, Zamora R, Boston K, Brown M, Ghaffariyan MR. 2019. Methods to manage and optimize forest biomass supply chains: A review. *Current Forestry Reports* 5: 124–141.
- [Agee JK](#). 1993. *Fire Ecology of Pacific Northwest Forests*. Island Press.
- [Agee JK](#), Skinner CN. 2005. Basic principles of forest fuel reduction treatments. *Forest Ecology and Management* 211: 83–96.
- [Allan RP](#), Arias PA, Berger S, Canadell JG, Cassou C, Chen D, Cherchi A, Connors SL, Coppola E, Cruz FA. 2023. Intergovernmental panel on climate change (IPCC). Summary for policymakers. Pages 3–32 in. Climate change 2021: The physical science basis. Contribution of working group I to the sixth assessment report of the intergovernmental panel on climate change. *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press.
- [\[AF\] American Forests](#). 2025. Effects of forest management and wood utilization on carbon sequestration and storage in California. Report to California Department of Forestry and Fire Protection.
- [Ammond SA](#), Litton CM, Ellsworth LM, Leary JK. 2013. Restoration of native plant communities in a Hawaiian dry lowland ecosystem dominated by the invasive grass *Megathyrsus maximus*. *Applied Vegetation Science* 16: 29–39.
- [Anderegg WRL](#), et al. 2020. Climate-driven risks to the climate mitigation potential of forests. *Science* 368: eaaz7005.
- [Anderegg WRL](#), Trugman AT, Vargas GG, Wu C, Yang L. 2025. Current forest carbon offset buffer pool contributions do not adequately insure against disturbance-driven carbon losses. *Global Change Biology* 31: e70251.
- [Anderson MK](#). 2006. The use of fire by Native Americans in California. *Fire in California's Ecosystems*. Pages 417–430 in Sugihara NG, ed. Berkeley (CA): University of California Press.
- [Arthur MA](#), Alexander HD, Dey DC, Schweitzer CJ, Loftis DL. 2012. Refining the oak-fire hypothesis for management of oak-dominated forests of the eastern United States. *Journal of Forestry* 110: 257–266.
- [Bacciu V](#), Sirca C, Spano D. 2022. Towards a systemic approach to fire risk management. *Environmental Science & Policy* 129: 37–44.
- [Badgley G](#), Chay F, Chegwiddden OS, Hamman JJ, Freeman J, Culenward D. 2022. California's forest carbon offsets buffer pool is severely undercapitalized. *Frontiers in Forests and Global Change* 5: 930426.
- [Balch JK](#), Bradley BA, Abatzoglou JT, Nagy RC, Fusco EJ, Mahood AL. 2017. Human-started wildfires expand the fire niche across the United States. *Proceedings of the National Academy of Sciences* 114: 2946–2951.
- [Balch JK](#), Bradley BA, D'Antonio CM, Gómez-Dans J. 2013. Introduced annual grass increases regional fire activity across the arid western USA (1980–2009). *Global Change Biology* 19: 173–183.
- [Barker J](#), Voorhis J, Crotty SM. 2025. Assessing costs and constraints of forest residue disposal by pile burning. *Frontiers in Forests and Global Change* 7: 1496190.
- [Bastin J-F](#), Finegold Y, Garcia C, Mollicone D, Rezende M, Routh D, Zohner CM, Crowther TW. 2019. The global tree restoration potential. *Science* 365: 76–79.
- [Birdsey R](#), Castanho A, Houghton R, Savage K. 2023. Middle-aged forests in the eastern U.S. have significant climate mitigation potential. *Forest Ecology and Management* 548: 121373.
- [Black B](#), Walker XJ, Berner LT, Dean J, Goetz SJ, Hansen WD, Potter S, Rogers BM, Talucci AC, Mack MC. 2026. Increased deciduous tree dominance reduces wildfire carbon losses in boreal forests. *Nature Climate Change* 16: 187–192.
- [Bobo JG](#), Jackson BE. 2024. North American and European conifer species evaluated for use as wood components in growing media: A mini review. *Acta Horticulturae* 131–138.
- [Boisramé G](#), Thompson S, Collins B, Stephens S. 2017. Managed wildfire effects on forest resilience and water in the Sierra Nevada. *Ecosystems* 20: 717–732.
- [Bousfield CG](#), Morton O, Lindenmayer DB, Pellegrini AF, Hethcoat MG, Edwards DP. 2025. Global risk of wildfire across timber production systems. *Nature Communications* 16: 4204.
- [Bower AD](#), Frerker KL, Pike CC, Labonte NR, Palik BJ, Royo AA, Anderson SM, Ferreira AR, Brandt LA. 2024. A practical framework for applied forestry assisted migration. *Frontiers in Forests and Global Change* 7: 1454329.
- [Bradley BA](#), Curtis CA, Fusco EJ, Abatzoglou JT, Balch JK, Dadashi S, Tuanmu M-N. 2018. Cheatgrass (*Bromus tectorum*) distribution in the intermountain western United States and its relationship to fire frequency, seasonality, and ignitions. *Biological Invasions* 20: 1493–1506.
- [Bremer LL](#), McGuire G, Hastings Silao Z, Kurashima N, Ticktin T, Crow SE, Giardina CP, Winter KB, DeMaagd N, Trauernicht C. 2025. Carbon benefits through agroforestry transitions on unmanaged fallow agricultural land in Hawai'i. *Scientific Reports* 15: 5097.
- [Bremer LL](#), Nathan N, Trauernicht C, Pascua P, Krueger N, Jokiel J, Barton J, Daily GC. 2021. Maintaining the many societal benefits of rangelands: The case of Hawai'i. *Land* 10: 764.
- [Bremer LL](#), Wada CA, Medoff S, Page J, Falinski K, Burnett KM. 2019. Contributions of native forest protection to local water supplies in East Maui. *Science of the Total Environment* 688: 1422–1432.
- [Brockway DG](#), Outcalt KW, Estes BL, Rummer RB. 2009. Vegetation response to midstorey mulching and prescribed burning for wildfire hazard reduction and longleaf pine (*Pinus palustris* Mill.) ecosystem restoration. *Forestry* 82: 299–314.
- [Brodie EG](#), Knapp EE, Brooks WR, Drury SA, Ritchie MW. 2024. Forest thinning and prescribed burning treatments reduce wildfire severity and buffer the impacts of severe fire weather. *Fire Ecology* 20: 17.

- Brooks ML, D'antonio CM, Richardson DM, Grace JB, Keeley JE, DiTomaso JM, Hobbs RJ, Pellant M, Pyke D. 2004. Effects of invasive alien plants on fire regimes. *BioScience* 54: 677–688.
- Broxton PD, Harpold AA, Biederman JA, Troch PA, Molotch NP, Brooks PD. 2015. Quantifying the effects of vegetation structure on snow accumulation and ablation in mixed-conifer forests. *Ecology* 8: 1073–1094.
- Buchholz T, Gunn J, Springsteen B, Marland G, Moritz M, Saah D. 2022. Probability-based accounting for carbon in forests to consider wild-fire and other stochastic events: Synchronizing science, policy, and carbon offsets. *Mitigation and Adaptation Strategies for Global Change* 27: 4.
- Buma B, Gordon DR, Kleisner KM, Bartuska A, Bidlack A, DeFries R, Ellis P, Friedlingstein P, Metzger S, Morgan G. 2024. Expert review of the science underlying nature-based climate solutions. *Nature Climate Change* 14: 402–406.
- Buonanduci MS, Donato DC, Halofsky JS, Kennedy MC, Harvey BJ. 2024. Few large or many small fires: Using spatial scaling of severe fire to quantify effects of fire-size distribution shifts. *Ecosphere* 15: e4875.
- Cabiyo B, Fried JS, Collins BM, Stewart W, Wong J, Sanchez DL. 2021. Innovative wood use can enable carbon-beneficial forest management in California. *Proceedings of the National Academy of Sciences* 118: e2019073118.
- [CNRA] California Natural Resources Agency. 2024. *California's Nature-Based Solutions Climate Targets*. California Natural Resources Agency.
- Campo J, Cammeraat EL, Gimeno-García E, Andreu V. 2022. Soil and organic carbon redistribution in a recently burned Mediterranean hill-slope affected by water erosion processes. *Geoderma* 406: 115539.
- Case MJ, Johnson BG, Bartowitz KJ, Hudiburg TW. 2021. Forests of the future: Climate change impacts and implications for carbon storage in the Pacific Northwest, USA. *Forest Ecology and Management* 482: 118886.
- Clark SA, Archer JN, Stephens SL, Collins BM, Hankins DL. 2024. Realignment of federal environmental policies to recognize fire's role. *Fire Ecology* 20: 74. s42408-024-00301-y.
- Clark PW, D'amato AW, Palik BJ, Woodall CW, Dubuque PA, Edge GJ, Hartman JP, Fitts LA, Janowiak MK, Harris LB. 2023. A lack of ecological diversity in forest nurseries limits the achievement of tree-planting objectives in response to global change. *BioScience* 73: 575–586.
- Clark-Wolf K, Higuera PE, Shuman BN, McLauchlan KK. 2023. Wildfire activity in northern Rocky Mountain subalpine forests still within millennial-scale range of variability. *Environmental Research Letters* 18: 094029.
- Covington WW, Moore MM. 1994. Southwestern ponderosa forest structure: Changes since Euro-American settlement. *Journal of Forestry* 92: 39–47.
- Crimmins AR, Avery CW, Easterling DR, Kunkel KE, Stewart BC, Maycock TK. 2023. *Fifth National Climate Assessment*. (18 March 2026; <https://repository.library.noaa.gov>).
- Crockett JL, Hurteau MD. 2024. Climate limits vegetation green-up more than slope, soil erodibility, and immediate precipitation following high-severity wildfire. *Fire Ecology* 20: 41.
- Cummins K, Noble J, Varner JM, Robertson KM, Hiers JK, Nowell HK, Simonson E. 2023. The Southeastern U.S. prescribed fire. *Permit Database: Hot Spots and Hot Moments in Prescribed Fire across the Southeastern USA* 6: 372.
- D'Amato AW, Bradford JB, Fraver S, Palik BJ. 2013. Effects of thinning on drought vulnerability and climate response in north temperate forest ecosystems. *Ecological Applications* 23: 1735–1742.
- Davis KT, et al. 2023. Reduced fire severity offers near-term buffer to climate-driven declines in conifer resilience across the western United States. *Proceedings of the National Academy of Sciences* 120: e2208120120.
- Davis KT, Dobrowski SZ, Higuera PE, Holden ZA, Veblen TT, Rother MT, Parks SA, Sala A, Maneta MP. 2019. Wildfires and climate change push low-elevation forests across a critical climate threshold for tree regeneration. *Proceedings of the National Academy of Sciences* 116: 6193–6198.
- Davis EJ, Huber-Stearns H, Caggiano M, McAvoy D, Cheng AS, Deak A, Evans A. 2022. Managed wildfire: A strategy facilitated by civil society partnerships and interagency cooperation. *Society & Natural Resources* 35: 914–932.
- Davis KT, Peeler J, Fargione J, Haugo RD, Metlen KL, Robles MD, Woolley T. 2024. Tamm review: A meta-analysis of thinning, prescribed fire, and wildfire effects on subsequent wildfire severity in conifer dominated forests of the western US. *Forest Ecology and Management* 561: 121885.
- Deak A, Fawcett JE, Quinn-Davidson L, Adam C, Weir JR, Stackhouse J. 2025. Burning from the ground up: The structure and impact of Prescribed Burn Associations in the United States. *International Journal of Wildland Fire* 34: WF24178.
- Diamond DD. 1998. *An Old-Growth Definition for Southwestern Subtropical Upland Forests*. U.S. Department of Agriculture, Forest Service, Southern Research Station.
- Dixit A, Burney O. 2024. Nursery cultural practices influence morphological and physiological aspen seedling traits: Implications for post-fire restoration. *Canadian Journal of Forest Research* 54: 1076–1084.
- Dobrowski SZ, et al. 2024. “Mind the Gap”—Reforestation needs vs. reforestation capacity in the western United States. *Frontiers in Forests and Global Change* 7: 1402124.
- Eisenberg C, Prichard S, Nelson MP, Hessburg P. 2024. *Braiding Indigenous and Western Knowledge for Climate-Adapted Forests: An Ecocultural State of Science Report*. Wise Path Forward.
- Elias M, Yackulic E, Duffy K, Saksa P, Sanchez DL, Pevzner N, Plumb S, Dyszynski J, Bracer C. 2025. Carbon finance for forest resilience in California. *Frontiers in Forests and Global Change* 7: 1507554.
- Ellis PW, et al. 2024. The principles of natural climate solutions. *Nature Communications* 15: 547.
- Falk DA, van Mantgem PJ, Keeley JE, Gregg RM, Guiterman CH, Tepley AJ, Young DJ, Marshall LA. 2022. Mechanisms of forest resilience. *Forest Ecology and Management* 512: 120129.
- Fargione JE, et al. 2018. Natural climate solutions for the United States. *Science Advances* 4: eaat1869.
- Fernandes PM, Rego FC, Rigolot E. 2011. The FIRE PARADOX project: Towards science-based fire management in Europe. *Forest Ecology and Management* 261: 2177–2178.
- Foster G, Rahmstorf S. 2026. Global warming has accelerated significantly. *Geophysical Research Letters* 53: e2025GL118804.
- Fulé PZ, Crouse JE, Roccaforte JP, Kalies EL. 2012. Do thinning and/or burning treatments in western USA ponderosa or Jeffrey pine-dominated forests help restore natural fire behavior? *Forest Ecology and Management* 269: 68–81.
- Griscom BW, et al. 2017. Natural climate solutions. *Proceedings of the National Academy of Sciences* 114: 11645–11650.
- Hamilton M, Nielsen-Pincus M, Evers CR. 2023. Wildfire risk governance from the bottom up: Linking local planning processes in fragmented landscapes. *Ecology & Society*, 28.
- Hanson PJ, et al. 2020. Rapid net carbon loss from a whole-ecosystem warmed peatland. *AGU Advances* 1: e2020AV000163.

- Hessburg PF, et al. 2025. The western North American forestland carbon sink: Will our climate commitments go up in smoke? *Frontiers in Ecology and the Environment* 23: e2869.
- Hiers JK, et al. 2020. Prescribed fire science: The case for a refined research agenda. *Fire Ecology* 16: 11.
- Higuera PE, Cook MC, Balch JK, Stavros EN, Mahood AL, St. Denis LA. 2023. Shifting social-ecological fire regimes explain increasing structure loss from western wildfires. *PNAS Nexus* 2: pgad005.
- Hoecker TJ, Parks SA, Krosby M, Dobrowski SZ. 2023. Widespread exposure to altered fire regimes under 2°C warming is projected to transform conifer forests of the western United States. *Communications Earth & Environment* 4: 295.
- Holden ZA, Swanson AK, Sadegh M, Luce CH, Noonan-Wright E, Parsons RA. 2025. Soil moisture is a stronger predictor of forest fire spread potential than weather in the U.S. Northern Rocky Mountains. *Geophysical Research Letters* 52: e2025GL116248.
- Hurteau MD, Goodwin MJ, Marsh C, Zald HS, Collins B, Meyer M, North MP. 2024. Managing fire-prone forests in a time of decreasing carbon carrying capacity. *Frontiers in Ecology and the Environment* 22: e2801.
- Hurteau MD, Jung CG, Francis EJ, Dobrowski SZ, Littlefield CE, Parks SA. 2025. Decreasing landscape carbon storage in western US forests with 2°C of warming. *Environmental Research: Ecology* 4: 041001.
- Hurteau M, North M. 2009. Fuel treatment effects on tree-based forest carbon storage and emissions under modeled wildfire scenarios. *Frontiers in Ecology and the Environment* 7: 409–414.
- [ISE] Institute for a Sustainable Environment. 2016. *Local Capacity for Integrated Forest and Wildfire Management*. University of Oregon.
- [INR] Institute for Natural Resources. 2023. *Natural and Working Lands Report*. Oregon State University.
- Jaffe DA, O'Neill SM, Larkin NK, Holder AL, Peterson DL, Halofsky JE, Rappold AG. 2020. Wildfire and prescribed burning impacts on air quality in the United States. *Journal of the Air & Waste Management Association* 70: 583–615.
- Jahrsdoerfer SE, Leslie DM. 1988. *Tamaulipan Brushland of the Lower Rio Grande Valley of South Texas: Description, Human Impacts, and Management Options*. U.S. Department of the Interior, Fish and Wildlife Service.
- Janowiak MK, Iverson LR, Fosgett J, Handler SD, Dallman M, Thomasma S, Hutnik B, Swanston CW. 2017. Assessing stand-level climate change risk using forest inventory data and species distribution models. *Journal of Forestry* 115: 222–229.
- Jerrett M, Jina AS, Marlier ME. 2022. Up in smoke: California's greenhouse gas reductions could be wiped out by 2020 wildfires. *Environmental Pollution* 310: 119888.
- Johnstone JF, Hollingsworth TN, Chapin FS, Mack MC. 2010. Changes in fire regime break the legacy lock on successional trajectories in Alaskan boreal forest. *Global Change Biology* 16: 1281–1295.
- Jolly WM, Cochrane MA, Freeborn PH, Holden ZA, Brown TJ, Williamson GJ, Bowman DMJS. 2015. Climate-induced variations in global wildfire danger from 1979 to 2013. *Nature Communications* 6: 7537.
- Jones MW, et al. 2024. Global rise in forest fire emissions linked to climate change in the extratropics. *Science* 386: eadl5889.
- Kalapodis N, Sakkas G. 2025. Integrated fire management and closer to nature forest management at the landscape scale as a holistic approach to foster forest resilience to wildfires. *Open Research Europe* 4: 131.
- Keeley JE. 2006. Fire management impacts on invasive plants in the western United States. *Conservation Biology* 20: 375–384.
- Kelp M, Burke M, Qiu M, Higuera-Mendieta I, Liu T, Diffenbaugh NS. 2025. Effect of recent prescribed burning and land management on wildfire burn severity and smoke emissions in the western United States. *AGU Advances* 6: e2025AV001682.
- Kilgore BM. 1973. The ecological role of fire in Sierran conifer forests: Its application to national park management. *Quaternary Research* 3: 496–513.
- Kimmerer R. 2011. Restoration and reciprocity: The contributions of traditional ecological knowledge. Pages 257–276 in Egan D, Hjerpe EE, Abrams J, eds. *Human Dimensions of Ecological Restoration*. Island Press/Center for Resource Economics.
- Kirschner JA, Clark J, Boustras G. 2023. Governing wildfires: Toward a systematic analytical framework. *Ecology & Society Ecology and Society* 28: Article 6.
- Kolden CA, Henson C. 2019. A socio-ecological approach to mitigating wildfire vulnerability in the wildland urban interface: A case study from the 2017 Thomas Fire. *Fire* 2: 9.
- Lake FK, Wright V, Morgan P, McFadden M, McWethy D, Stevens-Rumann C. 2017. Returning fire to the land: Celebrating traditional knowledge and fire. *Journal of Forestry* 115: 343–353.
- Larson AJ, Churchill D. 2012. Tree spatial patterns in fire-frequent forests of western North America, including mechanisms of pattern formation and implications for designing fuel reduction and restoration treatments. *Forest Ecology and Management* 267: 74–92.
- Larson AJ, Jeronimo SMA, Hessburg PF, Lutz JA, Povak NA, Cansler CA, Kane VR, Churchill DJ. 2022. Tamm review: Ecological principles to guide post-fire forest landscape management in the Inland Pacific and Northern Rocky Mountain regions. *Forest Ecology and Management* 504: 119680.
- Laughlin MM, Rangel-Parra LK, Morris JE, Donato DC, Halofsky JS, Harvey BJ. 2023. Patterns and drivers of early conifer regeneration following stand-replacing wildfire in Pacific Northwest (USA) temperate maritime forests. *Forest Ecology and Management* 549: 121491.
- Liang S, Hurteau MD, Westerling AL. 2018. Large-scale restoration increases carbon stability under projected climate and wildfire regimes. *Frontiers in Ecology and the Environment* 16: 207–212.
- Link NT, Johnstone JF, Walker XJ, Amundsen F, Berrios HK, Bibeau L, Cooley D, Erickson AC, Johnston C, Little JM. 2026. Mitigating increasing wildfire risk through fuel break innovations. *iScience* 29: 114391.
- Long JW, Lake FK, Goode RW, Burnette BM. 2020. How traditional tribal perspectives influence ecosystem restoration. *Ecopsychology* 12: 71–82.
- McDowell NG, et al. 2020. Pervasive shifts in forest dynamics in a changing world. *Science* 368: eaaz9463.
- McFarland JR, Coop JD, Balik JA, Rodman KC, Parks SA, Stevens-Rumann CS. 2025. Extreme fire spread events burn more severely and homogenize postfire landscapes in the Southwestern United States. *Global Change Biology* 31: e70106.
- Magerl A, Gingrich S, Matej S, Cunfer G, Forrest M, Lauk C, Schlaffer S, Weidinger F, Yuskiv C, Erb K. 2023. The role of wildfires in the interplay of forest carbon stocks and wood harvest in the contiguous United States during the 20th century. *Global Biogeochemical Cycles* 37: e2023GB007813.
- Marsh C, Crockett JL, Krofcheck D, Keyser A, Allen CD, Litvak M, Hurteau MD. 2022. Planted seedling survival in a post-wildfire landscape: From experimental planting to predictive probabilistic surfaces. *Forest Ecology and Management* 525: 120524.
- Marshall LAE, Fornwalt PJ, Stevens-Rumann CS, Rodman KC, Chapman TB, Schloegel CA, Stevens JT. 2024. What influences planted tree seedling survival in burned Colorado montane forests? *Forest Ecology and Management* 572: 122321.
- Marshall LAE, Fornwalt PJ, Stevens-Rumann CS, Rodman KC, Rhoades CC, Zimlinghaus K, Chapman TB, Schloegel CA. 2023. North-facing

- aspects, shade objects, and microtopographic depressions promote the survival and growth of tree seedlings planted after wildfire. *Fire Ecology* 19: 26.
- North MP, Stephens SL, Collins BM, Agee JK, Aplet G, Franklin JF, Fulé PZ. 2015. Reform forest fire management. *Science* 349: 1280–1281.
- North MP, Tompkins RE, Bernal AA, Collins BM, Stephens SL, York RA. 2022. Operational resilience in western US frequent-fire forests. *Forest Ecology and Management* 507: 120004.
- Oliveras Menor I, et al. 2025. Integrated fire management as an adaptation and mitigation strategy to altered fire regimes. *Communications Earth & Environment* 6: 202.
- Ott JE, Kilkenny FF, Jain TB. 2023. Fuel treatment effectiveness at the landscape scale: A systematic review of simulation studies comparing treatment scenarios in North America. *Fire Ecology* 19: 10.
- Palik BJ, Clark PW, D'Amato AW, Swanston C, Nagel L. 2022. Operationalizing forest-assisted migration in the context of climate change adaptation: Examples from the eastern USA. *Ecosphere* 13: e4260.
- Papa CC, DeLyser K, Clay K, Gadoth-Goodman D, Cooper L, Kurz WA, Magnan M, Ontl T. 2023. Modeling climate-smart forest management and wood use for climate mitigation potential in Maryland and Pennsylvania. *Frontiers in Forests and Global Change* 6: 1259010.
- Parks SA, Coop JD, Davis KT. 2025. Intensifying fire season aridity portends ongoing expansion of severe wildfire in Western US Forests. *Global Change Biology* 31: e70429.
- Parks SA, Miller C, Nelson CR, Holden ZA. 2014. Previous fires moderate burn severity of subsequent wildland fires in two large western US wilderness areas. *Ecosystems* 17: 29–42.
- Pascolini-Campbell M, Fisher JB, Cawse-Nicholson K, Lee CM, Stavros N. 2025. Assessment of spatial autocorrelation and scalability in fine-scale wildfire random forest prediction models. *Scientific Reports* 15: 21504.
- Paveglio TB, Edgeley CM. 2023. Variable support and opposition to fuels treatments for wildfire risk reduction: Melding frameworks for local context and collaborative potential. *Journal of Forestry* 121: 354–373.
- Pollet J, Omi PN. 2002. Effect of thinning and prescribed burning on crown fire severity in ponderosa pine forests. *International Journal of Wildland Fire* 11: 1–10.
- Prichard SJ, et al. 2021. Adapting western North American forests to climate change and wildfires: 10 common questions. *Ecological Applications* 31: e02433.
- Prichard SJ, O'Neill SM, Eagle P, Andreu AG, Drye B, Dubowy J, Urbanski S, Strand TM. 2020a. Wildland fire emission factors in North America: Synthesis of existing data, measurement needs and management applications. *International Journal of Wildland Fire* 29: 132–147.
- Prichard SJ, Povak NA, Kennedy MC, Peterson DW. 2020b. Fuel treatment effectiveness in the context of landform, vegetation, and large, wind-driven wildfires. *Ecological Applications* 30: e02104.
- Pyne SJ. 1981. Fire policy and fire research in the U.S. forest service. *Journal of Forest History* 25: 64–77.
- Radeloff VC, Mockrin MH, Helmers D, Carlson A, Hawbaker TJ, Martinuzzi S, Schug F, Alexandre PM, Kramer HA, Pidgeon AM. 2023. Rising wildfire risk to houses in the United States, especially in grasslands and shrublands. *Science* 382: 702–707.
- Rasch R, McCaffrey S. 2019. Exploring wildfire-prone community trust in wildfire management agencies. *Forest Science* 65: 652–663.
- Raviv M, Lieth JH, Bar-Tal A. 2019. *Soilless Culture: Theory and Practice: Theory and Practice*. Elsevier.
- Reid CE, Brauer M, Johnston FH, Jerrett M, Balmes JR, Elliott CT. 2016. Critical review of health impacts of wildfire smoke exposure. *Environmental Health Perspectives* 124: 1334.
- Reilly MJ, et al. 2022. Cascadia burning: The historic, but not historically unprecedented, 2020 wildfires in the Pacific Northwest, USA. *Ecosphere* 13: e4070.
- Robinne F, et al. 2021. Scientists' warning on extreme wildfire risks to water supply. *Hydrological Processes* 35: e14086.
- Salguero J, Li J, Farahmand A, Reager JT. 2020. Wildfire trend analysis over the contiguous United States using remote sensing observations. *Remote Sensing* 12: 2565.
- Sample M, et al. 2022. Adaptation strategies and approaches for managing fire in a changing climate. *Climate* 10: 58.
- Sanna A, Chamberlain C, Prichard SJ, Cansler CA, Hudak AT, Bienz C, Moskal LM, Kane VR. 2025. Assessing fuel treatments and burn severity using global and local analyses. *Fire Ecology* 21: 44.
- Schultz CA, McCaffrey SM, Huber-Stearns HR. 2019. Policy barriers and opportunities for prescribed fire application in the western United States. *International Journal of Wildland Fire* 28: 874–884.
- Shanley CS, Graves RA, Drever CR, Schindel M, Robertson JC, Case MJ, Biswas T. 2024. Mapping forest-based natural climate solutions. *Communications Earth & Environment* 5: 502.
- Shive KL, Coppoletta M, Wayman RB, Paulson AK, Wilson KN, Abatzoglou JT, Saberi SJ, Estes B, Safford HD. 2024. Thinning with follow-up burning treatments have increased effectiveness at reducing severity in California's largest wildfire. *Forest Ecology and Management* 572: 122171.
- Smith JE, Billmire M, French NHF, Domke GM. 2024. Application of the wildland fire emissions inventory system to estimate fire emissions on forest lands of the United States. *Carbon Balance and Management* 19: 26.
- Smithwick EAH, et al. 2024. Barriers and opportunities for implementing prescribed fire: Lessons from managers in the mid-Atlantic region. *United States Fire Ecology* 20: 77.
- Snieszko RA, Johnson JS, Kegley A, Danchok R. 2024. Disease resistance in whitebark pine and potential for restoration of a threatened species. *Plants, People, Planet* 6: 341–361.
- Stephens SL, et al. 2009. Fire treatment effects on vegetation structure, fuels, and potential fire severity in western U.S. forests. *Ecological Applications* 19: 305–320.
- Stephens SL, et al. 2012. Fuel treatment impacts on estimated wildfire carbon loss from forests in Montana, Oregon, California, and Arizona. *Ecosphere* 3: 1–17.
- Stephens SL, et al. 2014. Temperate and boreal forest mega-fires: Characteristics and challenges. *Frontiers in Ecology and the Environment* 12: 115–122.
- Stephens SL, Collins BM, Fettig CJ, Finney MA, Hoffman CM, Knapp EE, North MP, Safford H, Wayman RB. 2018. Drought, tree mortality, and wildfire in forests adapted to frequent fire. *BioScience* 68: 77–88.
- Stephens SL, Moghaddas JJ. 2005. Experimental fuel treatment impacts on forest structure, potential fire behavior, and predicted tree mortality in a California mixed conifer forest. *Forest Ecology and Management* 215: 21–36.
- Stephens SL, Thompson S, Boisramé G, Collins BM, Ponisio LC, Rakhmatulina E, Steel ZL, Stevens JT, van Wagendonk JW, Wilkin K. 2021. Fire, water, and biodiversity in the Sierra Nevada: A possible triple win. *Environmental Research Communications* 3: 081004.
- Stephens SL, Westerling AL, Hurteau MD, Peery MZ, Schultz CA, Thompson S. 2020. Fire and climate change: Conserving seasonally dry forests is still possible. *Frontiers in Ecology and the Environment* 18: 354–360.
- Stevens-Rumann CS, Morgan P. 2019. Tree regeneration following wildfires in the western US: A review. *Fire Ecology* 15: 15.

- Stevens-Rumann CS, Mueller SE, Newton K, Van Dusen HM. 2025. Extreme Colorado 2020 fires: Remotely sensed burn severity influenced by treatments, forest types, and days of burning. *Canadian Journal of Forest Research* 55: 1–22.
- Swain DL, Abatzoglou JT, Kolden C, Shive K, Kalashnikov DA, Singh D, Smith E. 2023. Climate change is narrowing and shifting prescribed fire windows in western United States. *Communications Earth & Environment* 4: 340.
- Trauernicht C, Brook BW, Murphy BP, Williamson GJ, Bowman DMJS. 2015. Local and global pyrogeographic evidence that indigenous fire management creates pyrodiversity. *Ecology and Evolution* 5: 1908–1918.
- Truettner CM, Poulson SR, Ziaco E, Csank AZ. 2025. Intraspecific dominance determines subseasonal *Pinus ponderosa* growth response to warm-season precipitation amid drought in Southern Nevada, USA. *Ecohydrology* 18: e70105.
- Turner MG, Romme WH, Tinker DB. 2003. Surprises and lessons from the 1988 Yellowstone fires. *Frontiers in Ecology and the Environment* 1: 351–358.
- Tyukavina A, Potapov P, Hansen MC, Pickens AH, Stehman SV, Turubanova S, Parker D, Zalles V, Lima A, Kommareddy I. 2022. Global trends of forest loss due to fire from 2001 to 2019. *Frontiers in Remote Sensing* 3: 825190.
- [USFS] USDA Forest Service. 2022a. *Confronting the Wildfire Crisis: A Strategy for Protecting Communities and Improving Resilience in America's Forests*. US Department of Agriculture.
- [USFS] U.S. Department of Agriculture Forest Service. 2022b. *Toward a National Wildfire Workforce: Opportunities for Improved Wildfire Response and Resilience*. US Department of Agriculture.
- [USFS] U.S. Department of Agriculture, Forest Service. 2024. *Carbon Stewardship on the National Forest System: Summary Analysis*. US Department of Agriculture.
- van Mantgem PJ, Stephenson NL, Knapp E, Battles J, Keeley JE. 2011. Long-term effects of prescribed fire on mixed conifer forest structure in the Sierra Nevada. *California Forest Ecology and Management* 261: 989–994.
- Van Wagtenonk JW. 2007. The history and evolution of wildland fire use. *Fire Ecology* 3: 3–17.
- Vorster AG, et al. 2021. Metrics and considerations for evaluating how forest treatments alter wildfire behavior and effects. *Journal of Forestry* 122: 13–30.
- Vose JM, Elliott K. 2016. Oak, fire, and global change in the eastern USA: What might the future hold? *Fire Ecology* 12: 160–179.
- Waldrop TA, Goodrick SL. 2012. *Introduction to Prescribed Fires in Southern Ecosystems*. Science Update SRS-054.
- Walker XJ, Mack MC, Black B, Dean J, Kemper LF, Potter S, Rogers BM, Truettner CM. 2025. Increasing wildfire frequency decreases carbon storage and leads to regeneration failure in Alaskan boreal forests. *Fire Ecology* 21: 57.
- Walker XJ, Okano K, Berner LT, Massey R, Goetz SJ, Johnstone JF, Mack MC. 2023. Shifts in ecological legacies support hysteresis of stand type conversions in boreal forests. *Ecosystems* 26: 1796–1805.
- [WSL] Washington State Legislature. 2021. *Revised Code of Washington § 70A.65.270: Natural Climate Solutions Account*.
- Westerling AL, Hidalgo HG, Cayan DR, Swetnam TW. 2006. Warming and earlier spring increase western U.S. forest wildfire activity. *Science* 313: 940–943.
- [USWFMMC] Wildland Fire Mitigation and Management Commission. 2023. *On Fire: The report of the Wildland Fire Mitigation and Management Commission*. US Department of Agriculture.
- Winter GJ, Vogt C, Fried JS. 2002. Fuel treatments at the wildland-urban interface: common concerns in diverse regions. *Journal of Forestry* 100: 15–21.
- Yackulic E, Elias M, Shannon J, Gilbert S, Koontz M, Plumb S, Sloggy M, Duffy K. 2025. Rising from the ashes: Treatments stabilize carbon storage in California's frequent-fire forests. *Frontiers in Forests and Global Change* 8: 1498430.
- Yurkonis KA, Dillon J, McGranahan DA, Toledo D, Goodwin BJ. 2019. Seasonality of prescribed fire weather windows and predicted fire behavior in the northern Great Plains, USA. *Fire Ecology* 15: 7.