Horizon Scan on Post-Wildfire Forest Restoration and Recovery in the Western US

Summary of 21 Final Topics

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INTERMOUNTAIN WEST TRANSFORMATION NETWORK

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PURPOSE

This document summarizes 21 topics identified through a **horizon scan** based around the following question: *What are the most important research topics that, if addressed, would help guide practice and policy in support of post-wildfire forest restoration and recovery in the western US?.* This document is meant to serve as a resource for practitioners and researchers who want to learn about the full set of 21 topics considered critical to advancing knowledge on post-wildfire forest restoration and recovery in the western US. A peer-reviewed article about these research priorities is currently under review.

Twenty-eight experts from researcher and practitioner organizations with expertise in forest ecology and management, hydrology, and the social sciences, participated in the horizon scan. Over the course of one year, these experts identified potential topics related to the question above, discussed the topics, and ranked the topics on two criteria:

1. **Potential for Significant Impact**: How addressing the topic could substantially contribute to improving post-fire forest restoration and recovery.
2. **Time-Sensitivity**: Why immediate attention to the topic is essential for guiding post-fire forest restoration and recovery.

The horizon-scanning approach identified a short list of 21 topics as the critical research priorities for addressing gaps in knowledge about post-wildfire forest restoration and recovery. These 21 topics are summarized in this document, grouped into three thematic areas:

- **Forest Ecology and Management**: Covering strategies for seed and seedlings, outplanting strategies, predictive models for reforestation, reburn, post-fire forest trajectories, assisted species migration, and climate-informed reforestation.
- **Hydrology**: Focusing on soil erosion mitigation, flood and debris flow mitigation, stream corridor restoration, post-fire water quantity and quality trajectory, and predictive models for watershed response.
- **Social Sciences**: Addressing community resilience and recovery, community engagement and equity, public support, traditional knowledge, economic valuation and pluriversal economies, institutional coordination, collaborative governance, pre-fire planning, and workforce development.

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As part of the horizon-scanning process, this short list of 21 topics was scored to prioritize the ones considered as having the most potential impact, and the most time-sensitive to address, for post-wildfire forest restoration and recovery. This final scoring led to 12 topics being identified under the three thematic areas:

- **Forest Ecology and Management**: seed and seedlings, outplanting strategies, post-fire forest trajectories, and climate-informed reforestation.
- **Hydrology**: soil erosion mitigation, flood and debris flow mitigation, and post-fire water quantity and quality trajectory.
- **Social Sciences**: institutional coordination, collaborative governance, pre-fire planning, community engagement and equity, and workforce development.

All 21 topics, and in particular the 12 topics identified as most critical, would help improve the equity, effectiveness, and efficiency of post-wildfire forest management and response. Most research topics will require interdisciplinary and convergent approaches to fully account for the diverse societal perspectives and the potential impacts on social and ecological outcomes.

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FORESTRY

Seed and seedlings – Components of the reforestation pipeline: What strategies can be applied that lead to greater seedling survival, establishment, and growth in the field?

There are many unknowns and challenges to post-wildfire reforestation at every stage of the reforestation process (Fargione et al., 2021). The elements of the *reforestation pipeline* (i.e., seed selection, nursery growth, outplanting, post-planting evaluation) are interconnected; a failure in any part of an individual element will result in a failure in the entire pipeline. Hotter and drier conditions are significant contributors to reforestation failures resulting in immediate impacts on reforestation efforts, by modifying planting environments to conditions that are inhospitable for seedling survival shortly after planting (Xu et al., 2019; Hammond et al., 2022). Seedling survival rates vary significantly due to genetics, seedling quality and traits, handling and planting methods, temporal and environmental conditions of the planting site, post-planting measurement techniques, and numerous other factors (Ouzts et al., 2015; Fargione et al., 2021; Marshall et al., 2024; Rodman et al., 2024). Therefore, it is critical to invest in research across the entire reforestation pipeline to improve seedling survival post-wildfire.

Seed source selection, which emphasizes a range of genetic sources for traits that increase the potential for genetic diversity and adaptability (Rehfeldt et al., 2014), is a critical research need relating to the reforestation pipeline. The climate is changing faster than trees can migrate and/or adapt through both natural regeneration and conventional tree planting practices (Williams and Dumroese, 2013). Consequently, it is fundamental that researchers understand how to build climate resiliency for future forests through the establishment of a network of provenance and common garden tests across a climatic gradient. This will enable the examination of a range of genetic sources for traits that may increase the potential for genetic diversity and adaptability that help define seed transfer guidelines that promote long-term reforestation success.

Current nursery practices typically grow seedlings under luxury resource conditions which do not match the hot, dry environments of most post-wildfire outplanting sites. A critical knowledge gap exists on the range of strategies that can be applied to condition seedlings in the nursery, morphologically and physiologically, to anticipate more stressful environmental planting conditions. Specifically, little is known about how the intensity, duration, timing, and types of nursery conditioning treatments (e.g., water and heat stressing) influence morphological and physiological traits across a range of species and genetic sources that ultimately lead to greater seedling survival in outplanting (Sloan et al., 2020; Pinto et al., 2023). Recent studies show that nursery cultural practices, in the form of limiting irrigation in the nursery, can result in a drought conditioning effect, thereby preparing seedlings for drier conditions on the outplanting site (Pinto et al., 2012; Sloan et al., 2020; Pinto et al., 2023). However, continued research is necessary to assist in illuminating strategies to increase post-wildfire seedling survival in a wide range of geographies. Ultimately, the success of the reforestation pipeline and overall seedling survival is based on defining the right combination of genetic sources (i.e., seed source), nursery cultural practices, and optimal outplanting strategies.

Outplanting strategies – Components of the reforestation pipeline: How do we optimize site selection and spatial patterns of outplantings to maintain/enhance ecosystem services in post-fire landscapes?

Planting trees is essential for post-wildfire recovery when natural regeneration is insufficient to restore high-severity burned areas to forest (Davis et al., 2024). Planted seedling survival rates during the early 21st century in the western US have been highly variable, with low success rates in some sites raising significant ecological and economic concerns (Ouzts et al., 2015). Recent planting studies have shown that survival is higher when seedlings are planted on cooler and wetter locations (Marsh et al., 2022a; Marshall et al., 2024, Rodman et al., 2024) and when they are planted at higher elevations than where the seeds were collected (Marshall et al., 2024; Moran et al., 2024). However, there is much to still be understood across a range of species and planting conditions, such as seasonality and timing of planting (e.g., Rodman et al., 2024), microsite influence on planting (Marsh et al., 2022b; Marshall et al., 2023), and longer-term survival rates which can inform planting densities that promote resilient future forest structure without subsequent interventions.

Historically, initiatives such as the REPLANT Act and Executive Order No. 14072 (2022) suggest a significant momentum to enhance reforestation efforts in the US. However, to achieve recovery objectives, as well as to minimize the economic waste of low seedling survival, it is essential to develop outplanting strategies that will improve survival rates of planted seedlings. There are many specific knowledge gaps that may greatly influence survival and planting seedling success such as, how to optimize seedling storage, handling, and transportation, how to reduce browsing and herbivory, the role of competing and facilitating vegetation in different landscapes, and how to increase survival and efficiency in outplanting. Additionally, there is a temporal window for effective reforestation, ideally after hillslope stabilization but before areas have converted to shrub or grasslands and water and nutrient availability for planted seedlings is reduced, and areas are beyond the climatic envelope that seedlings may endure (Lalor et al., 2023; Marsh et al., 2023; Crockett and Hurteau, 2024). A science-based approach is urgently needed to identify effective methods for alleviating planted seedling stressors and inhibitors and to operationalize optimal planting for the best outcomes in the most critical locations (North et al., 2019; White and Long, 2019; Stevens et al., 2021).

Predictive models for reforestation: How do we link site-level conditions and remote sensing data to develop and apply models to improve outplanting success?

High-severity wildfires in the western US are causing significant tree mortality and loss of seed sources vital for natural regeneration. This low survival rate stems from factors such as the loss of the protective overstory canopy, increased wildfire frequency and severity due to climate change, and altered site conditions. Research indicates novel patterns in tree regeneration in the West (Bell et al., 2014; Dobrowski et al., 2015), revealing changes in species composition and confirming a reduction in forested areas (Parks et al., 2019). Predictive models translate best available scientific knowledge into tools that can be readily interpreted and used by practitioners to help support management decisions (North et al., 2019; White and Long, 2019; Stevens et al., 2021). When combined with remote sensing and spatial data, these models offer valuable insights for assessing post-fire regeneration risks and informing planting prescriptions.

A growing number of tools are available to guide reforestation priorities and site-specific planting strategies. The Forest Vegetation Simulator (FVS) is widely used but lacks regeneration models in certain regions, like the Central Rockies (Keyser and Dixon, 2008). Emerging tools such as PostCRPT (Stewart et al., 2021), SRRT (Rodman et al., 2022), and RegenMapper (Holden et al., 2022) can pinpoint areas most likely to regenerate naturally, especially within recent fire perimeters. Integrating remote sensing with seedling survival monitoring can clarify how environmental conditions influence survival rates. Long-term vegetation studies also enhance understanding of directional change (Brusca et al., 2013; Guida et al., 2014), and when paired with high-resolution mapping and climate data, they effectively assess local risks (USDA Forest Service, 2023). Stevens et al. (2021) provide a comprehensive framework for planting strategies that can be enhanced with climate adaptation strategies and quality datasets, improving decision-making. These tools are especially beneficial for inexperienced practitioners, guiding site prioritization, species selection, and climate-smart practices. However, existing predictive models have geographic and species limitations. A unified tool encompassing all sites in the western US would significantly aid federal, state, local, private, and tribal entities involved in post-fire reforestation. A tool that integrates the likelihood of natural regeneration and the likelihood of planted seedling survival would also be beneficial.

The need for reforestation is increasing, yet resources remain limited. Large areas of forest cover lost to wildfires adversely affect the ecosystem, reducing winter snow retention, decreasing soil moisture, and raising near-ground temperatures. Tree seedlings occupy a narrower fundamental niche than mature trees, and high-severity fire can lead to conditions that prevent forest regrowth, potentially converting these areas to shrub or grasslands (Coop et al., 2020). Addressing this issue is urgent, as post-fire tree planting is currently limited across the Interior West (Dumroese et al., 2019) but is likely to increase in the coming years (Dobrowski et al., 2024). With the climate rapidly changing, the opportunity for reforestation may diminish as post-wildfire areas transition to less suitable habitats, affecting water and nutrient availability for seedlings. Developing and implementing predictive models that leverage scientific knowledge for reforestation could optimize resource use, especially if deployed promptly after wildfires, ensuring seed sources for natural succession before land-type conversions occur.

Reburn: How do we manage fire as part of post-fire recovery leading up to the next (inevitable) fire?

A historical perspective based on centuries of fire history reminds us that repeated fires were the norm, not the exception, in many ecosystems. The most widely used statistic to characterize fire regimes, the fire return interval, is a statistic of re-burning, and repeated fire exposure is the foundation of many contemporary prescribed fire programs. Areas such as the Gila Wilderness, Rincon Mountains, and other areas illustrate the key role that regular fire plays as a stabilizing force, helping ecosystems to adapt and maintain natural functions. In fact, preventing re-burning is a proven pathway toward type conversion in a fire-adapted system (What is a grassland without reburning? Not a grassland for long).

However, there is legitimate concern about re-burns in contemporary fire science and land management, especially when repeated fires occur with uncharacteristic severity or frequency. When re-burns do occur with high severity and/or short intervals, ecosystem reorganization can occur, altering forest trajectories. These changes can lead potentially to forest loss and watershed degradation, as well as reduced critical ecosystem services such as carbon sequestration. Thus, the central question is: how can we keep repeated appropriate fire on the landscape, while avoiding the adverse effects of uncharacteristically severe or short-interval fire?

The impact of this issue is profound: Addressing the impact of repeated fire is central to the stability and adaptability of post-fire restoration in the western US. Because of the high variability in outcomes following severe fire depending on forest type, fire interval, fire severity sequences, and other biophysical factors, we still have limited ability to predict post-fire trajectories. Most large wildfires leave complex mosaics of fire severity, ranging from unburned to severely impacted. These landscape legacies create a new template in which land management must operate, sometimes for decades. Some areas that undergo type conversion to more flammable vegetation types may lock into alternative states that become reinforced by repeated uncharacteristic fire, potentially precluding return to the original plant community. Increased prevalence of invasive species and conversion can increase the potential for future wildfires that reinforce a new ecosystem state unlike those that existed pre-fire.

The urgency of addressing this issue is self-evident. As wildland fire burned area increases, and the proportion of area burning at high severity also increases in many areas, the probability of re-burning with uncharacteristically high severity is rising rapidly. Since this combination of repeated burning and high severity is predicted to lead most rapidly to abrupt ecosystem change, a better understanding of the ecology of re-burns and feasible management strategies is crucial in fire science and management. Increasing burning at high severity due to changing climate conditions means that more area is also burning in uncharacteristically short intervals, which may complicate or constrain post-fire recovery efforts. Repeated fires have many potential compounding impacts, such as increased prevalence of regeneration failure (Stevens-Rumann and Morgan, 2016; Turner et al., 2019), larger and more continuous high severity areas (Harvey et al., 2023), and insufficient understanding of hydrologic processes and impacts to soils. Repeat high-severity fires can erode fire refugia and impair the ability of landscapes to recover through natural seed dispersal and recruitment.

At the same time, concerns about adverse effects of unsuitable reburning cannot lead managers back to a strategy of suppression. Despite recent increases in area burned, the US remains in a significant fire deficit (Parks et al. 2018). The challenge for post-fire management is to make landscapes ready for the next fire, and to ensure that fire can continue to play its essential stabilizing role.

Prioritizing post-fire forest recovery trajectories: When, where, and how to accept forest conversion, support natural regeneration, and/or intentionally perform reforestation?

As ecosystem conversion becomes an ever-growing concern across burned areas of western US forests (Coop et al., 2020; Guiterman et al., 2022), so does the concern about how to manage these transformed landscapes (Davis et al., 2024). Conversion of ecosystems to non-forest stands will result in the decline of many ecosystem services and human benefits such as carbon storage, wildlife habitat, biodiversity and water quality (Tepley et al., 2014). While numerous studies have examined post-fire forest trajectories (e.g., Stevens-Rumann and Morgan, 2019; Rodman et al., 2020; Davis et al., 2023), there is a critical need for clear guidance for decision-making about when natural forest recovery is likely versus active replanting is needed to support continued forest cover. Currently, US Forest Service policy mandates reforestation on all managed acres that have become “unforested” either because of wildfire or due to logging (e.g., 16 U.S.C. § 475, 16 U.S.C. § 551; 81 FR 24785). However, there are many areas that may not be suitable for regeneration now or in the coming decades, as the climate continues to warm, and areas become more arid (Davis et al., 2024). Additional studies are needed that examine natural forest recovery versus tree planting in the western US after fire (Ouzts et al., 2015; Rodman et al. 2024; Sorenson et al. 2025).

Land managers would greatly benefit from science-based decision-making frameworks focused on specific forest types and/or for specific regions. With the current and predicted changes in climate, a deeper focus on changes in temperature and drought during natural forest recovery or assisted reforestation is critical to establishing long-term forest resilience, either naturally or with human assistance (Chazdon et al., 2021; Falk et al., 2022; Seidl and Turner, 2022). Advancing this topic is extremely time sensitive as (1) the occurrence of wildfires causing large treeless patches is increasing (Singleton et al., 2019; Parks and Abatzoglou, 2020), (2) post-wildfire disturbances like wind events, drought, and re-burning can impact the potential trajectories of large treeless patches (e.g., Whitman et al., 2019; Turner et al., 2019; Braziunas et al., 2023; Davis et al., 2023), and (3) the gap between areas replanted and those that remain unforested post-wildfire continues to expand (Dobrowski et al., 2024). Providing clear, science-based decision-making support to managers about how to proceed in the immediate and intermediate (e.g., 2-10 year) post-wildfire timeframe will greatly benefit land managers and other interested parties in determining post-wildfire management actions, especially tree planting and/or accepting ecosystem conversions to occur.

Assisted tree species migration: What are the benefits and drawbacks of human-assisted movement of tree species and populations (i.e., translocation) to aid in intentional reforestation in post-fire forests?

Assisted migration (AM) exemplifies new strategic responses proposed to maintain biological diversity through a period of climate change. The velocity of climatic change raises concerns that the ability of many species to range-shift in response may be constrained under a variety of conditions, including dispersal barriers due to human land use. Currently there is very limited guidance on how, where, and if to implement AM. There is much debate over the morality of this topic. Critics describe this as “ecological gambling” (Ricciardi and Simberloff, 2009). Concerns include inadvertently introducing species that could become locally invasive, displacing native biota (as has occurred multiple times with introductions to islands); lack of essential symbionts (such as pollinators or food plants); contamination of locally-adapted gene pools; and the sheer number of species that may require assistance on a global scale, not to mention the high probability of failure. Supporters stress that establishing new tree regeneration now, will provide the seed source for the future forest that will be developing under future changed climate. Identifying the tradeoffs of tree species/genotypes with resilience to the various climatic conditions of frost, extreme temperatures, and drought conditions will be an important first step. Additionally, detailed risk analyses are needed given the potential risk of introducing new species.

Research, policy, and action on AM is urgent. This is driven by the speed of changing climate and the occurrence of large-scale disturbance events (i.e. major droughts, insect outbreaks, and wildfire) that provide opportunities for AM events. An increasing amount of high severity burned area is planted with conifer seedlings each year. The sooner we can establish guidelines for planting seedlings that will survive now and thrive under changing conditions, the fewer resources that will be wasted planting maladapted tree seedlings. Additionally, surveys suggest that some managers are already using AM but there are no clear policy frameworks that require climate-adapted planting strategies on public lands in the U.S. Susceptibility and tolerance of a species to climatic and disturbances changes throughout its development from seedling to mature tree. In the short-term, we need the ability to identify thresholds in climate variables for seedling survival and growth. In the long-term, as the tree matures, understanding the different climatic thresholds will be important for the sustainability and optimal growth of these forests. The urgency and time sensitivity of establishing a range of tree species and genotypes within a species is high since it will take decades for tree seedlings planted now to reach reproductive maturity.

Species and population sources for climate-informed reforestation: How can the understanding of how tree species and population sources influence forest resilience inform planting strategies in a changing climate?

Without deepening the knowledge and practice of science-based, climate-informed reforestation, the combination of hotter and drier conditions and increased wildfire activity suggest that the western US will experience higher rates of planting failure (e.g., Koehn et al., 2022) and simpler, less diverse landscapes. Paleoecology suggests that, without assistance, the current rate of warming is outpacing the landscape's rate of adjustment, with late-seral species taking even longer to adjust (Axelrod, 1958; Laughlin et al., 2011) and with high-severity wildfire catalyzing long-term change (Davis et al., 2024). Conventional reforestation assumes the adaptive capacity of many species or that seed collected at a given elevation zone will still be adapted to that elevation zone, regardless of warming. However, trees are long-lived and have different climatic thresholds during their various life stages and thus may not keep pace with climatic warming (Svenning and Sandel, 2013; Davis et al., 2020). Given current climatic trends and the predicted additional warming, conventional replanting strategies are likely to result in greater planting failure when compared to climate-informed reforestation (St. Clair et al., 2020; Sáenz-Romero et al., 2021; Looney et al., 2024).

Typically, seed collection is either done through wild seed collection or from specialized seed orchards which prioritize disease resistance, as most seed is for the replacement of commercial timber stocks in some regions of the US (Wilhelmi et al., 2017). In either wild seed collection or seed orchards we often do not account for genetic variability in seed and subsequently outplanted trees. Thus, improved identification of the commercial and non-commercial timber tree species that are best adapted physiologically to future climate and disturbance regimes and that cover the gradient of future climates will be needed to ensure climate-informed reforestation (Williams and Dumroese, 2013, Aitken and Bemmels, 2016; Palik et al., 2022; Agne and Slesak, 2024).

Seed sources that can produce robust, resilient seedlings for outplanting will greatly increase post-wildfire reforestation success. Identifying genotypes or species with improved adaptation to future climates to replace current maladapted genotypes/species is warranted. These seed sources might also be at high risk of loss as a result of wildfire, insects/disease, or harvests in the coming decades. Identifying future adapted species/genotypes, their locations, and their prevalence in the nursery seed inventory will aid in the prioritization of seed collection and preservation of these important sources. In turn, this knowledge will help to promote climate-resilient forests throughout the western US.

HYDROLOGY

Soil erosion mitigation: What pre- and post-fire management actions are most effective to mitigate soil loss and water turbidity post-fire?

Agricultural and residential water use in the western US is heavily reliant on forested headwater and reservoir systems, which are particularly sensitive to severe wildfire and sedimentation (Barnard et al., 2023). Many wildfire impacts are acute in the first few years post-fire, but loss of soil materials and nutrients can continue for decades (Rhoades et al., 2019). Impacts are also being compounded by climate-driven changes in rainfall (Touma et al., 2022). Excessive post-fire soil erosion can have significant economic impacts to downstream water users (Jones et al., 2022). Understanding how pre-fire treatments can influence post-fire soil movement and water quality outcomes will help to develop a more accurate estimate of return on investment for various treatment options (Hjerpe et al., 2024).

Post-fire soil retention strategies include seeding, mulching, emerging chemical treatments, and the construction of hillslope and in-channel structures to capture sediment. These strategies differ in their efficacy depending on the application and monitoring timeframe, terrain, rainfall regime, and severity of the burn (Girona-Garcia et al., 2021). More research is needed to understand the efficacy of erosion mitigation strategies across different conditions, the role of high precipitation intensity events in influencing treatment efficacy (Lopes et al., 2020), and the cost efficacy of post-fire treatments in the long term. This includes whether some treatments (e.g., chemicals or fertilizers) further reduce water quality, and whether other treatments like mulching inhibit vegetation recovery and promote invasive plant recruitment and growth. More work on the effectiveness of combined treatment approaches, and the impact at larger water supply catchment scales, is explicitly needed as well (Girona-Garcia et al., 2021; Gonçalves et al., 2025). Ecological and cost-efficacy assessments of these techniques can help guide financial resource allocation during the critical immediate-post-fire response.

Flood and debris flow mitigation: What pre- and post-fire management techniques are most effective to mitigate flooding and debris flow impacts through prevention and prediction?

About 90% of the total economic costs of wildfire take place after the burning has ceased, due to processes such as flooding and debris flows (Barrett, 2018; Hjerpe et al., 2023). Managing forests to minimize flood risk to downstream communities is therefore typically a cost-effective framework (Mueller et al., 2013). This includes pre-fire activities such as forest thinning to reduce burn-severity and resulting runoff intensity, as well as post-fire activities such as the construction of runoff retention structures. Once the fire has occurred, delays in implementing effective strategies can increase the magnitude of secondary disasters like floods and debris flows, causing further loss of life, property damage, and ecosystem degradation (Staley et al., 2018). The window for successful post-fire intervention is often narrow, with the first rainy season after a fire being a critical time for erosion and debris flows (Staley et al., 2013). The urgency is compounded by the need to protect water resources, as post-fire flooding can contaminate water supplies, damage essential infrastructure, and cause loss of human life (Gannon et al., 2022; Collar and Earles, 2023).

Prioritizing and implementing pre-fire management actions, and assessing and pre-organizing post-fire management actions, would together significantly reduce post-fire hydrologic event damage by optimizing resource allocation (Lopez et al., 2024). Two pre-fire actions that may potentially reduce the magnitude of post-fire flooding and debris flows are fuels management and the installation of simulated beaver structures, to reduce fire severity and to attenuate flooding, respectively (Lopez et al., 2024; Triantafillou and Wohl, 2024; Wohl et al., 2024). Community safety can be enhanced by better predictions of where post-fire hazards pose the greatest risk, leading to more robust disaster preparedness and evacuation plans (Edgeley and Colavito, 2022). More research is needed to develop forward-looking, climate-sensitive assessment protocols and models of post-fire hydrological event hazards (e.g., Touma et al., 2022). This knowledge would allow agencies to prioritize interventions that provide the greatest benefit in reducing flood and debris flow risks. Furthermore, this understanding would enable better long-term land use planning for fire-prone areas.

Stream corridor restoration: What is the effectiveness of various post-fire stream restoration techniques?

Stream corridors are one of the most hard-hit portions of a landscape following fire, both in terms of habitat and human habitations, due to post-fire floods and debris flows. Restoring these channel areas is necessary to reduce continued impacts (water quality, flooding) to downstream communities. Different techniques include hard-engineering (levees, riprap, grade control structures), process-based restoration (water and sediment detention ponds, floodplain reconnection, wood jam reintroduction), and others (Wohl et al., 2024). Each has strengths and weaknesses in terms of cost, durability, longevity, and effectiveness. Systematic research to identify situations that are appropriate for each technique, and the expected costs and benefits of implantation in any given scenario would save money and enhance ecosystem recovery.

In spite of the importance of stream corridors, almost nothing has been published regarding benefits, challenges, and scientific guidance for restoration following wildfires (this includes both river channels and floodplains). With billions of dollars spend on restoration in the U.S. annually and wildfire occurrences increasing, addressing this topic is important for guiding scientifically-based management of headwater systems following wildfires. Gaps in our understanding of post-wildfire river corridor restoration include responses of aquatic communities (e.g., fish, macroinvertebrates); impacts on river-floodplain and river-floodplain-groundwater connectivity; impacts on water deliveries to downstream water users; role of restoration on carbon sequestration; impacts on water quality and sediment delivery; and riparian forest responses following wildfires and restorations. These riparian habitats are a hotspot for biodiversity in most regions, so highly effective restoration here would have outsized impact on overall ecosystem health.

Post-wildfire stream restoration often occurs within the first three years of a major wildfire to mitigate the largest hydrologic and geomorphic consequences of degraded streams, such as large sediment loads or flash floods. Scientific guidance needs to be well established so that forest managers can quickly implement best practices for stream restoration following a wildfire. With wildfires growing in spatial extent and severity, developing guidelines for implementing stream restoration treatments during wildfire recovery periods is needed as soon as possible. Using the Colorado Front Range as an example, tens of millions of dollars are being spent on restoration with little scientific guidance.

Post-fire water quantity and quality trajectory: What factors explain the post-fire trajectories of snowpack dynamics, water quantity, and water quality through time?

There is substantial variability in how fire impacts water quantity and quality, due to the complexity of interacting factors such as soil type, climate, fire severity, and landscape heterogeneity, among others. Regarding water quantity, the removal of vegetation typically reduces transpiration and increases water yield, for at least six years (Williams et al., 2022). However, such impacts are not necessarily consistent across all fires or other forest disturbances (Goeking and Tarboton, 2020). Fires of different severity and pattern have a wide range of effects on forest structure and composition, which will then change snowpack accumulation and persistence by impacting shortwave and longwave radiation distribution, albedo, interception, and ablation, in some cases leading to reduced water availability (Biederman et al., 2022). All these interactions will be further modified by the aspect, burn pattern, burn size, and climate of the impacted forest, ultimately resulting in some cases where fire increases snowpack and water quantity, and other cases where it decreases them. Regarding water quality, removal of ground cover and the resulting loss of soil materials and nutrients can degrade vegetation productivity and water quality for periods even longer than the water quantity effects (Rhoades et al., 2019). Hydrologic changes can persist for decades following fire (Niemeyer et al., 2020) with variation in duration of effects attributed to the extent and severity of fire (Hallema et al., 2018) and rate of vegetation regrowth (Tague et al., 2019).

Advancing knowledge used to predict post-fire water quantity and quality trajectories would guide post-fire restoration and recovery actions by informing whether the post-fire forest structure is likely to be beneficial or detrimental to snowpack and water quantity, and how prone to elevated water turbidity it may be. For example, in some locations and at some fire sizes and severity, it may not be beneficial to replant trees because the existing post-fire forest structure optimizes snow accumulation. In other cases, replanting trees, reducing erosion, or modifying post-fire albedo could be important for maintaining or increasing snowpack and water availability (Giovando and Niemann, 2022; Reis et al., 2024). Several recent meta-analyses and regional studies have identified a consensus on the mechanisms involved but not the sum total of how they interact (e.g., Wagenbrenner et al., 2021). Explaining variation in watershed recovery time and trajectory is one of the most fundamental topics on which we need to advance our knowledge to effectively guide post-fire restoration and recovery. Without this understanding, it will be impossible to optimize restoration strategies. Money will be wasted applying restoration strategies where none are needed, and restoration strategies will be less effective because they have not been informed by factors that confer resilience to watersheds.

Predictive models for watershed hydrologic response: How can we improve prediction for post-fire hydrologic events through improved tools and data?

Runoff models (e.g., ParFlow), flow routing models (e.g., HEC-RAS), and erosion prediction tools (e.g., the Water Erosion Prediction Project – WEPP), allow decision makers and managers to predict post-wildfire effects on watersheds. These tools can assess the risk of flooding, sedimentation, etc. in order to make operational decisions that influence erosion reduction and public safety post-fire. While this suite of existing tools is operational, recent review papers on modeling post-fire hydrologic response highlight numerous gaps and opportunities for improvement (e.g., Partington et al., 2022; Ebel et al., 2023)

First, there is a need to validate the tools in more geographic settings to ensure they accurately predict wildfire-watershed effects across geographies. This requires field data collection across the West immediately after wildfires. A second need is to collect quantitative data on post-fire hydrologic processes (infiltration, overland flow, groundwater flow) at spatial scales that capture the heterogeneity of the response. Adequate model parameterization is critical for reliable, actionable output. Third, this hydrologic data collection needs to persist long enough to gain confidence in the validity of the models in the evolving post-fire landscape, such that planners can assess risks related to hydrological processes (water quality, debris flow and flooding, water yield) at short-, medium-, and long-term time scales.

Limitations in using physically-based models for post-fire recovery and restoration include lack of hydrologic models designed specifically for post-fire application, lack of guidance for using hydrologic models for post-wildfire application, inadequate representation of groundwater flow, subsurface flow, and soil-water processes, inadequate application for vegetation regrowth, and lack of access to computational resources. Addressing these limitations and weaknesses could provide significant impact in guiding post-fire restoration and recovery.

SOCIAL SCIENCE

Community resilience and recovery: What are the impacts of wildfire across different types of communities and what shapes a community's recovery process?

Improving community resilience and recovery post wildfire is a critical, time-sensitive issue, as loss of life, infrastructure, and social cohesion continue to escalate globally in the face of intensifying disasters (Edgeley and Paveglio, 2017). Federal agencies like FEMA are repeatedly criticized for inadequately addressing the diverse needs of communities after events like wildfires, underscoring the urgent need for empirically-driven, systemic changes to the recovery process (Edgeley and Paveglio, 2017). While prior research has revealed how communities navigate recovery assistance, significant gaps remain in understanding how compounding disasters in resource-constrained regions exacerbate unmet needs and inequities (Chase and Hansen, 2021; Edgeley, 2022; Moloney et al., 2023). Additionally, there is limited knowledge about the capacity of governmental and non-governmental entities to support long-term recovery as catastrophic events become more common. As funding and staffing for disaster response remains unstable, this challenge is compounded. Frameworks sensitive to community-scale factors are essential for both pre-disaster mitigation and equitable post-disaster recovery, yet their absence has created an ethically urgent imperative to center environmental justice concerns (Edgeley and Paveglio, 2017). Marginalized communities often bear the brunt of disaster impacts and face persistent, unseen challenges long after the emergency response and media attention have subsided. Addressing these disparities through holistic, community-driven recovery frameworks is not only a moral necessity, but also crucial for building resilience in the face of escalating climate-related disasters.

Community engagement and equity: How can we design post-fire recovery processes to be equitable, inclusive, reflective of community values, and attentive to social justice issues?

There is a critical gap in understanding community-level post-fire recovery through an equity lens, as most social science studies have focused on pre-fire mitigation and active fire response rather than recovery processes (Baker et al., 2024). The importance of advancing research on this topic is heightened by shifting demographic patterns in wildfire-affected areas in the western US. Historically, more affluent populations had higher exposure to wildfire risk due to their presence in the wildland-urban interface (Wigtil et al., 2016; Davies et al., 2018), but this pattern is changing as housing market pressures force more vulnerable populations into fire-prone regions (Thomas et al., 2022). This demographic shift, combined with increasing fire frequency, creates an urgent need to understand how different communities are differentially impacted by both wildfires and recovery processes. Vulnerabilities to wildfire impacts are shaped by intersecting factors including race, income, geographic location, and resource access (Ferreira et al., 2024).

Community engagement in post-fire recovery has demonstrated multiple benefits that warrant additional research attention. Studies have shown that such engagement leads to improved wellbeing and repaired place attachment through activities like replanting burned areas, increased public participation in land management decisions, and better understanding of federal post-fire processes (Ryan and Hamin, 2008; Edgeley, 2023). These outcomes are particularly significant as federal agency budgets continue to decrease, making community support increasingly crucial for effective recovery efforts (Colavito et al., 2023). There is also a need to integrate Indigenous ecological knowledge and community insights into post-fire restoration activities. Indigenous Peoples living in these landscapes have been managing wildfire for millennia prior to European settlement (Lake et al., 2017; Adlam et al., 2021; Long et al., 2021; Roos et al., 2021; Tom et al., 2023). Other authors have highlighted that inclusion and participatory processes that reflect community values and priorities have the potential to shift ecological and social outcomes (Löfqvist et al., 2022; Lambrou et al., 2023). This perspective underscores the need for research that can inform policy development, governance structures, and communication strategies that address differential vulnerability while promoting long-term resilience. Without immediate attention to these research priorities, recovery efforts risk perpetuating or exacerbating existing social and environmental injustices, making the development of equitable, inclusive, and community-driven recovery frameworks an urgent imperative in post-wildfire management research.

Public support: How do public perceptions and expectations interact with post-fire forest and watershed restoration practices?

Understanding public perceptions of restoration and recovery practices represents a nexus of environmental management and social science. As climate change intensifies wildfire frequencies and magnitudes, land management agencies confront increasingly complex challenges in implementing ecologically sound interventions. Current research underscores the profound impact of public support on management strategies. Managers have historically encountered significant resistance to evidence-based practices such as prescribed fire and salvage logging, indicating substantial sociocultural barriers to effective ecological restoration (Steelman and McCaffrey, 2011). These impediments can fundamentally compromise landscape resilience and community adaptive capacity.

Research reveals nuanced perspectives on forest management. Recent studies demonstrate relatively robust support for various forest treatment approaches, yet significant knowledge gaps persist regarding post-fire treatment perceptions, particularly among marginalized or understudied populations (Edgeley and Colavito, 2022; Colavito et al., 2023). Notably, perceptual variations emerge across demographic contexts, with rural communities often prioritizing immediate property protection while urban perspectives exhibit divergent interpretations. Edgeley's (2023) comprehensive review of southwestern wildfire social science research specifically highlighted public perception as a pivotal research domain. As wildfire regimes become increasingly unpredictable and destructive, interdisciplinary approaches that integrate ecological expertise with nuanced social understanding become imperative. The nexus of scientific intervention and community acceptance represents a critical frontier in environmental resilience and adaptive management.

Traditional knowledge: How can Indigenous land and fire stewardship be supported to inform post-fire restoration, recovery, and resilience in ways that respect Indigenous data sovereignty?

The integrating of Indigenous knowledges (IK) into the rehabilitation of forested lands impacted by high-intensity wildfires is underscored by the urgent need to restore ecosystems disrupted by colonial practices and historical fire regimes. High-intensity wildfires have surged due to the systematic marginalization of Indigenous fire stewardship, which has been severely limited by practices of genocide, forced relocation, and the delegitimization of traditional lifeways (Adams, 2024). Given the profound challenges in recovering these landscapes, there lies an unprecedented opportunity to not only rehabilitate burned areas but also to reaffirm Indigenous rights and methodologies in land management. Research regarding successful integration of IK emphasizes reclaiming the autonomy to implement traditional practices on ancestral lands and a co-management approach. Integration of IK must be utilized through authentic participation of Indigenous communities in stewardship practices (Lake, 2021). Adams (2024) advocates for the recognition of Indigenous fire data sovereignty principles in academic and fire management circles to foster genuine partnerships. This research highlights the critical role of traditional fire knowledge in guiding effective post-fire restoration efforts. The deployment of this knowledge is contingent upon respecting the specific contexts in which it is held and the intentions of Indigenous knowledge holders. Fostering collaboration between Indigenous communities and researchers is essential for developing impactful fire management strategies that honor traditional practices while addressing contemporary ecological challenges (Adams, 2024).

Economic valuation and pluriversal economies: How can recovery efforts support and honor communities to rebuild the multiple ways people live and work?

Wildfire recovery efforts face significant challenges in addressing the diverse needs of affected communities, particularly concerning equity, inclusivity, and justice. Current research has revealed critical gaps in understanding how different communities are impacted by and recover from wildfires (Thomas et al., 2022). Most studies have focused narrowly on pre-fire conditions or immediate fire impacts, with limited analysis of demographic factors beyond basic metrics like income and race. This restricted scope fails to capture the full spectrum of vulnerability factors, including sensitivity and adaptive capacity. Centering equity in decision-making processes, rather than solely focusing on landscape outcomes, could fundamentally transform recovery solutions (Lambrou et al., 2023). This approach becomes particularly crucial when considering communities with diverse economic structures, including what were historically termed "informal" or "parallel" economies. When disasters strike, communities often face pressure to conform to dominant bureaucratic and economic frameworks, particularly when engaging with federal assistance programs like FEMA. While these interventions can offer significant economic development opportunities, they risk undermining traditional practices and local economic values that are fundamental to community identity. The urgency of post-disaster response can lead to interventions that fail to consider the broader implications for community sustainability. The concept of the "pluriverse" has emerged as a framework for understanding how competing but co-existing economic realities intersect. This perspective highlights the importance of recognizing and preserving diverse economic practices during recovery efforts. Without careful consideration of differential vulnerability and pre-existing inequities, recovery initiatives may inadvertently perpetuate or worsen existing injustices. Moving forward, there is a critical need for research that examines how recovery efforts can support and honor the multiple ways people live and work while addressing historical inequities in disaster response and recovery.

Institutional coordination: What formal and informal institutional structures and approaches are necessary to better integrate the response to fires and post-wildfire impacts across scale?

Institutional coordination in wildfire response and recovery in the US remains a persistent challenge. Research is needed to understand and address the structural and cultural barriers to coordination across relevant governmental institutions at various scales. This includes examining how to integrate organizational and financial mechanisms while addressing social and cultural obstacles like mission misalignment across agencies (Fleming et al., 2015). Multiple government reports and academic studies have documented systemic failures in coordination across US agencies and governance levels (Cheng et al., 2015; WFMMC, 2023), as responding agencies often implement programs independently with policies that do not incentivize coordination. Challenges manifest in several ways: agencies conducting duplicate assessments, as seen after Colorado's Cameron Peak and East Troublesome Fires in 2020 (Carney et al., 2025; WFMMC, 2023), and programs operating in isolation due to hyper-specific focuses, for example, the Natural Resources Conservation Service's watershed focus versus the Federal Emergency Management Agency's built environment focus (Davis et al., 2022).

These coordination failures create inefficiencies and gaps in recovery efforts that communities cannot always afford to address as wildfire impacts intensify. Research examining real-world case studies after fire could provide crucial insights for developing effective local, state, and national coordination policies and guide integration efforts moving forward. In particular, examining the outcomes of recently established cross-institutional coordination efforts would provide insights into best practices and contribute to our understanding of sustainable solutions to institutional coordination in post-fire landscapes. For example, the recently established Interagency Post-Wildfire Integration Council represents a step toward better coordination, but its effectiveness has not yet been tested, and more research is needed to effectively inform its actions (USDA, 2025). With cascading post-fire hazards such as debris flows and flooding that produce impacts ranging from infrastructure destruction to community financial instability and mental health declines (Hjerpe et al. 2023; Edgeley et al. 2024; Houston et al. 2024), the need for research-informed solutions to institutional coordination challenges grows more urgent as wildfire events become more frequent and severe.

Collaborative governance: What types of collaborative governance structures and approaches can be developed to better prepare for wildfire recovery?

Recent papers highlight significant gaps in our understanding of optimal collaborative governance structures for post-wildfire recovery, making this a critical area for additional research (Moloney et al., 2023; Cheney et al., 2024). The significance of this research topic is amplified by several factors. First, existing collaborative and adaptive governance frameworks, while promising, have not adequately addressed the unique challenges of wildfire recovery (Huayhuaca et al., 2023). Miller et al. (2022) argue for the need to develop more robust forms of collaborative governance that can better handle the transboundary, uncertain, and contested aspects of wildfire management. Second, while polycentric governance approaches have emerged as a potential solution in some areas, research is needed to understand when and how to implement these strategies effectively for wildfire recovery (Carney et al., 2025; Buettner and Schultz, 2025). Finally, a critical area of inquiry under this topic is how to shift from reactive to anticipatory governance approaches. As Ruhl and Kundis Craig (2021) suggest, anticipatory strategies offer a framework for governing present actions while adapting to uncertain futures. This builds upon the adaptive governance literature (Sharma-Wallace et al., 2018) but emphasizes the need for longer-term policy visioning.

New research examining case studies of where and how collaborative governance approaches lead to optimal social and ecological post-wildfire recovery are needed. Some key research opportunities include understanding the conditions necessary for successful polycentric governance, identifying resource requirements for effective collaboration, documenting and analyzing challenges faced by groups attempting collaborative governance, and developing and testing frameworks for anticipatory governance in wildfire-prone regions. Several recent studies have noted the ad hoc nature of current post-wildfire governance arrangements (Edgeley, 2022; Moloney et al., 2023; Morgan et al., 2023), and without immediate research attention, communities across wildfire-prone regions will continue to struggle with uncoordinated and potentially ineffective recovery efforts.

Pre-fire planning: How can pre-fire planning processes include post-fire preparation and lead to better post-fire recovery outcomes?

Current wildfire planning in the US faces several limitations. Emergency management divisions often fail to anticipate extraordinary events or integrate post-wildfire readiness into all-hazard planning (Barrett, 2018). Recovery coordination frameworks vary significantly across US states and lack the flexibility to address complex governance arrangements (Burned Area Learning Network, 2018). For example, in New Mexico, unclear jurisdiction on state and private lands impeded efficient funding for post-fire recovery after the 2022 Hermits Peak-Calf Canyon fires (Buettner and Schultz, 2024). The absence of dedicated post-fire funding forces communities to rely on existing programs that have merely added post-fire recovery components. This situation is complicated by the involvement of multiple government agencies, each bearing only partial responsibility for recovery efforts.

Community wildfire planning is not federally required, and even when undertaken, can prove ineffective after a fire occurs because plans are not actually used, are out of date, or are not provided at appropriate decision-making junctures (Mockrin et al., 2020). Pre-fire plans could play a critical role in enabling communities to prioritize wildfire mitigation, reinforce infrastructure, develop necessary workforce capacity, and reduce wildfire risks to lessen post-fire impacts (Barrett, 2018). Without robust research-backed planning frameworks, however, communities remain vulnerable to cascading post-fire impacts. Practitioners in the US are increasingly looking to Community Wildfire Protection Programs (CWPP) as a potential solution for preparing and funding post-wildfire recovery (Evans, 2017); however, research and guidance on this approach remain limited and there is growing discourse about whether inclusion of recovery meets the intent of such documents. Research is also needed on how to develop scalable planning methods that can serve both fire-experienced and fire-inexperienced communities, standardize approaches while maintaining flexibility for local contexts, and create collaborative frameworks that provide timely, cross-jurisdictional recovery information (Abrams et al., 2015; Paveglio and Edgeley, 2017; Schumann III et al., 2020). Additional research would not only improve resource management and funding allocation but could also help bridge the gap between pre-fire preparation and post-fire recovery outcomes, ultimately building more resilient communities in the face of increasing wildfire threats.

Workforce development: How do we develop and maintain a restoration workforce?

Research on developing and maintaining a restoration workforce is critically urgent, as limited workforce capacity currently represents a major bottleneck in post-fire restoration efforts in the US. This gap in restoration workforce is clearly demonstrated by a backlog in post-wildfire reforestation on more than 400,000 hectares/year across the western US (Dobrowski et al., 2024). Wildland firefighters, who constitute a significant portion of the restoration workforce at the federal level in the US, must divide their time between suppression, prescribed fire operations, and restoration projects. This division of responsibilities, combined with the risk of burnout in understaffed local and state agencies (Cheng et al., 2015), creates a significant impediment to effective post-fire recovery. While surge capacity resources exist through various US government agencies to help address post-fire events, their utility is limited to immediate response efforts rather than long-term recovery. It is also plausible that such resources will become stretched thin during years with extensive fire activity, which are becoming increasingly common.

Some communities have shown promise in utilizing local workforce resources, such as businesses, non-governmental organizations, and community members with relevant skills (Buettner and Schultz, 2024), but research is needed to understand how to effectively integrate and scale these local workforce solutions. Innovative approaches like New Mexico's ‘All Hands All Lands’ teams (Morgan et al., 2023) demonstrate the potential of specialized workforces, but little is known on how to replicate and sustain such programs. The development of specialized teams could enable simultaneous execution of critical restoration activities, potentially transforming sporadic restoration efforts into systematic, sustainable programs. The significance of this research extends beyond immediate restoration needs. A well-developed local workforce strategy could create a positive feedback loop, where successful restoration projects contribute to both ecological and community resilience (Smith et al., 2025).

Advancing knowledge on how to develop, maintain, and expand the restoration workforce is crucial for keeping up with post-fire reforestation efforts and managing post-fire disasters such as flooding. There is a need to enhance both undergraduate and graduate-level degrees in forest ecology and management as well as forest policy, watershed management, and social sciences to maintain and grow the restoration workforce for management and policy positions in the US (Wagner et al., 2022). Additionally, vocational training in seed collection and processing, out-planting, nursery production, and wood utilization are needed (Vaughan et al., 2022). Without immediate research attention on how to incentivize and grow workforce development, the gap between restoration needs and implementation will continue to widen, potentially compromising the effectiveness of post-fire recovery efforts.

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