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A horizon scan to inform research priorities on post-wildfire forest restoration and recovery in the western United States

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The frequency, severity, and scale of extreme wildfire events is increasing globally, with certain regions such as the western United States disproportionately impacted. As attention shifts toward understanding how to adapt to and recover from extreme wildfire, there is a need to prioritize where additional research and evidence are needed to inform decision-making. In this paper, we use a horizon-scanning approach to identify key topics that could guide post-wildfire forest restoration and recovery efforts in the western United States over the next few decades. Horizon scanning is a method that

uses an iterative and structured expert-elicitation process to identify emerging themes or set research agendas. Experts from across researcher and practitioner organizations identified 12 topics as having the greatest potential impact, and being the most time-sensitive to address, for advancing knowledge on post-wildfire forest restoration and recovery. Five topics fall under the social sciences, including institutional coordination, collaborative governance, pre-fire planning, community engagement and equity, and workforce development; four topics relate to forest management, including seed and seedlings, outplanting strategies, post-fire forest trajectories, and climate-informed reforestation; and three relate to hydrology, including soil erosion mitigation, flood and debris flow mitigation, and post-fire water quantity and quality trajectories. While conducted for the contiguous western United States, this analysis is relevant for other regions where both people and forests are impacted by extreme wildfire events. Addressing these topics has the potential to improve the equity, effectiveness, and efficiency of post-wildfire forest restoration and recovery responses.

KEYWORDS

disaster, ecosystem sustainability, hazard, post-fire erosion, post-fire flooding, reforestation, wildfire, wildland fire

1 Introduction

The frequency, severity, and scale of extreme wildfire events is increasing globally, with some regions, including the western United States, disproportionately impacted (Cunningham et al., 2024; Parks et al., 2025). In the western United States, these trends are driven primarily by its land management history, specifically wildfire exclusion, which has led to unprecedented fuel accumulations across some ecosystems (Parks et al., 2018; Kreider et al., 2024). These trends in extreme wildfire events are being exacerbated by climate change, specifically through warmer temperatures, longer-term drought, and hydrological volatility (Parks and Abatzoglou, 2020; Wasserman and Mueller, 2023; Swain et al., 2025). Extreme wildfire events impact social and economic systems adversely, from the local to regional scale, driven in part by impacts to ecosystems and ecosystem services. In the United States, the costs of severe wildfires are estimated to be in the tens to hundreds of billions of dollars per year (Crowley et al., 2023), but the total costs can be difficult to quantify and rarely account for less tangible impacts (Hjerpe et al., 2023). These complex effects on both social and ecological systems require informed and coordinated approaches to post-fire management, and identifying and filling critical knowledge gaps could support such strategies.

The global wildfire crisis has prompted social and natural science research that focuses on evidence-informed management options before, during, and after fire (McCaffrey et al., 2013; Haghani et al., 2022; Gonçalves et al., 2025). A prominent theme in addressing the wildfire crisis is the need to shift toward more proactive and transformative management actions and increase the pace and scale of response and recovery (McWethy et al., 2019). The science around pre-fire mitigation and forest management during fire, while still essential, is more mature than the evidence informing post-fire restoration and recovery (Gonçalves et al., 2025). The larger emphasis on research before and during fire is most likely because of societal pressures to address the more immediate and tangible needs of wildfire risk reduction and fire suppression (Stephens and Ruth, 2005; Pechony and Shindell, 2010). As attention shifts toward understanding how to better live with wildfire and acknowledging recovery from fire as a central process in social and ecological fire adaptation, there is a need to prioritize the areas where additional research is needed to inform post-fire decision-making (Gonçalves et al., 2025).

We implemented a horizon scanning approach to identify research topics that could guide post-wildfire forest restoration and recovery efforts in the western United States over the next few decades. Horizon scanning is a method that has been used in conservation and environmental management to identify emerging threats and opportunities around a specific theme or topic (Wintle et al., 2020), and to set priorities for research agendas and management actions (Sutherland et al., 2011; Holterman et al., 2023). Horizon scanning uses a Delphi technique, which is an iterative and structured process that relies on experts to identify priority themes or topics (Mukherjee et al., 2015). The horizon scan method brings together insights from researchers, practitioners, and policy makers, and can be used to identify issues at multiple scales.

We conducted a horizon scan at the regional scale as a priority-setting exercise, 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 United States? We used a convergent approach to identify the most critical topics for post-wildfire forest restoration and recovery by including experts from multiple disciplinary backgrounds and a range of researcher and practitioner organizations. Convergent approaches address a specific and socially-relevant problem through integrating concepts

and methods across multiple disciplines (Finn et al., 2022; Morgan et al., 2025). Convergent approaches are especially relevant to disaster-related problems (Peek et al., 2020), and in the case of extreme wildfire events, there is a critical need to transcend disciplinary backgrounds to address the integrated challenges of post-wildfire forest restoration and recovery. Out of an original set of 31 topics, experts identified 12 priority topics that scored highest on two criteria: (1) as having the most potential impact on and (2) being the most time-sensitive to address for advancing post-wildfire forest restoration and recovery efforts. The 12 topics identified through our scan are intended to inform research agendas where addressing gaps in knowledge would improve the equity, effectiveness, and efficiency of post-wildfire restoration and recovery actions.

A specific goal of our scan was adoption of a social-ecological systems perspective on post-wildfire forest restoration and recovery (Schoennagel et al., 2017; McWethy et al., 2019). Emerging frameworks and review studies of post-fire topics often remain relatively siloed, focusing for example on forest ecology and management needs (e.g., North et al., 2019; Stevens et al., 2021; Larson et al., 2022) or the community and social aspects of wildfire response (e.g., Mockrin et al., 2020; Edgeley and Colavito, 2022). However, extreme wildfire events affect forest and ecological systems, associated ecosystem services, and directly and indirectly, social and economic systems. Addressing post-wildfire restoration and recovery, thus, requires careful attention to all aspects of these systems and the interactions and feedback between them. We also include a focus on post-wildfire effects to hydrological services in this horizon scan, because extreme wildfire events have a significant impact on downstream water quality and quantity (Hallema et al., 2018; Rhoades et al., 2019; Robinne et al., 2020) and about 70% of the population in the western United States depends on forested landscapes for water provisioning and regulation (Liu et al., 2021). While our scan is conducted for the contiguous western United States context, many of the social and ecological science topics identified are directly applicable to other regions experiencing an increase in extreme wildfire events that affect people and forests.

2 Materials and methods

Experts were invited to participate in this horizon scan by targeting a mix of researchers and practitioners in the contiguous western United States with relevant expertise in forest ecology and management, hydrology, or social sciences. A list of potential invitees was generated by the four leading authors based on their own networks and knowledge of the wildfire literature, aiming for a maximum of 30 participants to keep discussions and decision-making processes manageable (Sutherland et al., 2011). Of the 28 experts that agreed to participate in the scan based on their ability to commit time to the full process, 14 were affiliated with universities, four were affiliated with the science-management bridging Southwest Ecological Restoration Institutes, and 10 represented practitioner organizations, including United States federal government agencies, water utilities, non-profit organizations, and large, private land managers. These 28 experts are referred to in the rest of the paper as the core team and most are authors on this paper. The four leading authors organized and guided the horizon scanning process and are referred to below as the guiding team; they also participated as part of the core team. All 28 experts participated in a series of structured and iterative tasks that followed the general horizon scanning process outlined in Wintle et al. (2020): scan for potential topics, identify a long list of topics, score the topics to reduce to a shorter list of topics, investigate the topics, discuss the topics and revise if needed, and rescore the topics to select the final list of topics (Figure 1).

The guiding team developed an online survey form to scan for a broad set of topics related to post-wildfire forest restoration and recovery. The survey form consisted of the question "*What is a critical theme or topic that, if addressed, would advance decision making on post-wildfire forest restoration and recovery in the western United States over the next few decades?*" The survey also collected some basic information about the respondent. The core team was asked to submit at least one idea to the survey question and also asked to share the survey widely with their networks working on wildfire science and management; any respondent could submit multiple responses to the survey. The survey remained open for 6 weeks. This purposive (non-random) sampling resulted in a total of 106 unique responses from 86 individuals: 28 from the core team and 58 from outside the core team. Respondents self-identified as being affiliated with government agencies (46%), academic institutions (35%), non-governmental organizations (11%), Indigenous Nations (4%), civil society (1%), or independent (2%). Sixty-nine percent of respondents identified their primary

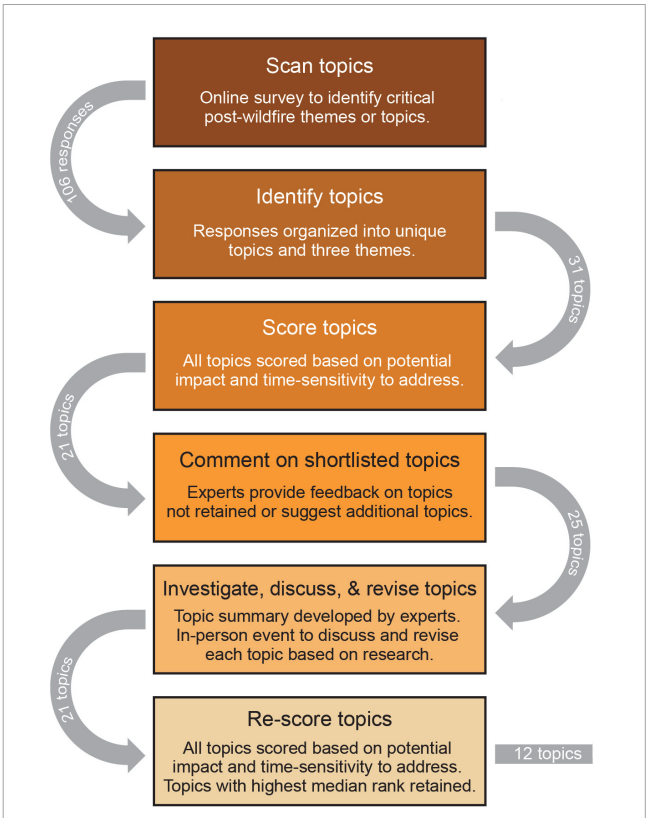

FIGURE 1
Horizon scan process followed in this study for identifying and scoring research topics on post-wildfire forest restoration and recovery.

disciplinary background as natural sciences, 16% as social sciences, and 15% as interdisciplinary sciences. Respondents had experience on post-fire restoration and recovery in the following contiguous western United States: New Mexico (19%), Colorado (14%), Arizona (14%), California (10%), Oregon (10%), Washington (10%), Idaho (8%), Montana (7%), Utah (4%), Wyoming (4%), and Nevada (2%).

The guiding team organized the 106 submitted responses into broader themes of forest ecology and management, hydrology, and social sciences, and then similar topics were grouped together. For each of the three broader themes, two people from the guiding team reviewed the groupings. After discussing the groupings, 31 unique topics were retained. The reduced list of 31 topics remained linked to the originally submitted 106 responses throughout the first scoring and investigation tasks to minimize any information being lost from the original submissions. The 31 topics were scored by the core team based on two criteria: (1) potential impact and (2) time-sensitivity to address. The core team scored each topic independently against these two criteria using a scale from 1 to 100 (low to high) in an online survey. The list of topics was randomized, and two different orderings were sent out to minimize bias from ordering. Each expert's scores were converted into a ranking and the median ranking across the core team members was calculated. Based on the relatively short list of our original set of topics, especially compared to other horizon scans [e.g., 187 topics in Dietz et al. (2021) and 102 topics in Sutherland et al. (2023)], the guiding team only removed those topics that clearly did not satisfy the two criteria and retained 21 of the original topics after the first round of scoring. These topics were sent to the core team where everyone had the opportunity to advocate for any topics that did not make the cutoff or suggest any new topics that were not included in the first round of scoring. Four topics were added through this process, leading to a list of 25 topics.

Each of these 25 topics was investigated in greater detail by two to three core team members. The reviews of each topic were collated into a report that was circulated to the core team prior to a 2 days, in-person discussion about the topics. The goals of the in-person event were to revise the list of topics and guiding questions, where needed, and to ensure all team members felt knowledgeable about the complete list of topics before their final scoring. Each expert participated in five, small-group discussions around a smaller set of topics within the same broader thematic area (i.e., forest ecology and management, hydrology, and social sciences), discussing the topic's potential impact and time-sensitivity relative to other topics in the theme. The suggestions for revising topics that emerged from the small group discussions were collated and reviewed by a set of self-selected experts on that topic from within the core team to finalize any suggested revisions. At the end of this process, the 25 topics discussed had been reframed into 21 topics: no topics were dropped, but some topics were combined because of overlap in focus. An evaluation of the in-person event suggested that the goal of increasing knowledge content across the topics was achieved, with almost 100% of participants responding that their understanding of topics outside their area of disciplinary expertise had increased moderately or extremely.

Following the in-person event, the 21 revised topics and guiding research questions were rescored independently by each of the core team members on the same two criteria using the same scale and online process. The median from the summarized rankings of the topics was used to determine the cutoff value. When the median was calculated across all 21 topics without considering the broader thematic area (i.e., forest ecology and management, hydrology, social sciences), 11 topics were ranked as having the most potential impact and being most time-sensitive to address. We also calculated the median value of the summarized rankings independently for the three themes of forest ecology and management, hydrology, and social sciences. This resulted in the same 11 topics being identified as having the most potential impact and being most time-sensitive as above, with one additional topic being included under the hydrology theme, for a total of 12 topics. We review these 12 topics in the results below and include summaries for the full list of 21 topics that emerged from the in-person discussions in the Supplementary Material 1.

3 Results

The 12 topics and guiding questions that were scored as having the most potential impact and being the most time-sensitive to address for post-wildfire forest restoration and recovery are presented under the broader themes of social sciences (five topics), forest ecology and management (four topics), and hydrology (three topics) (Table 1). The research needed to address any single topic may span disciplinary boundaries and addressing all themes and topics is needed to foster more resilient ecosystems and communities after fire (Figure 2).

3.1 Social science topics

3.1.1 Institutional coordination

Institutional coordination in wildfire response and recovery in the United States 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 United States agencies and governance levels (Cheng et al., 2015), 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), and programs operating in isolation due to hyper-specific focuses, for example, the United States Natural Resources Conservation Service's watershed focus versus the United States 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 in the United States and guide integration efforts moving forward. In

TABLE 1 Priority topics and guiding questions for advancing research on post-wildfire forest restoration and recovery in the western United States, grouped by overarching themes.

Social science topics
Institutional coordination: what formal and informal institutional structures and approaches are necessary to better integrate the response to wildfires and post-fire impacts across scale?
Collaborative governance: what types of collaborative governance structures and approaches can be developed to better prepare for wildfire recovery?
Pre-fire planning: how can pre-fire planning processes include post-fire preparation and lead to better post-fire recovery outcomes?
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?
Workforce development: how do we develop and maintain a restoration workforce?
Forest ecology and management topics
Seed and seedlings: what strategies can be applied that lead to greater seedling survival, establishment, and growth in the field?
Outplanting strategies: how do we optimize site selection and spatial patterns of outplantings to maintain/enhance ecosystem services in post-fire landscapes?
Prioritizing post-fire forest recovery trajectories: when, where, and how should we accept forest conversion, support natural regeneration, and/or intentionally perform reforestation?
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?
Hydrology topics
Soil erosion mitigation: what pre- and post-fire management actions are most effective to mitigate soil loss and water turbidity post-fire?
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?
Post-fire water quantity and quality trajectory: what factors explain the post-fire trajectories of snowpack dynamics, water quantity, and water quality through time?

particular, examining the outcomes of recently established cross-institutional coordination efforts would provide insights into best practices and contribute to our understanding of potential 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 severe.

3.1.2 Collaborative governance

Recent papers highlight significant gaps in our understanding of how to develop 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 desired social and ecological post-wildfire recovery outcomes 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.

3.1.3 Pre-fire planning

Current wildfire planning in the United States 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 the United 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, 2025). 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 (see section "3.1.1 Institutional coordination" above), each bearing only partial responsibility for recovery efforts.

Community wildfire planning is not federally required in the United States, 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

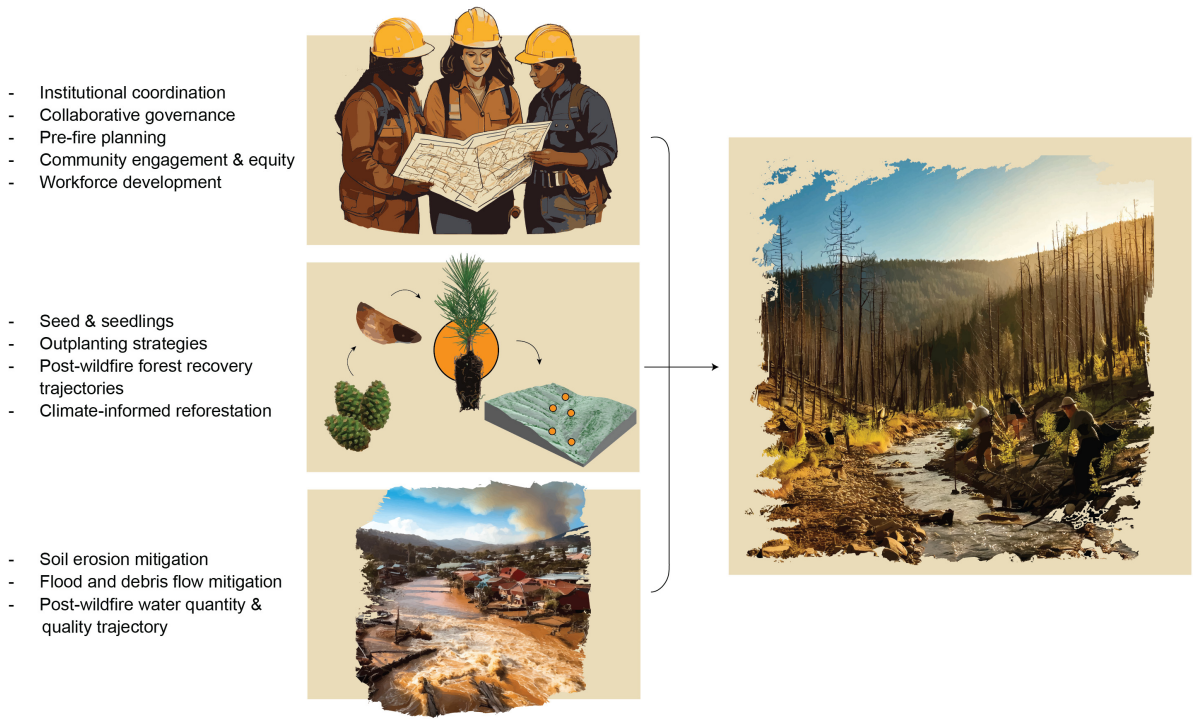

FIGURE 2
Summary of themes and topics identified as key priorities for research in order to advance post-wildfire forest restoration and recovery.

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 United States 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 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.

3.1.4 Community engagement and equity

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 United States. 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 severity, 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 United States federal post-fire processes (Ryan and Hamin, 2008; Edgeley, 2023). These outcomes are particularly significant as United States 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., 2023; 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.

3.1.5 Workforce development

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 United States. 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 United States (Dobrowski et al., 2024). Wildland firefighters, who constitute a significant portion of the restoration workforce at the federal level in the United States, 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 United States 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, 2025), 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 programs that can be sustained over time. 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 United States (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.

3.2 Forest ecology and management topics

3.2.1 Seed and seedlings – components of the reforestation pipeline

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 testing 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 under future climate scenarios.

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 outplanting strategies (discussed in see section "3.2.2 Outplanting strategies – components of the reforestation pipeline").

3.2.2 Outplanting strategies – components of the reforestation pipeline

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 United States 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 United States on public lands. 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 on all landownerships. 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. The ideal timing would be after hillslope stabilization but before areas have converted to shrub or grasslands and water and nutrient availability for planted seedlings is reduced (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 planting for seedling survival in the most critical locations (North et al., 2019; White and Long, 2019; Stevens et al., 2021).

3.2.3 Prioritizing post-fire trajectories

As ecosystem conversion becomes an ever-growing concern across burned areas of western United States 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, or alternatively, when vegetation type conversion should be accepted. On United States public lands, United States Forest Service policy mandates reforestation on all managed hectares 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 United States after fire (Ouzts et al., 2015; Rodman et al., 2024; Sorenson et al., 2025).

Public and private land managers would greatly benefit from science-based decision-making frameworks focused on specific forest types and/or for specific regions, especially if they are able to account for future moisture and temperature regimes. 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 years) 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.

3.2.4 Species and population sources for climate-informed reforestation

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 United States will experience higher rates of planting failure (e.g., Koehn et al., 2022) leading to 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 (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 (Clair et al., 2020; Sáenz-Romero et al., 2021; Looney et al., 2024).

Typically, seed collection is either conducted 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 the United States (Wilhelmi et al., 2017). In either wild seed collection or seed orchards, genetic variability in seed, and subsequently outplanted trees, is often inadequately recorded. Thus, improved identification of the commercial and non-commercial 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).

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 United States.

3.3 Hydrology topics

3.3.1 Soil erosion mitigation

Agricultural and residential water use in the western United States 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-García 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., 2021), 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-García 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.

3.3.2 Flood and debris flow mitigation

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 a 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 remote-sensing linked predictive models of post-fire hydrological event hazards like debris flow and land movement. This knowledge would allow areas that are located in the path of post-fire hydrological hazards advanced warning to evacuate before severe damages occur and allow agencies to prioritize pre- and post-fire interventions that provide the greatest benefit in reducing post-fire flood and debris flow risks. Furthermore, this understanding would enable better long-term land use planning for fire-prone areas, such as avoiding rebuilding in less stable sites.

3.3.3 Post-fire water quantity and quality trajectory

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 6 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 long wave 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.

4 Discussion and conclusion

Developing a proactive and transformative response to the wildfire crisis facing the western United States is necessary to ensure that ecosystems, ecosystem services, and the people affected by wildfire can recover and become more resilient to future events. This horizon scan lays out a systems-based research agenda to help address critical knowledge gaps that currently limit the equity, effectiveness, and efficiency of post-wildfire forest restoration and recovery. Decision makers and researchers in different parts of the western United States can now work together to decide which gaps need to be addressed for their specific area, how to address them, and ensure the social benefits outweigh the costs. Overall, embedding the research agenda identified by this horizon scan into policy and practice requires public engagement, political will, and funding. While United States federal research funding has historically provided many of the resources to advance wildfire science, there is increasing need to diversify funding sources. This could mean seeking more local and state funding, drawing on philanthropic sources, or developing more public-private partnerships. The latter has recently been engaged in pre-wildfire mitigation funding (e.g., Clavet et al., 2021), and similar arguments can be made for private investment in post-fire recovery and response. Below we briefly summarize how the 12 topics identified in this scan are reflected in the peer-reviewed wildfire science research.

Five priority topics were identified by this scan under the theme of social sciences. Several reviews of the wildfire research have identified substantial gaps in knowledge on the social, cultural, and economic dimensions of wildfire (McCaffrey et al., 2013; Thomas et al., 2022). The horizon scan topic of institutional coordination reflects the need to create organizational and financial structures across scales to align post-fire coordination; how to achieve this type of coordination across United States federal, state, and local agencies, especially with fluctuating budgets and leadership, remains a key research gap before, during, and after fire (Fleming et al., 2015; Davis et al., 2021). In addition to agency coordination, the horizon scan identified the need to increase collaboration with Tribal governments and non-government entities, such as community groups and non-governmental organizations, to address post-fire recovery. While collaborative governance models are an active area of research in the social sciences, many gaps remain in understanding how and when these models are effective (Carr Kelman et al., 2023), and in applying these lessons to governing wildfire-prone landscapes (Miller et al., 2022; Kirschner et al., 2023). The need to invest in pre-fire planning for wildfire response was also a priority topic identified in this scan. There is a lack of research on how land use planning can more effectively be used across diverse communities to prepare and respond to wildfire events (Mockrin et al., 2020).

The horizon scan topic of community engagement and equity reflects the need to engage and empower all types of communities to address post-fire recovery, pointing to a need to better understand what actions reduce barriers to engagement and how community values can be reflected in larger recovery processes (Ryan and Hamin, 2008; Burnett and Edgeley, 2023; Baker et al., 2024). This need is identified by a handful of other wildfire studies that highlight the need to integrate traditional, local, and Indigenous knowledge and perspectives into post-fire management (Thomas et al., 2022; Sousa et al., 2022). The horizon scan topic of workforce development is one recognized as a critical barrier in recent work on capacity-related gaps specific to post-wildfire reforestation in the western United States (Dobrowski et al., 2024). There are immediate actions that can be used to grow the restoration workforce such as increased wages, training opportunities, and flexible contract agreements. However, there are also key research questions about how to recruit and retain diverse populations into this workforce, from the boots-on-the-ground to research and management positions (Sharik et al., 2015; Haynes and Jacobson, 2015).

A growing number of empirical studies have shown that some forested landscapes are not regenerating after extreme wildfire events in the western United States, and in some cases, are converting to new ecosystem types (Haffey et al., 2018; Davis et al., 2020; Guiterman et al., 2022; Falk et al., 2022). This has led to

a handful of reviews highlighting post-wildfire forest ecology and management needs similar to three topics identified in our horizon scan: seed and seedlings and outplanting strategies, which are part of the reforestation pipeline, and post-wildfire forest trajectories. Specifically, recent reviews have called for more investment in the entire reforestation pipeline (Fargione et al., 2021), including new approaches to outplanting (North et al., 2019), in order to improve post-wildfire tree survival, as well as science-based frameworks to guide decision making around post-fire forest trajectories that optimize efficiency and effectiveness of restoration (Stevens et al., 2021; Larson et al., 2022). This horizon scan identified research questions around each of these three topics where more ecosystem-specific studies would help fill knowledge gaps. In addition to these topics, the horizon scan identified a fourth topic specific to understanding how seed and population sources influence future forest resilience: climate-informed reforestation (Dumroese et al., 2022). This need is one that has gained recent attention in forest ecology and ecosystem-management sectors given changing climate conditions (Cooper and MacFarlane, 2023).

The protection of water resources in the United States by minimizing post-wildfire impacts on water supply is considered a key public health issue at the national level (Robinne et al., 2021). Maintaining reliable post-wildfire water delivery to the public requires investing in infrastructure and implementing appropriate pre- and post-wildfire management actions. This horizon scan identified gaps in knowledge on the effectiveness of soil erosion mitigation and flood and debris flow mitigation actions as priority topics to address. As highlighted in Gonçalves et al. (2025), advancing post-fire soil stabilization and restoration research requires investments in pre- and post-fire data in basins with different soil-hydrologic and ecosystem characteristics across diverse geographies, as well as integration of advanced modeling tools and earth observation data. While additional empirical studies are being conducted, it is important that current post-fire hydrological mitigation actions continue to be deployed because these actions are better than doing nothing, despite gaps in knowledge around their effectiveness (Girona-García et al., 2021). A third area of hydrological inquiry identified by this horizon scan was the need for long-term and place-based research on post-wildfire water quantity and quality trajectories. Addressing gaps in knowledge on post-wildfire hydrological trajectories can help guide systems-based restoration and recovery strategies (Wagenbrenner et al., 2021; Collar et al., 2024).

As with any expert-elicitation process, this horizon scan reflects the knowledge and perspectives of the people that participated (Wintle et al., 2020). To minimize participation bias, our core team was selected to represent different disciplinary backgrounds and provide balance between researcher and practitioner perspectives. We recognize, however, that we did not have representation from all disciplines. For example, including expertise in other wildfire-impacted areas, such as air quality or wildlife, may have led to other post-fire issues being identified. We also did not have representation across all stakeholder types. While our initial scan for topics reached 86 individuals with good distribution across government agencies and academic institutions in the contiguous western United States, Indigenous Nations and non-governmental organizations were less well-represented. We also did not have any experts representing corporate forestry interests and only one, large private landowner participated in our core team. Additionally, while our scan captured ideas from experts across the contiguous western United States, the southwestern United States was more heavily represented in those original survey responses and in our core team. This could have led to identification of issues with more relevance to the arid Intermountain West and to public lands, compared to some other parts of the western United States. Overall, the need for research on any one of the 12 topics identified in this scan, within the western United States or globally, and across different landownerships, will vary depending on the social and ecological conditions found at a particular site. However, in general, there is a dearth of research on post-wildfire forest restoration and recovery globally (Gonçalves et al., 2025). For this reason, it is logical to infer that many of these topics will be research priorities widely.

This is the first horizon scan identifying research needs and knowledge gaps in post-wildfire forest restoration and recovery in the western United States. It identifies 12 topics that, if addressed, would have a large impact on advancing post-wildfire forest restoration and recovery through improving the equity, effectiveness, and efficiency of post-wildfire management and response. Implementation of several of these topics also needs to be maintained, or scaled up, while these research gaps are being filled, in order to reduce the large social and economic costs that communities face as a result of catastrophic wildfire. For example, investments in workforce development, reforestation, soil stabilization, and institutional coordination are happening, and should continue, as new science is conducted to improve the effectiveness and efficiency of those actions. There were also 9 additional research topics identified by this horizon scan as being critical to advance post-fire restoration and recovery (Supplementary materials 1); while not ranked as highly as the 12 topics presented in this paper, these topics would also benefit from research attention. The 12 topics identified by this horizon scan as having the most potential impact and being the most time-sensitive to address reflect the importance of taking a social-ecological systems approach to addressing post-wildfire forest restoration and recovery. Advancing these topics will often require interdisciplinary and convergent approaches to fully account for diverse societal perspectives and the potential impacts on social and ecological outcomes.

Data availability statement

The original contributions presented in this study are included in this article/Supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

KJ: Writing – original draft, Writing – review and editing, Conceptualization, Investigation, Project administration. DC: Conceptualization, Investigation, Writing – original draft, Writing – review and editing. MMor: Conceptualization, Investigation, Writing – original draft, Writing – review and editing. CS-R: Conceptualization, Investigation, Writing – original draft, Writing – review and editing. DA: Investigation, Writing –

review and editing. OB: Investigation, Writing – original draft, Writing – review and editing. JC: Investigation, Writing – review and editing. MC: Investigation, Writing – review and editing. CE: Investigation, Writing – review and editing. DF: Investigation, Writing – original draft, Writing – review and editing. LH: Investigation, Writing – review and editing. CM: Investigation, Writing – review and editing. CS: Investigation, Writing – review and editing. LM: Investigation, Writing – review and editing. RM: Investigation, Writing – review and editing. MMon: Investigation, Writing – review and editing. JP: Investigation, Writing – review and editing. MP: Investigation, Writing – review and editing. JR: Investigation, Writing – review and editing. MR: Investigation, Writing – review and editing. KR: Investigation, Writing – review and editing. JT: Investigation, Writing – review and editing. LT: Investigation, Writing – review and editing. Nv: Investigation, Writing – review and editing. AW: Investigation, Writing – review and editing. WB: Writing – original draft. AL: Writing – original draft. AM: Writing – original draft. LR: Writing – original draft. GR: Writing – original draft. JW: Writing – original draft.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Generative AI statement

The authors declare that no Generative AI was used in the creation of this manuscript.

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Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/ffgc.2025.1595886/full#supplementary-material

References

Abrams, J. B., Knapp, M., Paveglio, T. B., Ellison, A., Moseley, C., Nielsen-Pincus, M., et al. (2015). Re-envisioning community-wildfire relations in the US West as adaptive governance. *Ecol. Soc.* 20:34. doi: 10.5751/ES-07848-200334

Adlam, C., Almendariz, D., Goode, R. W., Martinez, D. J., and Middleton, B. R. (2021). Keepers of the flame: Supporting the revitalization of indigenous cultural burning. *Soc. Nat. Resour.* 35, 575–590. doi: 10.1080/08941920.2021.2006385

Aitken, S. N., and Bemmels, J. B. (2016). Time to get moving: Assisted gene flow of forest trees. *Evol. Appl.* 9, 271–290. doi: 10.1111/eva.12293

Axelrod, D. I. (1958). Evolution of the madro-tertiary geoflora. *Botan. Rev.* 24:2570. doi: 10.1007/BF02872570

Baker, B., Dinh, Y., Foxfoot, I. R., Ortiz, E., Sells, A., and Anderson, S. E. (2024). Social inequity and wildfire response: Identifying gaps and interventions in Ventura County, California. *Fire* 7:41. doi: 10.3390/fire7020041

Barnard, D. M., Green, T. R., Mankin, K. R., DeJonge, K. C., Rhoades, C. C., Kampf, S. K., et al. (2023). Wildfire and climate change amplify knowledge gaps linking mountain source-water systems and agricultural water supply in the western United States. *Agric. Water Manag.* 286:108377. doi: 10.1016/j.agwat.2023.108377

Barrett, K. (2018). *The full community costs of wildfire*. Bozeman, MT: Headwaters Economics, 50.

Biederman, J. A., Robles, M. D., Scott, R. L., and Knowles, J. F. (2022). Streamflow response to wildfire differs with season and elevation in adjacent headwaters of the Lower Colorado River Basin. *Water Resour. Res.* 58:e2021WR030687. doi: 10.1029/2021WR030687

Braziunas, K. H., Kiel, N. G., and Turner, M. G. (2023). Less fuel for the next fire? Short—interval fire delays forest recovery and interacting drivers amplify effects. *Ecology* 104:e4042. doi: 10.1002/ecy.4042

Buettner, W., and Schultz, C. (2025). Governing across jurisdictions in post-wildfire response and recovery: An analysis of the 2022 Hermit's Peak Calf Canyon Wildfire. *J. Environ. Manag.* 38:125272. doi: 10.2139/ssrn.4985328

Burned Area Learning Network, (2018). Examining federal policies that guide and constrain burned area emergency response policy on federal, state and private lands. 4. Available online at: https://www.conservationgateway.org/

ConservationPractices/FireLandscapes/FireLearningNetwork/USFLNPublications/Documents/134-NotesFromTheField-BALN-BAER.pdf (accessed February 15, 2025).

Burnett, J. T., and Edgeley, C. M. (2023). Factors influencing flood risk mitigation after wildfire: Insights for individual and collective action after the 2010 Schultz Fire. *Int. J. Disaster Risk Reduct.* 94:103791. doi: 10.1016/j.ijdrr.2023.103791

Carney, C. P., Schultz, C. A., and Greiner, M. S. (2025). Complexities in post-wildfire governance: Lessons from Colorado's 2020 wildfires. *Fire Ecol.* 21:4. doi: 10.1186/s42408-024-00344-1

Carr Kelman, C., Brady, U., Raschke, B. A., and Schoon, M. L. (2023). A systematic review of key factors of effective collaborative governance of social-ecological systems. *Soc. Nat. Resour.* 36, 1452–1470. doi: 10.1080/08941920.2023.2228234

Chazdon, R. L., Falk, D. A., Banin, L. F., Wagner, M., Wilson, S. J., Grabowski, R. C., et al. (2021). The intervention continuum in restoration ecology: Rethinking the active-passive dichotomy. *Restor. Ecol.* 32:e13535. doi: 10.1111/rec.13535

Cheney, A., Jones, K., Stevens-Rumann, C., and Salerno, J. (2024). Perceived changes in social-ecological resilience in fire-prone ecosystems in Colorado. *Ecol. Soc.* 29:405. doi: 10.5751/ES-15436-290405

Cheng, T., Ekarius, C., and Gibbs, D. (2015). *Innovations in forestry and fire mitigation: A Report on Colorado solutions for senator Michael Bennet*. Available online at: https://www.sanjuancitizens.org/wp-content/uploads/2015/06/Fire-Forest-Outcomes-Report.pdf (accessed February 15, 2025).

Clair, J. B., Howe, G. T., and Kling, J. G. (2020). The 1912 douglas-fir heredity study: Long-term effects of climatic transfer distance on growth and survival. *J. For.* 118:fvz064. doi: 10.1093/jofore/fvz064

Clavet, C., Topik, C., Harrell, M., Homes, P., Healy, R., and Wear, D. (2021). *Wildfire resilience funding: Building blocks for a paradigm shift*. Arlington, VA: The Nature Conservancy.

Colavito, M., Edgeley, C., and vonHedemann, N. (2023). *Public experiences with wildfire and flooding: A case study of the 2019 museum fire near Flagstaff, Arizona*. Flagstaff, AZ: Ecological Restoration Institute, Northern Arizona University.

Collar, N. M., and Earles, T. A. (2023). Unique challenges posed by fire disturbance to water supply management and transfer agreements in a headwaters region. *J. Environ. Manag.* 339:7956. doi: 10.1016/j.jenvman.2023.117956

Collar, N. M., Moody, J. A., and Ebel, B. A. (2024). Rainfall as a driver of post-wildfire flooding and debris flows: A review and synthesis. *Earth Sci. Rev.* 260:104990. doi: 10.1016/j.earscirev.2024.104990

Coop, J. D., Parks, S. A., Stevens-Rumann, C. S., Crausbay, S. D., Higuera, P. E., Hurteau, M. D., et al. (2020). Wildfire-driven forest conversion in western North American landscapes. *BioScience* 70, 659–673. doi: 10.1093/biosci/biaa061

Cooper, L., and MacFarlane, D. (2023). Climate-smart forestry: Promise and risks for forests, society, and climate. *PLoS Clim.* 2:e0000212. doi: 10.1371/journal.pclm.0000212

Crockett, J. L., and Hurteau, M. D. (2024). Ability of seedlings to survive heat and drought portends future demographic challenges for five southwestern US conifers. (2024). *Tree Physiol.* 44:tad136. doi: 10.1093/treephys/tpad136

Crowley, C., Miller, A., Richardson, R., and Malcom, J. (2023). *Increasing damages from wildfires warrant investment in Wildland fire management*. Washington, DC: United States Department of the Interior.

Cunningham, C. X., Williamson, G. J., and Bowman, D. M. J. S. (2024). Increasing frequency and intensity of the most extreme wildfires on Earth. *Nat. Ecol. Evol.* 8, 1420–1425. doi: 10.1038/s41559-024-02452-2

Davies, I. P., Haugo, R. D., Robertson, J. C., and Levin, P. S. (2018). The unequal vulnerability of communities of color to wildfire. *PLoS One* 13:e0205825. doi: 10.1371/journal.pone.0205825

Davis, E. J., Huber-Stearns, H., Caggiano, M., McAvoy, D., Cheng, A. S., Deak, A., et al. (2022). Managed wildfire: A strategy facilitated by civil society partnerships and interagency cooperation. *Soc. Nat. Resourc.* 35, 914–932. doi: 10.1080/08941920.2022.2092803

Davis, E. J., Huber-Stearns, H., Cheng, A. S., and Jacobson, M. (2021). Transcending parallel play: Boundary spanning for collective action in wildfire management. *Fire* 4:41. doi: 10.3390/fire4030041

Davis, K. T., Higuera, P. E., Dobrowski, S. Z., Parks, S. A., Abatzoglou, J. T., Rother, et al. (2020). Fire-catalyzed vegetation shifts in ponderosa pine and Douglas-fir forests of the western United States. *Environ. Res. Lett.* 15:1040b8. doi: 10.1088/1748-9326/abb9df

Davis, K. T., Robles, M. D., Kemp, K. B., Higuera, P. E., Chapman, T., Metlen, K. L., et al. (2023). Reduced fire severity offers near-term buffer to climate-driven declines in conifer resilience across the western United States. *Proc. Natl. Acad. Sci. U.S.A.* 120:e2208120120. doi: 10.1073/pnas.2208120120

Davis, K. T., Wynecoop, M., Rozance, M. A., Swensen, K. B., Lyons, D. S., Dohrn, C., et al. (2024). Centering socioecological connections to collaboratively manage post-fire vegetation shifts. *Front. Ecol. Environ.* 22:e2739. doi: 10.1002/fee.2739

Dietz, S., Beazley, K. F., Lemieux, C. J., St Clair, C., Coristine, L., Higgs, E., et al. (2021). Emerging issues for protected and conserved areas in Canada. *Facets* 6, 1892–1921. doi: 10.1139/facets-2021-0072

Dobrowski, S. Z., Aghai, M. M., Chichilnisky, Du Lac, A., Downer, R., Fargione, J., et al. (2024). 'Mind the Gap'—reforestation needs vs. reforestation capacity in the western United States. *Front. Forests Glob. Change* 7:1402124. doi: 10.3389/ffgc.2024.1402124

Dumroese, R., Kasten, J. A., Balachowski, D. F., and Horning, M. E. (2022). "Reforestation to mitigate changes to climate: More than just planting seedlings," in *Proceedings of the 15th world forestry congress: Building a green, healthy, and resilient future with forests, food and agriculture organization of the United Nations, Korean forest service*, (Daejeon), 7.

Edgeley, C. M. (2022). Exploring the social legacy of frequent wildfires: Organizational responses for community recovery following the 2018 Camp Fire. *Int. J. Disaster Risk Reduct.* 70:102772. doi: 10.1016/j.ijdrr.2021.102772

Edgeley, C. M. (2023). Social science to advance wildfire adaptation in the southwestern United States: A review and future research directions. *Int. J. Wildland Fire* 32:3102. doi: 10.1071/WF23102

Edgeley, C. M., and Colavito, M. M. (2022). Characterizing divergent experiences with the same wildfire: Insights from a survey of households in evacuation, postfire flood risk, and unaffected areas after the 2019 Museum Fire. *J. For.* 120, 660–675. doi: 10.1093/jofore/fvac018

Edgeley, C. M., Colavito, M. M., vonHedemann, N., and Burnett, J. T. (2024). Voluntary uptake of flood insurance in post-fire landscapes: Insights from household surveys after two wildfires in northern Arizona. *Environ. Res. Commun.* 6:061006. doi: 10.1088/2515-7620/ad5647

Evans, A. (2017). *State of the knowledge about post-fire response. Burned area learning network*. 21. Available online at: http://www.conservationgateway.org/ConservationPractices/FireLandscapes/FireLearningNetwork/NetworkProducts/Pages/BALN-StateKnowledgePostFireResources.aspx (accessed February 15, 2025).

Falk, D. A., Mantgem, P. J. V., Keeley, J., Gregg, R. M., Guiterman, C. H., Tepley, A. J., et al. (2022). Tamm review: Mechanisms of forest resilience. *For. Ecol. Manag.* 512:120129. doi: 10.1016/j.foreco.2022.120129

Fargione, J., Haase, D. L., Burney, O. T., Kildisheva, O. A., Edge, G., Cook-Patton, S. C., et al. (2021). Challenges to the reforestation pipeline in the United States. *Front. For. Glob. Change* 4:629198. doi: 10.3389/ffgc.2021.629198

Ferreira, R., Davidson, T., Buttell, F., Contillo C. M., Leddie, C., Leahy, C., et al. (2024). Barriers to equitable disaster recovery: A scoping literature review. *Int. J. Disaster Risk Reduct.* 110:4628. doi: 10.1016/j.ijdrr.2024.104628

Finn, D., Mandli, K., Bukvi, A., Davis, C. A., Haacker, R., Morss, R. E., et al. (2022). Moving from interdisciplinary to convergent research across geoscience and social sciences: Challenges and strategies. *Environ. Res. Lett.* 17:061002. doi: 10.1088/1748-9326/ac7409

Fleming, C. J., McCartha, E. B., and Steelman, T. A. (2015). Conflict and collaboration in wildfire management: The role of mission alignment. *Public Admin. Rev.* 75, 445–454. doi: 10.1111/puar.12353

Gannon, B. M., Wei, Y., Thompson, M. P., Scott, J. H., and Short, K. C. (2022). System analysis of wildfire–water supply risk in Colorado, USA with monte carlo wildfire and rainfall simulation. *Risk Analysis* 42, 406–424. doi: 10.1111/risa.13762

Giovando, J., and Niemann, J. D. (2022). Wildfire impacts on snowpack phenology in a changing climate within the Western U.S. *Water Resour. Res.* 58:1569. doi: 10.1029/2021WR031569

Girona-García, A., Vieira, D. C. S., Silva, J., Fernández, C., Robichaud, P. R., and Keizer, J. J. (2021). Effectiveness of post-fire soil erosion mitigation treatments: A systematic review and meta-analysis. *Earth Sci. Rev.* 217:103611. doi: 10.1016/j.earscirev.2021.103611

Goeking, S. A., and Tarboton, D. G. (2020). Forests and water yield: A synthesis of disturbance effects on streamflow and snowpack in western coniferous forests. *J. For.* 118:fvz069. doi: 10.1093/jofore/fvz069

Gonçalves, J., Portela, A. P., Regos, A., Sil, Â, Marcos, B., Alonso, J., et al. (2025). Fostering post-fire research towards a more balanced wildfire science agenda to navigate global environmental change. *Fire* 8:51. doi: 10.3390/fire8020051

Guiterman, C. H., Gregg, R. M., Marshall, L. A. E., Beckmann, J. J., Mantgem, P. J. V., Falk, D. A., et al. (2022). Vegetation type conversion in the US Southwest: Frontline observations and management responses. *Fire Ecol.* 18:6. doi: 10.1186/s42408-022-00131-w

Haffey, C., Sisk, T. D., Allen, C. D., Thode, A. E., and Margolis, E. Q. (2018). Limits to ponderosa pine regeneration following large high-severity forest fires in the United States Southwest. *Fire Ecol.* 14, 143–163. doi: 10.4996/fireecology.1401143163

Haghani, M., Kuligowski, E., Rajabifard, A., and Kolden, C. A. (2022). The state of wildfire and bushfire science: Temporal trends, research divisions and knowledge gaps. *Saf. Sci.* 153:105797. doi: 10.1016/j.ssci.2022.105797

Hallema, D. W., Sun, G., Caldwell, P. V., Norman, S. P., Cohen, E. C., Liu, Y., et al. (2018). Burned forests impact water supplies. *Nat. Commun.* 9:1307. doi: 10.1038/s41467-018-03735-6

Hammond, W. M., Williams, A. P., Abatzoglou, J. T., Adams, H. D., Klein, T., López, R., et al. (2022). Global field observations of tree die-off reveal hotter-drought fingerprint for Earth's forests. *Nat. Commun.* 13:1761. doi: 10.1038/s41467-022-29289-2

Haynes, N. A., and Jacobson, S. (2015). Barriers and perceptions of natural resource careers by minority students. *J. Environ. Educ.* 46, 166–182. doi: 10.1080/00958964.2015.1011595

Hjerpe, E. E., Colavito, M. M., Edgeley, C. M., Burnett, J. T., Combrink, T., Vosick, D., et al. (2023). Measuring the long-term costs of uncharacteristic wildfire: A case study of the 2010 Schultz Fire in Northern Arizona. *Int. J. Wildland Fire.* 32, 1474–1486. doi: 10.1071/WF23036

Hjerpe, E. E., Colavito, M. M., Waltz, A. E. M., and Meador, A. S. (2024). Return on investments in restoration and fuel treatments in frequent-fire forests of the American west: A meta-analysis. *Ecol. Econ.* 223:108244. doi: 10.1016/j.ecolecon.2024.108244

Holterman, D., Wright, P., and Jacob, A. (2023). Advancing evidence-based decision-making in large landscape conservation through the social sciences: A research agenda for the Yellowstone to Yukon Region. *Mt. Res. Dev.* 43:8. doi: 10.1659/mrd.2023.00008

Houston, D., Pérez Figueroa, O., Jong-Levinger, A., Schubert, J. E., and Sanders, B. F. (2024). Spatial optimism and cross-over effects in the perceptions of interconnected wildfire, flood, and mudslide hazards. *Environ. Behav.* 56, 19–58. doi: 10.1177/00139165241275482

Huayhuaca, C., Brown, H., and Sanderson, J. (2023). *Collaborative readiness: Preparing landscapes and communities to receive and recover from wildfire.* Flagstaff, AZ: Southwest Ecological Restoration Institutes.

Jones, K. W., Gannon, B., Timberlake, T., Chamberlain, J. L., and Wolk, B. (2022). Societal benefits from wildfire mitigation activities through payments for watershed services: Insights from Colorado. *Forest Policy Econ.* 135:102661. doi: 10.1016/j.forpol.2021.102661

Kirschner, J. A., Clark, J., and Boustras, G. (2023). Governing wildfires: Toward a systematic analytical framework. *Ecol. Soc.* 28:6. doi: 10.5751/ES-13920-280206

Koehn, C. R., Petrie, M. D., and Hubbard, R. M. (2022). Not only severe events: Moderate dry periods impact the hydraulic functioning and survival of planted ponderosa pine seedlings. *Forests* 13:370. doi: 10.3390/f13030370

Kreider, M. R., Higuera, P. E., Parks, S. A., Rice, W. L., White, N., and Larson, A. J. (2024). Fire suppression makes wildfires more severe and accentuates impacts of climate change and fuel accumulation. *Nat. Commun.* 15:2412. doi: 10.1038/s41467-024-46702-0

Lake, F. K., Wright, V., Morgan, P., McFadzen, M., McWethy, D., and Stevens-Rumann, C. (2017). Returning fire to the land: Celebrating traditional knowledge and fire. *J. For.* 115, 343–353. doi: 10.5849/jof.2016-043R2

Lalor, A. R., Law, D. J., Breshears, D. D., Falk, D. A., Field, J. P., Loehman, R. A., et al. (2023). Mortality thresholds of juvenile trees to drought and Heatwaves: Implications for forest regeneration across a landscape gradient. *Front. For. Glob. Change* 6:8159. doi: 10.3389/ffgc.2023.1198156

Lambrou, N., Kolden, C., Loukaitou-Sideris, A., Anjum, E., and Acey, C. (2023). Social drivers of vulnerability to wildfire disasters: A review of the literature. *Landsc. Urban Plann.* 237:104797. doi: 10.1016/j.landurbplan.2023.104797

Larson, A. J., Jeronimo, S. M. A., Hessburg, P. F., Lutz, J. A., Povak, N. A., Cansler, C. A., et al. (2022). Tamm Review: Ecological principles to guide post-fire forest landscape management in the Inland Pacific and Northern Rocky Mountain regions. *For. Ecol. Manag.* 504:119680. doi: 10.1016/j.foreco.2021.119680

Laughlin, D. C., Fulé, P. Z., Huffman, D. W., Crouse, J., and Laliberté, E. (2011). Climatic constraints on trait—based forest assembly. *J. Ecol.* 99, 1489–1499. doi: 10.1111/j.1365-2745.2011.01885.x

Liu, N., Caldwell, P. V., Dobbs, G. R., Miniat, C. F., Bolstad, P. V., Nelson, S. A. C., et al. (2021). Forested lands dominate drinking water supply in the conterminous United States. *Environ. Res. Lett.* 16, 084008. doi: 10.1088/1748-9326/ac09b0

Löfqvist, S., Kleinschroth, F., Bey, A., De Bremond, A., DeFries, R., Dong, J., et al. (2023). How social considerations improve the equity and effectiveness of ecosystem restoration. *BioScience* 73, 134–148. doi: 10.1093/biosci/biac099

Long, J. W., Lake, F. K., and Goode, R. W. (2021). The importance of Indigenous cultural burning in forested regions of the Pacific West, USA. *Forest Ecol. Manag.* 500:119597. doi: 10.1016/j.foreco.2021.119597

Looney, C. E., Stewart, J. A. E., and Wood, K. E. A. (2024). Mixed-provenance plantings and climatic transfer-distance affect the early growth of knobcone-monterey hybrid pine, a fire-resilient alternative for reforestation. *N. Forests* 55, 543–565. doi: 10.1007/s11056-023-09991-9

Lopes, A. R., Girona—García, A., Corticeiro, S., Martins, R., Keizer, J. J., and Vieira, D. C. S. (2021). What is wrong with post—fire soil erosion modelling? A meta—analysis on current approaches, research gaps, and future directions. *Earth Surf. Process. Landforms* 46, 205–219. doi: 10.1002/esp.5020

Lopez, M., Margolis, E., Tillery, A., Bassett, S., and Hook, A. (2024). Pre-fire assessment of post-fire debris-flow hazards in the Santa Fe Municipal Watershed. *Int. J. Wildland Fire* 33:3065. doi: 10.1071/WF23065

Marsh, C., Blankinship, J. C., and Hurteau, M. D. (2023). Effects of nurse shrubs and biochar on planted conifer seedling survival and growth in a high-severity burn patch in New Mexico, USA. *For. Ecol. Manag.* 537:120971. doi: 10.1016/j.foreco.2023.120971

Marsh, C., Crockett, J. L., Krofcheck, D. J., Keyser, A. R., Allen, C. D., Litvak, M. E., et al. (2022a). Planted seedling survival in a post-wildfire landscape: From experimental planting to predictive probabilistic surfaces. *For. Ecol. Manag.* 525:120524. doi: 10.1016/j.foreco.2022.120524

Marsh, C., Krofcheck, D., and Hurteau, M. D. (2022b). Identifying microclimate tree seedling refugia in post-wildfire landscapes. *Agric. For. Meteorol.* 313:108741. doi: 10.1016/j.agrformet.2021.108741

Marshall, L. A. E., Fornwalt, P. J., Stevens-Rumann, C. S., Rodman, K. C., Rhoades, C. C., Zimlinghaus, et al. (2023). North-facing aspects, shade objects, and microtopographic depressions promote the survival and growth of tree seedlings planted after wildfire. *Fire Ecol.* 19:26. doi: 10.1186/s42408-023-00181-8

Marshall, L. A., Fornwalt, P. J., Stevens-Rumann, C. S., Rodman, K. C., Chapman, T. B., Schloegel, C. A., et al. (2024). What influences planted tree seedling survival in burned Colorado montane forests? *For. Ecol. Manag.* 572:122321. doi: 10.1016/j.foreco.2024.122321

McCaffrey, S., Towan, E., Stidham, M., and Shindler, B. (2013). Social science research related to wildfire management: An overview of recent findings and future research needs. *Int. J. Wildland Fire* 22, 15–24. doi: 10.1071/WF11115

McWethy, D. B., Schoennagel, T., Higuera, P. E., Krawchuk, M., Harvey, B. J., Metcalf, E. C., et al. (2019). Rethinking resilience to wildfire. *Nat. Sustain.* 2, 797–804. doi: 10.1038/s41893-019-0353-8

Miller, B. A., Yung, L., Wyborn, C., Essen, M., Gray, B., and Williams, D. R. (2022). Re-Envisioning wildland fire governance: Addressing the transboundary, uncertain, and contested aspects of wildfire. *Fire* 5:49. doi: 10.3390/fire5020049

Mockrin, M. H., Fishler, H. K., and Stewart, S. I. (2020). After the fire: Perceptions of land use planning to reduce wildfire risk in eight communities across the United States. *Int. J. Disaster Risk Reduct.* 45:101444. doi: 10.1016/j.ijdrr.2019.101444

Moloney, K., Vickery, J., Hess, J., and Errett, N. (2023). After the fire: A qualitative study of the role of long-term recovery organizations in addressing rural communities' post-wildfire needs. *Environ. Res. Health* 1:021009. doi: 10.1088/2752-5309/acd2f7

Moran, E. V., DeSilva, R., Canning, C., and Wright, J. W. (2024). Testing source elevation versus genotype as predictors of sugar pine performance in a post—fire restoration planting. *Ecosphere* 15:e70010. doi: 10.1002/ecs2.70010

Morgan, M., Lin, Y., Walsh-Dilley, M., Webster, A., Stone, A., Chief, K., et al. (2025). Convergence, transdisciplinarity, and team science: An interepistemic approach. *Ecol. Soc.* 30:art3. doi: 10.5751/ES-15492-300103

Morgan, M., Webster, A., Piccarello, M., Jones, K., Chermak, J., McCarthy, L., et al. (2023). Adaptive governance strategies to address wildfire and watershed resilience in New Mexico's upper Rio Grande watershed. *Front. Clim.* 5:1062320. doi: 10.3389/fclim.2023.1062320

Mueller, J. M., Swaffar, W., Nielsen, E. A., Springer, A. E., and Lopez, S. M. (2013). Estimating the value of watershed services following forest restoration. *Water Resour. Res.* 49, 1773–1781. doi: 10.1002/wrcr.20163

Mukherjee, N., Huge, J., Sutherland, W. J., McNeill, J., Van Opstal, M., Dahdouh—Guebas, F., et al. (2015). The Delphi technique in ecology and biological conservation: Applications and guidelines. *Methods Ecol. Evol.* 6, 1097–1109. doi: 10.1111/2041-210X.12387

Niemeyer, R. J., Bladon, K. D., and Woodsmith, R. D. (2020). Long—term hydrologic recovery after wildfire and post—fire forest management in the interior Pacific Northwest. *Hydrol. Process.* 34, 1182–1197. doi: 10.1002/hyp.13665

North, M. C., Stevens, J. T., Greene, D. F., Coppoletta, M., Knapp, E. E., Latimer, A. M., et al. (2019). Tamm review: Reforestation for resilience in dry western U.S. forests. *Forest Ecol. Manag.* 432, 209–224. doi: 10.1016/j.foreco.2018.09.007

Ouzts, J., Kolb, T., Huffman, D., and Sánchez Meador, A. (2015). Post-fire ponderosa pine regeneration with and without planting in Arizona and New Mexico. *Forest Ecol. Manag.* 354, 281–290. doi: 10.1016/j.foreco.2015.06.001

Palik, B. J., Clark, P. W., D'Amato, A. W., Swanston, C., and Nagel, L. (2022). Operationalizing forest—assisted migration in the context of climate change adaptation: Examples from the eastern USA. *Ecosphere* 13:e4260. doi: 10.1002/ecs2.4260

Parks, S. A., and Abatzoglou, J. T. (2020). Warmer and drier fire seasons contribute to increases in area burned at high severity in western US forests from 1985 to 2017. *Geophys. Res. Lett.* 47:e2020GL089858. doi: 10.1029/2020GL089858

Parks, S. A., Guiterman, C. H., Margolis, E. Q., Lonerman, M., Whitman, E., Abatzaglou, J. T., et al. (2025). Widespread evidence of a North American fire deficit despite recent increased high severity wildfire. *Nat. Commun.* 16:1493. doi: 10.1038/s41467-025-56333-8

Parks, S. A., Holsinger, L. M., Panunto, M. H., Jolly, W. M., Dobrowski, S. Z., and Dillon, G. K. (2018). High-severity fire: Evaluating its key drivers and mapping its probability across western US forests. *Environ. Res. Lett.* 13:044037. doi: 10.1088/1748-9326/aab791

Paveglio, T., and Edgeley, C. (2017). Community diversity and hazard events: Understanding the evolution of local approaches to wildfire. *Nat. Hazards* 87, 1083–1108. doi: 10.1007/s11069-017-2810-x

Pechony, O., and Shindell, D. T. (2010). Driving forces of global wildfires over the past millennium and the forthcoming century. *Proc. Natl. Acad. Sci. U.S.A.* 107, 19167–19170. doi: 10.1073/pnas.1003669107

Peek, L., Tobin, J., Adams, R. M., Wu, H., and Mathews, M. C. (2020). A framework for convergence research in the hazards and disaster field: The natural hazards engineering research infrastructure CONVERGE facility. *Front. Built Environ.* 6:2020. doi: 10.3389/fbuil.2020.00110

Pinto, J. R., Marshall, J. D., Dumroese, R. K., Davis, A. S., and Cobos, D. R. (2012). Photosynthetic response, carbon isotopic composition, survival, and growth of three stock types under water stress enhanced by vegetative competition. *Can. J. Forest Res.* 42, 333–344. doi: 10.1139/x11-189

Pinto, J. R., Sloan, J. L., Ervan, G., and Burney, O. T. (2023). Physiological and morphological responses of Pinus ponderosa seedlings to moisture limitations in the nursery and their implications for restoration. *Front. Plant Sci.* 14:1127656. doi: 10.3389/fpls.2023.1127656

Rehfeldt, G. E., Jaquish, B. C., Sáenz-Romero, C., Joyce, D. G., Leites, L. P., St Clair, J. B., et al. (2014). Comparative genetic responses to climate in the varieties of *Pinus ponderosa* and *Pseudotsuga menziesii*: Reforestation. *For. Ecol. Manag.* 324, 138–146. doi: 10.1016/j.foreco.2014.02.041

Reis, W., McGrath, D., Elder, K., Kampf, S., and Rey, D. (2024). Quantifying aspect—dependent snowpack response to high—elevation wildfire in the southern rocky mountains. *Water Resour. Res.* 60:e2023WR036539. doi: 10.1029/2023WR036539

Rhoades, C. C., Nunes, J. P., Silins, U., and Doerr, S. H. (2019). The influence of wildfire on water quality and watershed processes: New insights and remaining challenges. *Int. J. Wildland Fire* 28, 721–725. doi: 10.1071/WFv28n10_FO

Robinne, F. N., Hallema, D. W., Bladon, K. D., and Buttle, J. M. (2020). Wildfire impacts on hydrologic ecosystem services in North American high-latitude forests: A scoping review. *J. Hydrol.* 581:124360. doi: 10.1016/j.jhydrol.2019.124360

Robinne, F. N., Hallema, D. W., Bladon, K. D., Flannigan, M. D., Boisramé, G., Bréthaut, C. M., et al. (2021). Scientists' warning on extreme wildfire risks to water supply. *Hydrol. Process.* 35:e14086. doi: 10.1002/hyp.14086

Rodman, K. C., Fornwalt, P. J., Holden, Z. A., Crouse, J. E., Davis, K. T., Marshall, L. A. E., et al. (2024). Green is the new black: Outcomes of post-fire tree planting across the US Interior West. *For. Ecol. Manag.* 574:122358. doi: 10.1016/j.foreco.2024.122358

Rodman, K. C., Veblen, T. T., Battaglia, M. A., Chambers, M. E., Fornwalt, P. J., Holden, Z. A., et al. (2020). A changing climate is snuffing out post—fire recovery in Montane forests. *Glob. Ecol. Biogeogr.* 29, 2039–2051. doi: 10.1111/geb.13174

Roos, C. I., Swetnam, T. W., Ferguson, T. J., Liebmann, M. J., Loehman, R. A., Welch, J. R., et al. (2021). Native American fire management at an ancient wildland–urban interface in the Southwest United States. *Proc. Natl. Acad. Sci. U.S.A.* 118:e2018733118. doi: 10.1073/pnas.2018733118

Ruhl, J. B., and Kundis Craig, R. (2021). 4° Celsius. *Minnesota Law Rev.* 106, 191–282. Available online at: https://www.eli.org/sites/default/files/files-pdf/4%20Degrees%20Celsius.pdf

Ryan, R. L., and Hamin, E. (2008). Wildfires, communities, and agencies: Stakeholders' perceptions of postfire forest restoration and rehabilitation. *J. For.* 106, 370–379. doi: 10.1093/jof/106.7.370

Sáenz-Romero, C., O'Neill, G., Aitken, S. N., and Lindig-Cisneros, R. (2021). Assisted migration field tests in Canada and Mexico: Lessons, limitations, and challenges. *Forests* 12:9. doi: 10.3390/f12010009

Schoennagel, T., Balch, J. K., Brenkert-Smith, H., Dennison, P. E., Harvey, B. J., Krawchuk, M. A., et al. (2017). Adapt to more wildfire in western North American forests as climate changes. *Proc. Natl. Acad. Sci. U.S.A.* 114, 4582–4590. doi: 10.1073/pnas.1617464114

Schumann, I., Mockrin, M., Syphard, A. D., Whittaker, J., Price, O., Gaither, C. J., et al. (2020). Wildfire recovery as a "hot moment" for creating fire-adapted communities. *Int. J. Disaster Risk Reduct.* 42:101354. doi: 10.1016/j.ijdrr.2019.101354

Seidl, R., and Turner, M. G. (2022). Post-disturbance reorganization of forest ecosystems in a changing world. *Proc. Natl. Acad. Sci. U.S.A.* 119:e2202190119. doi: 10.1073/pnas.2202190119

Sharik, T. L., Lilieholm, R. J., Lindquist, W., and Richardson, W. W. (2015). Undergraduate enrollment in natural resource programs in the United States: Trends, drivers, and implications for the future of natural resource professions. *J. For.* 113, 538–551. doi: 10.5849/jof.14-146

Sharma-Wallace, L., Velarde, S. J., and Wreford, A. (2018). Adaptive governance good practice: Show me the evidence! *J. Environ. Manag.* 222, 174–184. doi: 10.1016/j.jenvman.2018.05.067

Singleton, M. P., Thode, A. E., Sánchez Meador, A. J., and Iniguez, J. M. (2019). Increasing trends in high-severity fire in the southwestern USA from 1984 to 2015. *For. Ecol. Manag.* 433, 709–719. doi: 10.1016/j.foreco.2018.11.039

Sloan, J. L., Burney, O. T., and Pinto, J. R. (2020). Drought-conditioning of quaking aspen (*Populus tremuloides michx.*) seedlings during nursery production modifies seedling anatomy and physiology. *Front. Plant Sci.* 11:557894. doi: 10.3389/fpls.2020.557894

Smith, C. S., DeMattia, E. A., Albright, E., Bromberger, A. F., Hayward, O. G., Mackinson, I. J., et al. (2025). Beyond despair: Leveraging ecosystem restoration for psychosocial resilience. *Proc. Natl. Acad. Sci. U.S.A.* 122:e2307082121. doi: 10.1073/pnas.2307082121

Sorenson, Q. M., Young, D. J. N., and Latimer, A. M. (2025). Tree planting outcomes after severe wildfire depend on climate, competition, and priority. *For. Ecol. Manag.* 575:122346. doi: 10.1016/j.foreco.2024.122346

Sousa, J., Çinar, C., Carmo, M., and Malagoli, M. A. S. (2022). Social and historical dimensions of wildfire research and the consideration given to practical knowledge: A systematic review. *Nat Hazards* 114, 1103–1123. doi: 10.1007/s11069-022-05460-2

Staley, D. M., Kean, J. W., Cannon, S. H., Schmidt, K. M., and Laber, J. L. (2013). Objective definition of rainfall intensity–duration thresholds for the initiation of post-fire debris flows in southern California. *Landslides* 10, 547–562. doi: 10.1007/s10346-012-0341-9

Staley, D. M., Tillery, A. C., Kean, J. W., McGuire, L. A., Pauling, H. E., Rengers, F. K., et al. (2018). Estimating post-fire debris-flow hazards prior to wildfire using a statistical analysis of historical distributions of fire severity from remote sensing data. *Int. J. Wildland Fire* 27:595. doi: 10.1071/WF17122

Stephens, S. L., and Ruth, L. W. (2005). Federal forest—fire policy in the United States. *Ecol. Appl.* 15, 532–542. doi: 10.1890/04-0545

Stevens, J. T., Haffey, C. M., Coop, J. D., Fornwalt, P. J., Yocom, L., Allen, C. D., et al. (2021). Tamm review: Postfire landscape management in frequent-fire conifer forests of the southwestern United States. *For. Ecol. Manag.* 502:119678. doi: 10.1016/j.foreco.2021.119678

Stevens-Rumann, C. S., and Morgan, P. (2019). Tree regeneration following wildfires in the western US: A review. *Fire Ecol.* 15, 1–17. doi: 10.1186/s42408-019-0032-1

Sutherland, W. J., Bennett, C., Brotherton, P. N. M., Butterworth, H. M., Clout, M. N., and Côte, I. M. (2023). A global biological conservation horizon scan of issues for 2023. *Trends Ecol. Evol.* 38:5. doi: 10.1016/j.tree.2022.10.005

Sutherland, W. J., Fleishman, E., Mascia, M. B., Pretty, J., and Rudd, M. A. (2011). Methods for collaboratively identifying research priorities and emerging issues in science and policy. *Ecol. Evol.* 2, 238–247. doi: 10.1111/j.2041-210X.2010.00083.x

Svenning, J. C., and Sandel, B. (2013). Disequilibrium vegetation dynamics under future climate change. *A. J. Bot.* 100, 1266–1286. doi: 10.3732/ajb.1200469

Swain, D. L., Prein, A. F., Abatzoglou, J. T., Albano, C. M., Brunner, M., Diffenbaugh, N. S., et al. (2025). Hydroclimate volatility on a warming Earth. *Nat. Rev. Earth Environ.* 6:35050. doi: 10.1038/s43017-024-00624-z

Tague, C. L., Moritz, M., and Hanan, E. (2019). The changing water cycle: The eco-hydrologic impacts of forest density reduction in Mediterranean (seasonally dry) regions. *WIREs Water* 6:e1350. doi: 10.1002/wat2.1350

Tepley, A. J., Swanson, F. J., and Spies, T. A. (2014). Post—fire tree establishment and early cohort development in conifer forests of the western Cascades of Oregon, USA. *Ecosphere* 5, 1–23. doi: 10.1890/ES14-00112.1

Thomas, A. S., Escobedo, F. J., Sloggy, M. R., and Sánchez, J. J. (2022). A burning issue: Reviewing the socio-demographic and environmental justice aspects of the wildfire literature. *PLoS One* 17:e0271019. doi: 10.1371/journal.pone.0271019

Tom, E., Adams, M. M., and Goode, R. W. (2023). Solastalgia to Soliphilia: Cultural fire, climate change, and indigenous healing. *Ecopsychology* 15:85. doi: 10.1089/eco.2022.0085

Touma, D., Stevenson, S., Swain, D. L., Singh, D., Kalashnikov, D. A., and Huang, X. (2022). Climate change increases risk of extreme rainfall following wildfire in the western United States. *Sci. Adv.* 8:abm0320. doi: 10.1126/sciadv.abm0320

Triantafillou, S., and Wohl, E. (2024). Geomorphic characteristics influencing post-fire river response in mountain streams. *Geomorphology* 466:9446. doi: 10.1016/j.geomorph.2024.109446

Turner, M. G., Braziunas, K. H., Hansen, W. D., and Harvey, B. J. (2019). Short-interval severe fire erodes the resilience of subalpine lodgepole pine forests. *Proc. Natl. Acad. Sci. U.S.A.* 116, 11319–11328. doi: 10.1073/pnas.1902841116

USDA (2025). *Interagency post-fire integration council*. Washington, DC: USDA.

Vaughan, D., Edgeley, C., and Han, H. S. (2022). Forest contracting businesses in the US southwest: Current profile and workforce training needs. *J. For.* 120, 186–197. doi: 10.1093/jofore/fvab060

Wagenbrenner, J. W., Ebel, B. A., Bladon, K. D., and Kinoshita, A. M. (2021). Post-wildfire hydrologic recovery in Mediterranean climates: A systematic review and case study to identify current knowledge and opportunities. *J. Hydrol.* 602:126772. doi: 10.1016/j.jhydrol.2021.126772

Wagner, R. G., Bellisario, K. M., and Kong, N. N. (2022). Change in doctoral dissertation topics in forest resources from US universities over four decades. *Forest Sci.* 68, 226–236. doi: 10.1093/forsci/fxac004

Wasserman, T. N., and Mueller, S. E. (2023). Climate influences on future fire severity: A synthesis of climate-fire interactions and impacts on fire regimes, high-severity fire, and forests in the western United States. *Fire Ecol.* 19:43. doi: 10.1186/s42408-023-00200-8

White, A. M., and Long, J. W. (2019). Understanding ecological contexts for active reforestation following wildfires. *N. Forests* 50, 41–56. doi: 10.1007/s11056-018-9675-z

Whitman, E., Parisien, M.-A., Thompson, D. K., and Flannigan, M. D. (2019). Short-interval wildfire and drought overwhelm boreal forest resilience. *Sci. Rep.* 9:18796. doi: 10.1038/s41598-019-55036-7

Wigtil, G., Hammer, R. B., Kline, J. D., Mockrin, M. H., Stewart, S. I., Roper, D., et al. (2016). Places where wildfire potential and social vulnerability coincide in the coterminous United States. *Int. J. Wildland Fire* 25:896. doi: 10.1071/WF15109

Wilhelmi, N. P., Shaw, D. C., Harrington, C. A., Clair, J. B., and Ganio, L. M. (2017). Climate of seed source affects susceptibility of coastal Douglas−fir to foliage diseases. *Ecosphere* 8:e02011. doi: 10.1002/ecs2.2011

Williams, A. P., Livneh, B., McKinnon, K. A., Hansen, W. D., Mankin, J. S., Cook, B. I., et al. (2022). Growing impact of wildfire on western US water supply. *Proc. Natl. Acad. Sci. U.S.A.* 119:e2114069119. doi: 10.1073/pnas.2114069119

Williams, M. I., and Dumroese, R. K. (2013). Preparing for climate change: Forestry and assisted migration. *J. For.* 111, 287–297. doi: 10.5849/jof.13-016

Wintle, B. C., Kennicutt, I., and Sutherland, W. J. (2020). "Scanning horizons in research, policy and practice," in *Conservation research, policy and practice, ecological reviews*, ed. W. J. Sutherland (Cambridge: Cambridge University Press), 29–47. doi: 10.1017/9781108638210.003

Wohl, E., Fryirs, K., Grabowski, R. C., Morrison, R. R., and Sear, D. (2024). Enhancing the natural absorbing capacity of rivers to restore their resilience. *BioScience* 74, 782–796. doi: 10.1093/biosci/biae090

Xu, B., Arain, M. A., Black, T. A., Law, B. E., and Pastorello, G. Z. (2019). Seasonal variability of forest sensitivity to heat and drought stresses: A synthesis based on carbon fluxes from North American forest ecosystems. *Glob. Change Biol.* 26, 901–918. doi: 10.1111/gcb.14843